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Validation of the ISP131001 Sensor for Mobile Peripheral Body Temperature Measurement

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Abstract

Previous studies have indicated that temperature regulation is related to social behavior (for an overview, see IJzerman et al., 2015; IJzerman & Hogerzeil, 2017). However, precise causal relationships between temperature and social behaviors are unclear. These links may be better understood by frequently measuring temperature in daily life and mapping those measurements onto social behaviors. The primary purpose of the present study was to enable such studies by validating a new wireless temperature sensor, the Insight SiP ISP131001, for human peripheral temperature measurement in daily life. In our exploratory dataset, we found moderately high correlations between two ISP131001 sensors and a comparison sensor (r = .81 for the average of our two ISP sensors). These correlations [replicated/did not replicate] in our confirmatory dataset (r = .xx for the average of our two ISP sensors). A secondary purpose of this report is the inclusion of a standard set of relevant measures for social thermoregulation research. We propose that this standard protocol of measures be included in future social thermoregulation studies in order to facilitate and encourage data re-use and aggregation across studies.

Keywords: *peripheral temperature measurement, mobile measurement, validation, measurement protocol, social thermoregulation.*

Introduction

Compared to other core survival needs in humans, temperature has been examined only sparingly (but see, Ekman et al., 1983, as a first notable example to the contrary). Humans and other endotherms need to constantly regulate temperature due to external fluctuations in the environment (Cannon, 1932). A notable exception to this dearth of research on temperature are findings on social thermoregulation (IJzerman et al., 2015), which have suggested that temperature regulation can affect social behavior. But research on social thermoregulation has not been able to show exactly whether and how people's temperature is causally linked to their social behaviors. To facilitate such research, we validate a new wireless device, the ISP131001 mobile temperature sensor, so that peripheral body temperature can be measured in everyday life. Further, to better map out social thermoregulatory mechanisms, we have identified important predictors of temperature regulation. We have created a protocol so that these predictors are recorded in social thermoregulation research from here on forward. Better documentation of such known correlates can help map social thermoregulatory mechanisms across studies.

Social Thermoregulation

In the last few years, researchers have found links between social relationships and temperature regulation, or *social thermoregulation*. The basic idea is that other people can help us regulate our temperature in a variety of ways that likely extends beyond huddling and hugging (IJzerman et al., 2015; IJzerman et al., 2018) Without adequate thermoregulation, one dies. Because regulation of body temperature is expensive energetically, animals (including humans) can reduce these energy expenditures by regulating temperature with the help of conspecifics (e.g., IJzerman et al., 2018; for a review, see IJzerman et al., 2015).

Newborns rely on social thermoregulation when they must depend on their parents to regulate their temperature (see Winberg, 2005). In adults, thermoregulation has been linked to social behaviors in various studies. IJzerman and colleagues for instance find that exclusion (versus inclusion) in a ball-tossing game leads to lower peripheral temperature (IJzerman et al., 2012). Recently, IJzerman, Neyroud, Courset, Schrama, and Pronk (2018) found in one study and two replications (one of which was pre-registered) that holding colder (versus warmer) cups lead to think people of loved ones (and this depends on previous relationships).

Although these results seem to demonstrate a straightforward and strong link between temperature regulation and interpersonal processes, not all of the effects in this literature have been successfully replicated (e.g., original study Williams & Bargh, 2008, failed replication Lynott et al., 2014; original study Bargh & Shalev, 2012, failed replication Wortman, Donnellan & Lucas, 2014), very few studies have been pre-registered, and many (if not most) studies relied on small sample sizes too low to provide meaningful evidence (e.g., IJzerman & Semin, 2009; Williams & Bargh, 2008). Promisingly, a recent meta-analysis of social thermoregulation research does seem to provide general support for a link between social relationships and temperature, one that holds when applying various known techniques to reduce the effects of publication bias as much as possible (IJzerman, Hadi, Coles, Sarda, Klein, & Ropovik, unpublished manuscript).

One of the most convincing findings on social thermoregulation comes from two studies conducted in 12 countries suggesting that the variety and complexity of our relationships can protect our bodies from the cold (IJzerman et al., 2018). Despite these positive findings, the exact *causal* relationships and mechanisms are not yet well understood. Do peripheral temperature changes lead to changes in social behavior and in turn protect core body temperature? And, are peripheral temperature changes in response to social events epiphenomenal or an important chain in a larger causal process? To better understand and model such predictors, future studies need to systematically investigate the relationship between temperature fluctuations and social behaviors. This requires 1) studying (peripheral and core) temperature changes in daily life and 2) measuring known predictors (like height, sex, weight, medicine use, health, and relationship variables) so as to map social context onto temperature fluctuations.

Choosing and validating the ISP131001 sensor for use in daily life

To enable peripheral temperature measurement in daily life, we need a valid and reliable device that is easy to use and comfortable to wear for long periods. We considered several options (please see Table 1 for a list of possible options; see also IJzerman, Heine, et al., 2017). Wireless solutions are needed if we expect participants to wear these devices as they go through their lives. It is also important that the data is recorded frequently (several times per minute) and only saved on one's own server. Moreover, if we ever want to use a sensor that we can rely on for application together with other devices, it is vital that the firmware is open. This allows us to alter the frequency of measurement and it allows us to communicate measurement information to a device that can manipulate temperature (an actuator). Further, we preferred a sensor that could measure every second. Finally, if we are to implement the solution in larger, multi-site studies, the solution needs to be affordable. Because of all those reasons, we chose the ISP131001 sensor.

The ISP131001 sensor is a wireless device that measures temperature, movement, and air pressure. It is small, mobile, records temperature frequently (once per second), and affordable (< 100 Euros per sensor). It is composed of a small processor, a temperature sensor, and a thin cable connecting the sensor to a battery. The overall size of the device is 12.5 x 25 x 3 mm. The sensor communicates via Bluetooth Low Energy with an open source smartphone app that our lab, the CO-RE Lab, developed: the *Bio-App for Bonding* (Frederiks et al., 2018; IJzerman et al., 2018). The smartphone app has a temperature module that displays a running log of temperature measurements (see Figure 1 for a photo of the sensor and the smartphone application). Beyond the temperature module, we also programmed an algorithm into the app to record infant crying, a module to record electrodermal activity, a module to self-report experienced affect through a dial button, an existing experience sampler module, and a module to turn on a device to manipulate temperature, the EmbrWave (Frederiks et al., 2018).

However, as the ISP131001 sensor had not been used in behavioral science before, it is unknown how accurate or suitable it is for research. As such, we chose to validate the sensor with a better-known (and non-mobile) sensor (the *ADInstruments MLT422/A Skin Temperature Probe)* to gauge its suitability for studying human peripheral skin temperature. To also determine whether a more comfortable position than the finger can be used, we attached the sensor to two different body parts: the index finger and the wrist. Moreover, to understand the reactivity of the sensors in different temperature conditions, in addition to baseline temperature measurements, we also we took measurements after participants dipped their hands in cold or hot water. Finally, as we more generally seek to link social behavior to temperature, we also make available a protocol for measuring important variables related to peripheral temperature on the OSF (https://osf.io/xf7uk/?view_only=6fe177e8ed514528b2940b87159a82e6).

Research Overview

We investigated three research questions: To what level are the ISP131001 sensors correlated with the validation sensor overall, regardless of the position of the sensors on the finger/wrist or the temperature condition (baseline, cold, hot; Research Question 1)?; Are the sensors reliably correlated to our validation sensor regardless of the position of the mobile sensor (fingertip/wrist; Research Question 2)?; Are the mobile and validation sensors reliably correlated at different temperature levels (baseline, cold, hot; Research Question 3)? We also conducted auxiliary analyses based on these findings to have more insight about the optimal uses of the ISP131001 sensors. Finally, we included a standard protocol measuring variables related to temperature regulation, which we hope will be reused in thermoregulation studies that follow ours. By measuring these known predictors across studies, meta-analysts can then gather data from different studies to start to map how social behavior maps onto temperature regulation and how these are (potentially) moderated by people's social networks and by people's self-reported individual differences.

Method

Power Analysis and Participants

In order to determine sample size, we ran a power analysis in PANGEA (Westfall, 2015) with a crossed with random stimuli-in-treatments (Clark, 1973) design. We specified participants as a random factor and device, condition (baseline, hot, cold) and position of the sensor (index or wrist) as fixed factors. Assuming an effect size of r =.40[1] (d =.87), 24 participants would allow 99% power. With 12 participants (e.g., after splitting the data into exploratory and confirmatory datasets) we would have 89% power for the same effect sizes. Notably, we did not have any a priori expectations for what magnitude of correlation to expect and the mere presence of a correlation is only minimally informative for the current question ("is the ISP131001 suitable for studying human peripheral temperature?"). Thus, below we focus on observed effect sizes and confidence intervals.

24 participants, 18 women and 6 men (M_{age} = 24.4, SD_{age} = 4.28) took part in this study. Participants were recruited either via our student participant pool or by inviting people from around the building where we conducted our study. The study took approximately 45 minutes for each participant to complete.

Procedure and Materials

[1]The choice of this expected correlation is partly arbitrary, but we undershot what we expected, for the purpose of our power analysis. We performed various power analyses considering different scenarios. Even if it was probably justified to expect a correlation higher than r = .40 (as one should expect that two measures measuring the same should have quite a high correlation), we decided to take a lower bound in order to ensure that our study would have sufficient power.

The entire study took place in a lab room at Université Grenoble Alpes[2]. The study consisted of two parts. First, participants completed a questionnaire measuring variables related to social thermoregulation. Next, we measured the peripheral body temperature of the participants in three temperature conditions: baseline, after dipping their hand in cold water, and after dipping their hand in hot water.

Questionnaire Details: After filling out informed consent forms, participants completed a questionnaire in Qualtrics, where they answered questionnaires theoretically related to social thermoregulation. These questionnaires were completed in a random order and demographics were answered after the last questionnaire. The entire dataset and questionnaire are available on the OSF Project Page: https://osf.io/4nkqe/?view_only=c1b69f7103d743338cabb8b69c48f344 & https://osf.io/7h5sc/?view_only=c1b69f7103d743338cabb8b69c48f344. The latest update of the protocol using these questionnaires will be posted on the OSF as well (https://osf.io/xf7uk/?view_only=6fe177e8ed514528b2940b87159a82e6). The following scales were included in this questionnaire (all reliabilities are reported based on the exploratory subset and will be updated after the inclusion of the confirmatory analyses):

The *Experiences in Close Relationship-Revised (ECR-R;* Wei et al., 2007) questionnaire is a 36-item questionnaire measuring adult attachment in close relationships. Sample item: "I turn to my partner for many things, including comfort and reassurance". Response options ranged from 1= *strongly disagree*, to 7 = *strongly agree.* The questionnaire is composed of 2 subscales: one measuring anxiety (α = 0.94; ω_h: 0.61; ω_t: 0.97) and other one measuring avoidance (α = 0.97; ω_h: 0.88; ω_t: 0.98.[3]

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[2] We measured ambient temperature with a Tempo Disc Bluetooth Temperature Sensor Beacon and Data The room averaged 24.15 (*SD* = 1.14) degrees Celsius between the different sessions.

[3] We always first report Cronbach's alpha, because it is the most well-known measure of reliability. Cronbach's alpha is suboptimal as a reliability measure as it tends to underfit data for heterogeneous samples. We therefore also report the Omega Coefficient, which is a more robust estimate of our scales' reliabilities (Dunn, Baguley, & Brunsden, 2014; Revelle & Zinbarg, 2009; Sijtsma, 2009).

The Social Thermoregulation and Risk Avoidance Questionnaire (STRAQ-1; Vergara et al., 2019) is composed of 23 items and 4 subscales. The most important scale for this type of research is the Social Thermoregulation subscale (α = 0.77; ω_h: 0.64; ω_t: 0.89; Sample item: "When I feel cold I seek someone to cuddle with"), which measures individual differences in the desire to rely on other people to regulate temperature, the Solitary Thermoregulation subscale (α = 0.82; ω_h: 0.45; ω_t: 0.94; Sample item: "When I feel cold I don't turn on the heater"), which measures individual differences in the degree to which people desire to regulate temperature by themselves and High temperature sensitivity (α = 0.91; ω_h: 0.68; ω_t: 0.98; Sample item: " I am sensitive to heat "). Response options for the entire scale ranged from 1= *strongly disagree*, to 5 = *strongly agree*.

The Social Network Index (SNI; Cohen et al., 1997) measures the number and type of social networks a person engages in frequently, including friends, family, romantic partners, co-workers and others (12 total). For each relationship participants have to say if they have some contacts in that social domain and with how many people they have contacts at least once every two weeks. Answers are scored from 0 to 12, with 12 indicating that a participant is engaged in all types of social relationships. This questionnaire is composed of 3 subscales: the level of social embeddedness, the social network diversity, and the network size (no reliability information available for this scale).

Single-Item Questions: At the end of the questionnaire we also asked participants questions about their sex, age, height, weight, native language, whether they are in a romantic relationship or not, and the country of birth of their parents[4].We also added questions on whether people smoke (and, if yes, how many cigarettes per day), whether they use medication (and, if yes, which kind of medication), and whether they use birth control pills

[4] We asked participants for their parents' birth country, as asking about ethnicity is not permitted in France.

(only for women). Finally, we asked our female participants to predict their next menstrual cycle[5].

Temperature Measurements: Once participants completed the questionnaire, we began the peripheral body temperature measurement portion of the study. We used 3 sensors: two wireless ISP131001 sensors (ISP131001 Sensor 1, ISP131001 Sensor 2), and the wired comparison device: the ADInstruments MLT422/A Skin Temperature Probe (Liu, Zhu, Wang, Ye, & Li, 2013; Gao, Chong, Zhang, Cheng, & Zhu, 2012). We attached the temperature sensors to the participant's non-dominant hand: two sensors were attached to the index finger and the other one to the wrist (note: The finger is typically known as the most sensitive place to measure peripheral temperature changes; Huizenga et al., 2004). We measured on the wrist as well because this would be much more comfortable for participants to wear at home if the wrist showed similar results as the fingertip. The comparison sensor (the ADInstruments MLT422/A Skin Temperature Probe), was always attached to the finger, along with one of the two ISP131001 sensors. The other ISP131001 was attached to the wrist, and we randomly varied which of the two ISP131001 sensors was attached in which location in case there were unit-specific differences.

In order to assess the sensor across various temperature ranges, we measured the peripheral body temperature of each participant in three conditions: (1) at baseline, (2) after the participant dipped their hand in cold water (10 degrees Celsius) for 20 seconds, (3) after the participant dipped their hand in hot water (40 degrees Celsius) for 20 seconds (see Figure 2, for a schematic overview on our temperature's measurements). Every session followed the same order for temperature measurement. First, we recorded peripheral body temperature with all three devices for 5 minutes as a baseline measurement. After this, we removed the sensors

[5] Note that we should have asked a backward counting question (Gangestad et al., 2016; Vickers, 2017) but this was a mistake on our side in our protocol. This has been updated on our OSF page: https://osf.io/xf7uk/wiki/home/?view_only=6fe177e8ed514528b2940b87159a82e6 ,

from the participants' hands and we had participants dip their non-dominant hand in a cold (on average 10 degrees Celsius) water bath for approximately 20 seconds. We used a *Techne FTE10 ADC* liquid bath and a *Cold pressor Techne RU 200* to cool the water. Once participants dried their hands, we reconnected the 3 temperature sensors in the same positions as before and then measured peripheral body temperature for 5 minutes. Then, after again removing sensors from participants' hand, they again dipped their non-dominant hand in the same water bath, but now with hot (40 degrees Celsius) water for 20 seconds. We used a *Techne immersion circulator TE-10A Tempette* to heat the water and keep it at constant temperature. Once participants dried their hands, we again measured peripheral body temperature with our 3 devices for 5 minutes in the same positions. When the third peripheral body temperature recording was finished, the study was complete. Finally, we thanked the participant and briefly explained the objective of the study.

Results

Analysis Plan

All analyses were conducted in R (R Core Team, 2012), primarily using mixed effects models with the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) to examine the relationship between the temperature readings from our three sensors. We used mixed models because the temperature was measured more than once on the same participant. The ISP131001 sensors recorded temperature approximately once per second for a total of 15 minutes. The mixed models allow us to consider both the variability within and between participants. The dataset and analysis code are available on the OSF page: https://osf.io/hbcw7/?view_only=c1b69f7103d743338cabb8b69c48f344 . In accordance with the guidelines for Exploratory Reports, we split our data into two random samples: we used the first sample (12 participants) to explore our data, leaving the remaining data (12 participants) to confirm our predictions[6]. The confirmatory data will give us the least biased estimate of the performance of the ISP sensors. For the moment we only present exploratory results from our first sample and we have not analyzed nor examined the confirmatory data split. As we have two ISP sensors, we present two separate but identical analyses for each research question: first we present the relationship between our first ISP sensor (ISP Sensor 1) and the MLT probe, and then a parallel analysis examining the relationship between the second ISP sensor (ISP Sensor 2) and the MLT probe (see Table 2 for more details on the analyses). Finally, we added auxiliary analysis testing the relationship between the average of the ISP sensors and the MLT probe. We do not analyze the questionnaire data, as the sample size is too small to draw any meaningful conclusions.

Exploratory Results (12 participants)

Research Question 1: How correlated are the ISP131001 sensors with the validation sensor? We ran linear mixed effect models to assess the correlation between our new sensors and the validation sensor. We reported complementary information for analyses testing Research Question 1, such as Standardized coefficients, *p*-values, and η_p^2 in Table 3. The $R^2$of the full model testing the relationship between ISP Sensor 1 and the MLT probe was .71, 95% CI = [.70, .72]. This analysis revealed a positive relationship between these two sensors (r = 0.55, 95% CI = [.53, .56])[7], such that temperature readings from ISP Sensor 1 are strongly related to temperature changes in the MLT probe, when we controlled for sensor position and participant temperature condition.

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[6] The third author performed the data split and the first author analyzed the results, without having access to the second half of the data.

[7] The reported R^2 has been calculated by applying the Nakagawa and Schielzeth approach. More precisely it is a marginal R^2, which is more appropriate for use with mixed effects models compared to the R^2 calculation used in standard regression. Please note that the interpretation of this statistical index is similar to the interpretation of R^2 in standard regression, but the calculation is not equivalent to the R^2 calculation in standard regression (Nakagawa & Schielzeth, 2012)

We then ran the same analysis with the second ISP unit (ISP Sensor 2). This is partially a replication and partially to test a second ISP unit for consistency. The R^2 of the full model was .63, 95% CI = [.63, .64]. These analyses revealed a significant positive relationship between ISP Sensor 2 and the MLT probe (r = 0.36, CI = [.34, .38]), such that temperature changes on ISP Sensor 2 are related to temperature changes in the MLT probe, when we controlled for the others variables. Thus, for the second ISP sensor the correlations with the MLT probe were lower than our first sensor. Altogether, this suggests that there is a considerable amount of noise when using the ISP Sensor on the finger and on the wrist.

Research Question 2: Are the sensors reliably correlated to our validation sensor regardless of the position of the mobile sensor? In order to answer our second research question, we first examined the correlation between our new sensors and the validation sensors at different sensor positions (finger/wrist). Again, we reported complementary information for analyses testing Research Question 2, such as Standardized coefficients, *p*-values and η_p^2 in Table 4. Analyses testing the relationship between ISP Sensor 1 and the MLT probe indicated that the correlation between these two sensors was larger when sensors were placed in the same position (i.e., both on the finger): (r = 0.61, 95% CI = [.59, .62]), than when one was on the finger and one was on the wrist: (r = 0.32, 95% CI = [.30, .34]). Similarly, analyses testing the relationship between ISP Sensor 2 and the MLT probe showed that the correlation between these two sensors was bigger when sensors were placed in the same position: (r = 0.50, 95% CI = [.49, .51]), than in different positions: (r = 0.04, 95% CI = [.03, .06). These analyses suggest that the wrist does not correlate very well with temperature changes on the finger in our study.

Research Question 3: Are the mobile and validation sensors reliably correlated at different temperature levels? In order to answer our third research question, we examined the correlation between our new ISP sensors and the validation sensor at different temperature levels (baseline, cold, hot). Again, we reported complementary information for all the analyses testing Research Question 3, such as Standardized coefficients, *p*-values, and η_p^2 in Table 5. Analyses testing the relationship between ISP Sensor 1 and the MLT probe showed that the relationship between the two sensors was stronger at baseline (r = 0.80, 95% CI = [.79, .80]) than in the hot (r = 0.55, 95% CI = [.54, .56]) and cold conditions (r = 0.55, 95% CI = [.55, .58]). Similarly, analyses testing the relationship between ISP Sensor 2 and the MLT probe again revealed that the correlation between these two sensors was stronger at baseline (r = 0.77, 95% CI = [.76, .78]) than in hot (r = 0.39, 95% CI = [.37, .40]) or cold condition (r = 0.33, 95% CI = [.32, .35]). These analyses suggest that the ISP sensors (who measure more infrequently) do not capture changes as well as the validation sensor (which measures every millisecond).

Auxiliary analysis testing the relationship between the average of the ISP sensors and the MLT probe.

After we exploring the sensors individually and finding somewhat lower correlations than we had hoped, we decided to explore an alternative way to use the ISP sensors in hopes of increasing accuracy. As the correlations decreased when we manipulated peripheral temperature, we suspected that accuracy was simply lower due to less frequent measurements. We therefore now tried averaging the readings between the two ISP sensors (one on the wrist and one on the finger) and comparing that average with the MLT probe, our validation sensor. We used the same overall linear mixed effects model as before, but replaced the individual measures from the two ISP sensors with their average reading per each timepoint. We also removed the position variable as it does not make sense with the present model[8].

The R^2 of the full model was .84, 95% CI = [.83, .84]. Again, we reported complementary information for all the analyses that follow, such as standardized coefficients,

[8] Here the two ISP sensor were always placed in different positions.

p-values, and η_p^2 in Table 6. Analysis again revealed a significant positive relationship between the average of the ISP sensors and the MLT probe (*r* = 0.82, 95% CI = [.82, .83]), such that temperature changes averaged between the ISP sensors were highly correlated with temperature changes in the MLT probe, controlling for temperature condition. The correlation between the average of the ISP sensors and the MLT probe was stronger at baseline (*r* = 0.91, 95% CI = [.91, .91]) than in hot (*r* = 0.84, 95% CI = [.83, .84]) or cold conditions (*r* = 0.87, 95% CI = [.86, .87]). A visual representation of exploratory correlations between sensors is presented in Figure 3. These analyses show that the correlation between the average of our two sensors (placed in different positions) is higher than previous correlations in which we used the ISP sensors units separately. In addition, the two sensors together seem to capture change in temperature better, as the correlation with the validation sensor increased in the hot and cold conditions.

Confirmatory Results

Based on these exploratory findings, we propose that averaging readings from two ISP sensors produces the most suitable and accurate method for use in daily life. Therefore, in our confirmatory results we focus on the correlation between the average of the two ISP sensors and the MLT probe. Because the size of the correlation is critical to our interpretation, we focus on the effect size in our confirmatory analysis. We will use a relatively arbitrary effect size difference of r = .15 change from our exploratory result as replicating the effect with a similar effect size. Both the point estimate and confidence interval range have to fall within this +/- .15 range to be considered a replication. Confirmatory results larger than that range will be considered substantially stronger correlations, while confirmatory results smaller than that range will be considered substantially weaker correlations. In the case the point estimate falls within the +/- .15 range, but the 95% CI does not, we will include a note acknowledging the ambiguity. In addition, we will re-run the exploratory results for the individual sensors and report those results in table XX as unbiased estimates of the true correlation in those various scenarios. However, to constrain our flexibility in interpreting the results, we do not focus on these results as the basis for our overall conclusions.

Relationship between the average of the ISP sensors and the MLT probe

We conducted exactly the same analyses on the average of two sensors as presented in the exploratory section, but this time using the remaining 12 participants from our holdout sample. As our main confirmatory analyses, we have chosen to conduct only the correlation between MLT probe and the averaged ISP sensors, as 1) the average of the two sensors has a higher correlation and 2) the average of the sensors seems to capture change better than one sensor alone (as auxiliary analyses to again demonstrate the superiority of the two averaged sensors).

The R^2 of the full model was XX, 95% CI = [.XX, .XX]. Again, we reported complementary information for all the analyses that follow, such as Standardized coefficients, *p*-values, and η_p^2 in in Table XX. Analysis revealed a [significant positive/negative;/non-significant positive/negative] relationship between the average of the ISP sensors and the MLT probe (r = XX, 95% CI = [.XX, XX]), such that temperature changes averaged between the ISP sensors were XX correlated with temperature changes in the MLT probe, controlling for temperature condition. According to previously stated criteria, the observed confirmatory effect for this overall correlation [replicates our exploratory result, is weaker than our exploratory result, is stronger than our exploratory result]. [IF THE 95% CI CROSSES THRESHOLDS: Note, however, that the 95% CI of our replication effect did not fall fully within our defined effect size range, and therefore this interpretation is not entirely conclusive.] The correlation between the average of the ISP sensors and the MLT probe [varied, did not vary] between temperature conditions: r = XX 95%, CI = [.XX, XX] at baseline, r = XX, 95% CI = [.XX, XX] in the hot condition, and r = XX, 95% CI = [.XX, XX]) in the cold condition. Therefore, [like our exploratory result, the size of this correlation varied between temperature conditions/unlike our exploratory result, this correlation was consistent across temperature conditions]

Discussion

[This is an initial draft, we'll go into more detail depending on our confirmatory analyses]

Our primary goal was to validate the ISP131001 sensor for use in human peripheral temperature measurement. Thus, in two independent samples with sufficient power, (considering our power analysis) we tested the degree to which our mobile ISP131001 sensor, or the average of two ISP sensors, correlated with measurements taken by a comparison device (the MLT422/A Skin Temperature Probe). Our analyses indicate a correlation between our ISP131001 sensors and the MLT probe, suggesting that the ISP131001 sensor is a [very accurate and highly suitable, reasonably accurate but imperfect, insufficiently accurate] device for these purposes. A secondary purpose was to create a standard protocol of relevant measures for social thermoregulation research. The entire questionnaire is available on the OSF page: https://osf.io/7h5sc/?view_only=c1b69f7103d743338cabb8b69c48f344 . We encourage social thermoregulation researchers to use this protocol in future studies to facilitate data re-use and aggregation, and ensure relevant variables are measured.

Our exploratory results on the correlation between each individual ISP sensor and the validation sensor indicate that this correlation was far from perfect, and varied based on the position of measurement and the temperature condition (whether the participant was measured at baseline, or had dipped their hand in cold or warm water). We note that the correlation between the two sensors is stronger when both sensors were positioned on the finger, compared to when one is on the finger and the other is on the wrist. Our exploratory results also show that averaging the readings from two ISP sensors results in a substantially higher correlation with the validation sensor. The higher correlation from averaging two ISP sensors held across all three temperature conditions (baseline, hot, cold). Thus, the two sensors together seem to capture change in temperature better than only one sensor. These exploratory findings suggest that individual ISP sensors *may* be suitable for mobile temperature measurement depending on the application and the degree of precision required. However, using a second ISP device and averaging the two temperatures appears to be a much more precise solution, suitable for a wide range of studies examining peripheral temperature in humans.

[If confirmatory global correlation replicates exploratory global correlation, and correlations at different conditions are consistent/inconsistent with exploratory global correlation][9][10]

Our confirmatory results show a high correlation between the average measure of two ISP sensors and the validation sensor. This correlation was [consistent, inconsistent] across temperature conditions. [It is possible that the ISP sensors took longer to stabilize after a temperature change, as compared to the MLT sensor which was more responsive, ISP sensors and MLT sensor take similar amount of time to stabilize after a temperature change]. We can conclude that the ISP131001 sensor (which is wireless and mobile) could be a viable alternative to measure peripheral body temperature depending on the needs of the researcher. Experimenters should gauge for themselves whether these mobile temperature sensors are suitable for their research question on a case-by-case basis, and should keep into account a loss of accuracy when they plan their studies. This study in lab settings was necessary to validate the ISP sensor: a wireless device that is easy and comfortable to wear and carry around at all times. But, accuracy in the field is still unknown. More research will be needed

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[9] Both the correlation coefficient and confidence interval ranges have to fall within +/- .15 range (i.e. exploratory r = .8, 95% CI = [.79, .81]; confirmatory r = .7, 95% CI = [.68, .72]).
[10] More details on inconsistent results across temperature conditions and inconsistency between correlation coefficient and confidence interval in confirmatory results will be discussed in the final version of the discussion, according to our results.

1) to validate the ISP sensor outside of the laboratory, and 2) to study the relationship between temperature fluctuations and social behaviors in more ecologically valid situations, for instance by asking participants to wear ISP sensors for several days and filling questionnaires about their interpersonal relationship.

[If confirmatory global correlation shows stronger correlations then exploratory global correlation, and correlations at different conditions are consistent/inconsistent with exploratory global correlation][11][12]

Our confirmatory results show a nearly perfect correlation between the average measure of two ISP sensors and the validation sensor. This correlation was [consistent, inconsistent] across temperature condition. These findings allow us to conclude that the ISP131001 sensor (which is wireless, mobile) is a very good alternative to measure peripheral body temperature in daily life. This study in lab settings was necessary to validate the ISP sensor: a wireless device that is easy and comfortable to wear and carry around at all times. But, accuracy in the field is still unknown. More research will be needed 1) to validate the ISP sensor outside of the laboratory, and 2) to study the relationship between temperature fluctuations and social behaviors in more ecologically valid situations, for instance by asking participants to wear ISP sensors for several days and filling questionnaires about their interpersonal relationship.

[11] Both the correlation coefficient and confidence interval ranges are larger than +/- .15 range (i.e. exploratory r = .8, 95% CI = [.79, .81]; confirmatory r = .98, 95% CI = [.97, .99]).

[12] More details on inconsistent results across temperature conditions and inconsistency between correlation coefficient and confidence interval in confirmatory results will be discussed in the final version of the discussion, according to our results.

[If confirmatory global correlation shows weaker correlations then exploratory global correlation, and correlations at different conditions are consistent/inconsistent with exploratory global correlation][13][14]

Our confirmatory results indicate a far from perfect correlation between the average measure of two ISP sensors and the validation sensor. This correlation was [consistent, inconsistent] across temperature condition. [It is possible that the ISP sensors took longer to stabilize after a temperature change, as compared to the MLT sensor which was more responsive, ISP sensors and MLT sensor take similar amount of time to stabilize after a temperature change]. These results may be problematic, suggesting that the ISP sensors took longer to stabilize after a temperature change and may be less reliable or accurate than we had hoped. We conclude that the ISP131001 sensor is likely not a viable alternative to measure peripheral human body temperature if precise and reliable measurement is critical. However, experimenters should gauge for themselves whether these mobile temperature sensors are suitable for their research question on a case-by-case basis, and should take into account a loss of accuracy or reliability when they plan their study. Future studies (or improvements) are necessary before endorsing the general use of the device instead of available alternatives.

Limitations

In terms of the study itself, a firm limitation is that the two ISP sensors were never attached in exactly the same position on the body: they were rotated between one being attached on the finger and the other on the wrist, or vice-versa. [Therefore, it is impossible to conclude whether the observed accuracy benefit from averaging across two ISP units requires the sensors to be in different positions, or if, for example, two ISP sensors could be attached

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[13] Both the correlation coefficient and confidence interval range are smaller than +/- .15 range (i.e. exploratory r = .8, 95% CI = [.79, .81]; confirmatory r = .62, 95% CI = [.61, .63]).

[14] More details on inconsistent results across temperature conditions and inconsistence between correlation coefficient and confidence interval in confirmatory results will be discussed in the final version of the discussion, according to our results.

to the wrist.] It is also impossible to directly compare the two ISP sensors when they're measuring exactly the same temperature to inform about how consistently different individual ISP sensors measure. In future studies it would be informative to attach several ISP sensors in the same position, to be fully certain that they are measuring the same underlying temperature, to directly rest reliability between units. A second limitation is that we are not certain that the lower correlations after participants dipping their hands in cold or hot water wasn't simply due to a less solid connection for the sensor (due for example to the moisture after water bath). A third limitation is that our ISP sensors seem to overestimate the temperature (at least as compared to our reference sensor). We suspect that this is due to a calibration issue. Because of this, we recommend using two sensors to get the most accurate reading of temperature with the ISP sensor. A fourth limit is that it seems that our manipulation in hot condition did not work as expected, as the participants have a slightly higher temperature in baseline condition, than in hot condition. In future studies it would be better to use a stronger manipulation of hot condition (for instance by asking participants to dip their hand in cold water) in order to better study the sensitivity of sensors to heat.

In general, there are trade-offs when considering which method of peripheral temperature measurement to use. The ISP131001 sensor only measures temperature once per second, for example, whereas the MLT probe measures every millisecond. Thus, for research questions requiring extremely responsive or accurate temperature measurement, there is likely no alternative to traditional wired temperature sensors.

Constraints on Generality

We think that the devices should perform similarly as the present report across various populations and scenarios, but consider possible differences in accuracy in different temperature conditions (e.g., in very hot or cold environments the devices may be less accurate as compared to room temperature). A critical consideration is that the device should maintain secure skin contact throughout the measurement period.

Conclusion

To date, peripheral temperature has been measured mostly by non-mobile solutions that are hard to use in everyday situations. In this article we have investigated a new, convenient wireless temperature sensor: the ISP131001. According to our results, this sensor [shows/unfortunately doesn't show] promise as a device to study temperature constantly in daily life. The device was [highly accurate, moderately accurate, not at all accurate] overall, [and performed consistently across different conditions/but varied in accuracy across different conditions]. Accuracy [improved/didn't improve] when using two devices simultaneously and averaging across their temperature readings. With this information from our investigation of the ISP131001 and various temperature measurement solutions, and the protocol of measurements we have proposed to identify links between thermoregulation and social behaviors, we hope to give future researchers a better sense for their options for peripheral temperature measurement in the lab and in daily life.

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Table 1. Specifications of existing solutions measuring peripheral temperature

Device	Wireless	Data saved on one's own server only?	Recording frequency
Thermistors	No	Yes	Once per second
Thermocouples	No	Yes	Once per second
iButton	Yes	Yes	Once per minute
BlueMaestro Tempodisc	Yes	No	Once per second
ISP131001 sensor	Yes	Yes	Once per second

Table 2: Overview of our Analyses

Research Question	DV	IV	Random factors
1.How correlated are the sensors overall, regardless of the position of the sensors or the temperature condition?	MLT probe	-ISP sensor (1 or 2 according to the analysis) -2 orthogonal contasts for the temperature condition (C1: comparing cold and hot taken together to the baseline, and C2: comparing cold to hot) -centered variable for sensor positions - interaction terms	slope and intercept of participant number.
2. Are the sensors sufficiently correlated regardless of the position of the sensor?	MLT probe	-ISP sensor (1 or 2 according to the analysis) -2 orthogonal contasts for the temperature condition -dummy coded variable for sensor positions - interaction terms	slope and intercept of participant number.
3. Are the sensors sufficiently correlated at different temperature levels?	MLT probe	-ISP sensor (1 or 2 according to the analysis) - dummy coded variable for the temperature condition -centered variable for sensor positions -interaction terms	slope and intercept of participant number.

Table 3: Standardized coefficients, p-values, and η_p^2 for the analyses testing our Research Question 1.

	Standardized coefficients (beta)	η_p^2
MLT ~ ISP1 (overall)	.62***	.30
MLT ~ ISP 2 (overall)	. 33***	.13

* denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$.

Table 4: Standardized coefficients, p-values, and η_p^2 for the analyses testing Research Question 2.

	Standardized coefficients (beta)	η_p^2
MLT ~ ISP1 (same position)	.62***	.37
MLT ~ ISP1 (different position)	.62***	.10
MLT ~ ISP 2 (same position)	.33***	.25
MLT ~ ISP 2 (different position)	.33	.01

* denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$.

Table 5: Standardized coefficients, p-values and η_p^2 for the analyses testing Research Question 3.

	Standardized coefficients (beta)	η_p^2
MLT ~ ISP1 (baseline)	.93***	.64
MLT ~ ISP1 (hot)	.59***	.30
MLT ~ ISP1 (cold)	.59***	.32
MLT ~ ISP 2 (baseline)	.80***	.60
MLT ~ ISP 2(hot)	.34***	.15
MLT ~ ISP 2 (cold)	.32***	.11

* denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$.

Table 6: Standardized coefficients, p-values, and η_p^2 for the correlation between the average of the two ISP sensors and the MLT probe.

	Standardized coefficients (beta)	η_p^2
MLT ~ ISP $_{average}$ (overall)	.71***	.68
MLT ~ ISP $_{average}$ (baseline)	.87 ***	.84
MLT ~ ISP $_{average}$ (hot)	.72*	.70
MLT ~ ISP $_{average}$ (cold)	.72**	.75

* denotes p < 0.05, ** denotes p < 0.01, and *** denotes p < 0.001.

Figure 1. Sensor and Smartphone Application. Picture of the hand is one of the co-authors and thus posted with consent.

Figure 2. Schematic overview of position of our temperature measurements. Picture of the hand is one of the co-authors and thus posted with consent.

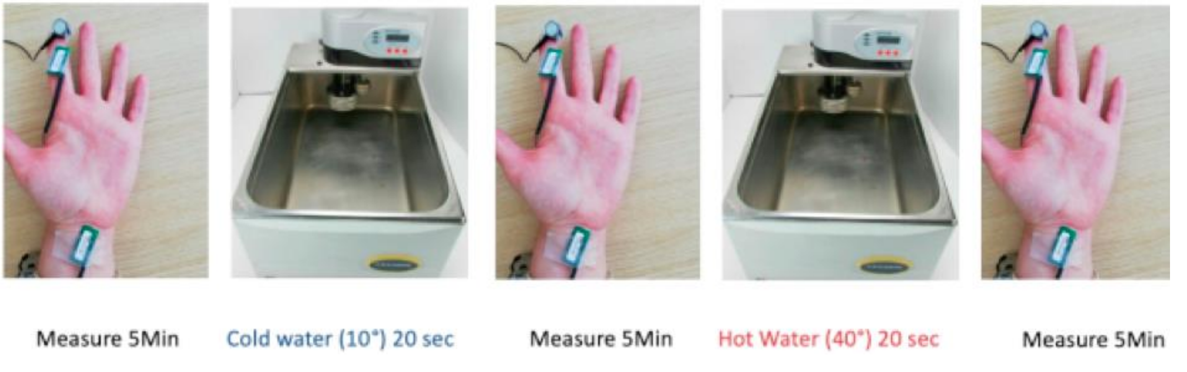

Figure 3. Visual representation of exploratory correlations between sensors in 3 experimental conditions.