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Infant heat balance in hot, dry conditions: Implications for infant health in a warming world

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ABSTRACT

Infants (<1 year) are among the most vulnerable groups during extreme heat. Whereas caregiver dependence contributes to this vulnerability, the role of infants' thermoregulatory system remains unclear. This study examined the thermoregulatory responses of twenty healthy, term-born infants (3–13 months) during short-term exposure trials in controlled environments at 23 °C and 34 °C, 20% relative humidity. Estimated core temperature, local and mean skin temperatures, heart rate, and whole-body sweat rate (WBSR) were measured. Heat balance components (dry heat loss, wet heat loss, heat storage, and metabolic heat production) were calculated to quantify heat strain and heat exchange pathways. Outcomes were compared between trials (paired *t*-tests). At 34 °C, infants showed higher tympanic (+0.4 °C, $p < 0.001$) and temporal (+0.4 °C, $p < 0.001$) temperatures, as well as mean skin temperature (+2.2 °C, $p = 0.002$) and WBSR (+74.1 $g/m^2/h$, $p < 0.001$) compared to 23 °C. The primary heat exchange pathway differed between trials; dry heat loss constituted 72% of total heat loss (defined as the sum of dry and wet heat loss) at 23 °C but only 11% at 34 °C. Overall heat storage did not differ between trials ($p = 0.844$). At 23 °C, heat storage was slightly below zero (95% CI [−1.95, −0.14] W), while at 34 °C it was not significantly different from zero (95% CI [−2.47, 0.14] W). Age was related to wet heat loss at 34 °C, with older infants exhibiting higher rates ($\beta = 6.4$; 95% CI [2.2, 10.3]). Overall, infants showed no net heat storage over the 60-min exposure at 34 °C, 20% relative humidity, and relied primarily on wet heat loss for heat dissipation. However, over-reliance on evaporative cooling may become dangerous when sweating is restricted by high relative humidity or clothing, emphasizing the importance of facilitating adequate sweat evaporation and hydration in infants exposed to heat.

1. Introduction

By 2050, almost every child on the planet will frequently be exposed to heatwaves, regardless of whether global warming is limited to 1.7 °C, under a low-emission scenario, or rises to 2.4 °C, under a very high-emission scenario (UNICEF, 2022). Already, one in five children faces at least twice as many extremely hot days as their grandparents' generation (UNICEF, 2024). These numbers reflect alarming climate trends, with global surface temperatures rising faster in the past 50 years than at any other time in the past two millennia, and heatwaves becoming more frequent, intense, and prolonged (Seneviratne et al., 2021). As a result, exposure to extreme heat, which can result in heat stress, has become an increasing threat to children worldwide, with infants being particularly vulnerable.

Heat stress occurs when the human body cannot dissipate enough excess heat to maintain a stable core temperature, which can lead to heat-related illnesses, ranging from mild heat rashes to life-threatening heatstroke or organ failure (Gagnon et al., 2025). Thermoregulation depends on the dynamic balance between internal heat production and heat exchange with the environment through evaporation, radiation, convection, and conduction (Périard et al., 2021). External factors, such as air temperature, humidity, solar radiation, wind speed, and clothing insulation, can disrupt this thermal balance and increase the risk of heat-related illness (Pryor et al., 2015).

Epidemiological studies have consistently identified infants (age <1 year) as a particularly vulnerable group during times of extreme heat, because they face increased heat-related morbidity (Lakhoo et al., 2022; Mannan et al., 2011; Teyton et al., 2024) and mortality (Basagaña et al.,

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2011; Basu and Ostro, 2008; Geruso and Spears, 2018; Scovronick et al., 2018). Their vulnerability results from both their behavioral dependence on adult caregivers and their unique physiological characteristics. Specifically, infants cannot change clothing, seek shade, or adjust fluid intake themselves, and they typically signal thermal stress or discomfort only through behavioral responses such as crying (Mangus and Canares, 2019; Williams, 2021). Caregivers often rely on their own thermal perceptions when dressing infants or ensuring they are hydrated, which can lead to overheating or dehydration (Folkerts et al., 2020). Extreme examples of infants' dependency on caregivers have been well documented, such as pediatric vehicular heatstroke, which illustrates how rapidly heat stress can occur when protective actions are lacking (Duzinski et al., 2014).

A narrative review by Van de Kamp and Daanen (2025) highlighted key physiological features that further increase infants' vulnerability in the heat when compared to older children and adults. These features include a higher body surface area-to-mass ratio, which leads to more dry heat gain from the environment when ambient temperatures exceed skin temperature, and increased size-adjusted metabolic heat production, resulting in a higher need for heat loss to maintain thermal balance.

Experimental studies by Tsuzuki and colleagues have shown that infants experience higher rises in core temperature than older individuals under identical short-term environmental exposures. In Tsuzuki-Hayakawa et al. (1995), mothers and their young children (mean age: 2.1 years) were exposed to hot and humid conditions (35 °C, 70% relative humidity (RH)) for 30 min. The study found that the infants' rectal temperature increased immediately upon entering the hot environment and remained significantly higher compared to both the control period and to that of their mothers, whose rectal temperature remained unchanged. More recently, Tsuzuki (2023) compared the thermoregulatory response of children from different age groups under the same conditions (35 °C, 70% RH) for 30 min, and observed that the increase in rectal temperature in infants (<1 year) was significantly higher than in children aged between 2 and 8 years.

Yet, comprehensive data on infant thermoregulatory responses to heat, even under moderate heat conditions, remain scarce, likely due to ethical and/or methodological constraints. As a result, current public health guidance is predominantly based on epidemiological studies, and inference from physiological studies on other age groups, rather than direct physiological evidence collected from research trials in this population. Studies that assess the complete heat balance equation, including dry and wet heat exchange pathways and heat storage, are urgently needed to understand if, and how, infants can maintain thermal balance under a variety of environmental conditions.

Therefore, we investigated the acute thermophysiological responses of infants during controlled exposure trials under 23 °C, 20% RH and 34 °C, 20% RH conditions. The goal of this study is to generate knowledge that can contribute to evidence-based guidance for caregivers, clinicians, and public health professionals to better assess and deal with heat-related health risks in infants, and guide future research on infant thermoregulation. Specifically, we aimed to: 1) describe physiological differences in core and skin temperatures, heart rate, and whole-body sweat rate (WBSR) across trials; 2) compare the heat balance of infants (including dry and wet heat loss, heat storage, and metabolic heat production) across trials; and 3) explore the influence of age, sex and body surface area-to-mass ratio on the infants' heat balance.

2. Methods

2.1. Participants

Twenty healthy, term-born infants, aged between 3 and 13 months and living in the Netherlands, were included in the study. Preterm infants (<37 weeks gestational age) and infants with any medical conditions were excluded. Participants were recruited from the Sarphati Cohort, a longitudinal research cohort in Amsterdam which follows children from birth to 18 years old (Sarphati Cohort, 2025), and through word of mouth. Written informed consent was obtained from all parents or guardians before their infants' participation in this study. This study was approved by the Scientific and Ethical Review Board of the Faculty of Behavioral and Movement Sciences of the Vrije Universiteit Amsterdam (approval number VCWE-2024–138R1). Data were collected between February and July 2025. Participant characteristics are shown in Table 1.

2.2. Study design

Participation consisted of two visits to a climate-controlled chamber at the Vrije Universiteit Amsterdam (b-Cat B.V., Tiel, the Netherlands). During the visits, infants participated in two trials, in randomized order: 1) 34 °C at 20% RH, representing a high ambient temperature increasingly observed in the Netherlands (Van Oldenborgh, 2020), and 2) 23 °C at 20% RH, representing a baseline temperature condition. Minimal airflow was maintained to ensure consistent exposure (< 0.2 m/s). The exposure trials lasted 90 min, with the first 30 min serving as a familiarization period.

Before entering the climatic chamber, infants were fitted with a fresh diaper and were recently fed according to the parents' or guardians' usual practice. All clothing, except for the diaper, was removed. Infants were positioned in a portable crib centrally located in the climatic chamber, allowing them to lie down, sit, sleep, or play. Parents or guardians were invited to accompany their infant and the researchers into the climatic chamber, staying within the infant's sight, while being instructed to minimize physical contact. In case of distress or crying, parents or guardians could console or comfort the infant as needed, while still aiming to limit physical contact. Food or drinks could be provided during the trial on request of the parent or guardian, with intake weighed before consumption. The parent or guardian could decide to stop the exposure trial at any time.

2.3. Measurements

Body height was measured during the first visit by measuring tape. Body mass was determined by a scale accurate to 5 g (Platform scale SATEX SA-1 250, Weegtechniek Holland B.V., Zeewolde, The Netherlands), before and after each exposure trial. Body surface area (BSA) was estimated using Mosteller's formula (Mosteller, 1987) - which provides accurate values for infants (Verbraecken et al., 2006):

$$BSA = \sqrt{\frac{(weight\ (kg) \times\ height\ (cm))}{3600}} \tag{1}$$

Whole-body sweat rate (WBSR) was derived from the difference between pre- and post-exposure body mass, corrected for intake of any fluids or foods during the exposure trial, and normalized for BSA and exposure duration in hours. Body mass was measured with the diaper on before and after each trial. The diapers were not changed during the exposure. Therefore, any urine or stool remained within the diaper, and changes of body mass therefore reflected evaporative losses, since the diapers contained a water-impermeable layer.

Table 1
Characteristics of infant participants. M: male; F: Female; BSA: Body surface area, determined by Mosteller (1987). BSA/Mass indicates body surface area-to-mass ratio.

Number of participants (M/F)	20 (8 / 12)
	Mean (SD)
Age [weeks]	33.7 (11.7)
Height [cm]	68.4 (6.1)
Body mass [kg]	7.95 (1.16)
BSA [m^2]	0.39 (0.05)
BSA/Mass [m^2/kg]	0.049 (0.003)

Physiological data were collected at 10-min intervals throughout the 90-min exposure trial. Body core temperature was estimated using tympanic temperature (Braun Thermoscan® PRO 6000, Welch Allyn, Skaneateles Falls, NY, USA) and temporal artery temperature (Withings Thermo, Withings, Issy-les-Moulineaux, France). While core temperature is often estimated using rectal temperature, its measurement can be upsetting for parents and distressing for infants (Kai, 1993; Maxton et al., 2004). The current methods were chosen to minimizing discomfort, while still providing accurate readings in infants (Allegaert et al., 2014; Fujii et al., 2024). At each measurement time point, three consecutive measurements were taken. If the difference between the minimum and the maximum exceeded 0.3 °C, a fourth reading was obtained, and the median of the closest three values was used for analysis.

Skin temperature was assessed at seven predefined anatomical sites using a FLIR T560 infrared camera (Teledyne FLIR, Wilsonville, OR, USA). These sites included: the forehead ($T_{forehead}$), cheek (T_{cheek}), left upper chest ($T_{upper,\ chest}$), lower arm ($T_{lower,\ arm}$), dorsal hand ($T_{dorsal,\ hand}$), shin (T_{shin}), and dorsal foot ($T_{dorsal,\ foot}$). Mean skin temperature (mean T_{skin}) was calculated from the local skin sites using an area-weighted formula validated for infants (Puhakka et al., 1994):

$$Mean\ T_{skin} = 0.14 \times T_{forehead} + 0.05 \times T_{cheek} + 0.34 \times T_{upper\ chest} + 0.14 \times T_{lower\ arm} + 0.05 \times T_{hand,\ dorsal} + 0.21 \times T_{shin} + 0.07 \times T_{foot,\ dorsal} \quad (2)$$

Additionally, an iButton (DS1922L, Maxim Integrated Products Inc., Sunnyvale, CA, USA) was attached to the top of the infant's left foot to monitor local skin temperature.

Heart rate was derived from continuous video recordings using the Eulerian Video Magnification (EVM) technique, following the method of Wu et al. (2012). At each 10-min interval, a 20-s video fragment was selected from just before the corresponding temperature measurement. These video segments were cropped and zoomed in on the infant's face to reduce background noise and enhance signal quality. A bandpass filter of 1.75–2.67 Hz, corresponding to the normal heart rate range in infants (105–160 bpm) (Fleming et al., 2011), was applied to isolate relevant frequency components. The amplification factor (α) was manually optimized for each fragment to enhance subtle color variations in the skin due to pulsatile blood flow. Additionally, heart rate was monitored by the Owlet Dream Sock (Owlet, Inc., Utah, United States) worn on the infant's right foot. Both methods were included to provide complementary estimates of heart rate using different measurement principles (optical video-based extraction during rest vs. continuous photoplethysmography). Given these methodological differences, absolute values were not expected to be identical and were not directly compared. Instead, heart rate values were evaluated within each method across conditions.

Ambient temperature was measured using a Greisinger GMH 3211 reference thermometer (Greisinger Electronic GmbH, Regenstauf, Germany), positioned near the infant.

2.4. Data analysis

Heat balance calculations were performed to quantify heat exchange with the environment and estimate heat storage for each infant during each exposure trial. Calculations followed the formula:

$$Q_{sto} = Q_{prod} - (Q_{wet} + Q_{dry}) \quad (3)$$

Where Q_{sto} is rate of heat storage in watts (W); Q_{prod} is metabolic heat production in W; Q_{wet} is wet heat loss in W combining both sweat and respiratory evaporation and transepidermal water loss; and Q_{dry} is dry heat loss in W and the sum of convection, radiation, and dry respiratory heat fluxes. Total heat loss was defined as the sum of Q_{wet} and Q_{dry}. Conductive losses were assumed negligible. Dry (Q_{dry}) and wet (Q_{wet}) heat losses and heat storage (Q_{sto}) were estimated directly from the physiological measurements. Tympanic temperature was used as the estimate of core temperature in the heat balance calculations, given its lower variability relative to temporal artery measurements in previous studies (Allegaert et al., 2014; Bijur et al., 2016), and the interest in capturing within-subject changes in the current study. Metabolic heat production (Q_{prod}) was derived as the residual. The calculations of each heat balance component were based on Daanen et al. (2006), with an updated specific heat capacity coefficient of 2.98 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ (Xu et al., 2023). The heat balance components were calculated for the period after the 30-min familiarization period. Wet heat loss was based on body mass change over the full trial duration as the weighing system was located outside the climatic chamber and intermediate measurements would have disturbed the environmental conditions. Wet heat loss for the post-familiarization period was estimated by assuming a constant sweat rate over time. All calculations are described in detail in Supplementary Material 1.

All data were checked for missing values, outliers, and measurement errors prior to analysis. Isolated, individual missing values that occurred within a time series (e.g., if the iButton briefly came loose from the foot), were linearly interpolated between adjacent time points, excluding baseline or end-point measurements. Missing values that could not be interpolated were excluded from the specific analysis by pairwise deletion.

Descriptive statistics are presented as mean ± SD. To compare physiological variables between the two trials, paired t-tests were performed on mean values obtained after a 30-min familiarization period. Normality was assessed by Q-Q plots, histograms, and Shapiro-Wilk tests, with Wilcoxon signed-rank tests as sensitivity checks when normality was uncertain. P-values were adjusted for multiple comparisons by controlling the false discovery rate using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 2018).

Differences in heat balance components between trials were also assessed with paired t-tests and adjusted using the Benjamini-Hochberg procedure. Linear mixed-effects models were used to assess the influence of age, sex, and body surface area-to-mass ratio on the heat balance components. The model accounted for repeated measures, including subject as a random intercept and trial as a fixed effect, along with the relevant covariates and interaction terms between trial and each covariate. Model assumptions, including normality and homoscedasticity of residuals, were evaluated using simulated residuals from the DHARMa package (Hartig, 2024). As minor deviations from model assumptions were observed, bootstrapped 95% confidence intervals for fixed effects were calculated using 1000 parametric bootstrap samples (bootMer in R), providing robust estimates of uncertainty.

All data processing and statistical analyses were performed in R (v4.4.2) within the RStudio environment (v2025.05.1.513). Statistical significance was set at $p < 0.05$.

3. Results

All twenty infants attended both exposure trials. Two trials (both at 23 °C) ended at 80 min due to infant fussiness; all other 38 trials were fully completed to 90 min. The mean ambient temperature in the climatic chamber was 23.2 ± 0.4 °C for the 23 °C trial and 33.9 ± 0.5 °C for the 34 °C trial.

Table 2 and Fig. 1 provide an overview of the infants' thermophysiological responses across the two experimental trials (23 °C, 20% RH and 34 °C, 20% RH). Table 2 presents the mean values after the familiarization period ($T \geq 30$ min), and Fig. 1 illustrates the change over time in these variables across the full measurement period. No violations of the assumptions underlying the paired t-tests were observed for any of the physiological variables. Overall, the 34 °C trial resulted in higher temporal, tympanic, and skin temperatures, elevated heart rate, and greater WBSR compared to the 23 °C trial.

Mean skin temperature, derived from thermal images at seven

Table 2
Thermophysiological responses of infants measured across two trials (23 °C, 20% RH and 34 °C, 20% RH). Values represent mean ± SD, calculated after the familiarization period (T ≥ 30 min). Statistical comparisons between trials were performed using paired *t*-tests, with p-values adjusted for multiple comparisons with Benjamini-Hochberg corrections. EVM: Eulerian Video Magnification; bpm: beats per minute; RH: relative humidity.

	23 °C, 20% RH	34 °C, 20% RH	
	Mean ± SD	**Mean ± SD**	**P-value**
Temporal temperature (°C)	37.2 ± 0.2	37.6 ± 0.4	<0.001
Tympanic temperature (°C)	36.9 ± 0.3	37.3 ± 0.2	<0.001
Mean skin temperature (thermal imaging) (°C)	32.3 ± 1.2	34.5 ± 2.5	0.002
Local skin temperature foot (iButton) (°C)	30.1 ± 1.5	35.3 ± 0.9	<0.001
Heart rate (Owlet Dream Sock) (bpm)	133.1 ± 15.2	144.1 ± 11.4	0.001
Heart rate (EVM) (bpm)	122.0 ± 4.9	126.8 ± 7.0	<0.001
Whole-body sweat rate ($g/m^2/h$)	59.1 ± 18	133.2 ± 37.3	<0.001

predetermined skin sites, was 32.3 ± 1.2 °C in the 23 °C trial and 34.5 ± 2.5 °C in the 34 °C trial (p = 0.002). Except for the forehead, all local skin sites were significantly warmer under the 34 °C trial compared to 23 °C (Fig. 2; Supplementary Table 1). The lack of a significant difference observed at the forehead location is likely due to the relatively high local skin temperature at 23 °C, reflecting a smaller range for potential increases compared to more peripheral skin sites. The largest difference was observed at the foot: 28.8 ± 2.7 °C at 23 °C and 34.2 ± 2.4 °C at 34 °C (p < 0.001). iButton skin temperature measurements confirmed this by showing a difference in foot temperature of similar magnitude (30.1 ± 1.5 °C at 23 °C and 35.3 ± 0.9 °C at 34 °C, p < 0.001). The differences in local skin temperature of the foot between iButton and thermal imaging measurements are likely caused by methodological variation.

Heart rate showed higher values during the 34 °C trial, irrespective of measurement method. Using the Owlet Dream Sock, mean heart rate was 133.1 ± 15.2 bpm at 23 °C and 144.1 ± 11.4 bpm at 34 °C (p = 0.001). The EVM analysis showed values of 122.0 ± 4.9 bpm at 23 °C and 126.8 ± 7.0 bpm at 34 °C (p < 0.001). In addition, EVM showed a temporary drop in heart rate between 40 and 60 min at 34 °C, which was not seen in the Owlet heart rate data and is likely due to methodological sensitivity to the recording conditions (e.g., variability in movement or lighting conditions).

WBSR, normalized to BSA, was significantly higher at 34 °C when compared to 23 °C: 133.2 ± 37.3 $g/m^2/h$ vs. 59.1 ± 18 $g/m^2/h$ (p < 0.001) (Fig. 3). The difference in sweat rate between both trials varied considerably across participants, ranging from 16.7 to 141.8 $g/m^2/h$.

The average heat balances for both trials are presented in Table 3 and visualized in Fig. 4. The assumptions for paired t-tests were met for all components of the heat balance. In the 23 °C trial, most heat loss occurred through dry heat loss, whereas in the 34 °C trial, heat loss mainly depended on wet heat loss. On average, dry heat loss was 34 ± 6 W (72% of total heat loss) in 23 °C and 4 ± 9 W (11% of total heat loss) in 34 °C, while wet heat loss was 13 ± 5 W (28% of total heat loss) in 23 °C and 32 ± 12 W (89% of total heat loss) in 34 °C. Average heat storage did not differ significantly between trials over the 60-min exposure (p = 0.844). At 23 °C, heat storage was slightly below zero (95% CI [−1.95, −0.14] W). At 34 °C, it was not significantly different from zero (95% CI [−2.47, 0.14] W), indicating no evidence for overall net heat storage during this period. Metabolic heat production, derived as the residual of the other components of the heat balance, was significantly higher in the 23 °C trial compared to 34 °C (47.8 ± 9.2 W vs. 34.9 ± 16.1 W; p = 0.006). Since infants were able to move freely in the crib, the higher metabolic heat production at 23 °C likely reflects higher activity levels at this temperature or a thermoregulatory response to counteract heat loss.

Linear mixed-effects models with bootstrapped 95% confidence intervals were used to assess the influence of age, sex, and body surface area-to-mass ratio on the heat balance of infants, accounting for the two trials (Table 4). As minor deviations from model assumptions were observed, all fixed-effect estimates are reported with bootstrapped confidence intervals. A significant interaction effect of Age × Trial (34 °C) was found for wet heat loss (β = 6.4; 95% CI [2.2, 10.3]), while there was no significant effect of age for the 23 °C trial (Fig. 5). No other effects of age, sex, or body surface area-to-mass ratio on the heat balance outcomes were observed.

4. Discussion

The present study shows that healthy, term-born infants (3–13 months) maintained thermal balance adequately during a 60-min exposure under controlled conditions of 34 °C, 20% RH, with minimal airflow while only wearing a diaper. This was achieved through a shift in their thermoregulatory strategy, moving from primarily dry to wet heat loss mechanisms. Dry heat loss constituted 34 ± 6 W (72% of total) at 23 °C and only 4 ± 9 W (11% of total) at 34 °C. Wet heat loss was 13 ± 5 W (28% of total) at 23 °C and 32 ± 12 W (89% of total) at 34 °C. WBSR was 133.2 ± 37.3 $g/m^2/h$ at 34 °C and 59.1 ± 18 $g/m^2/h$ at 23 °C. Metabolic heat production was lower in the 34 °C trial. Mean heat storage remained near zero, indicating that the infants' thermoregulatory system effectively responded to short-term environmental heat under low-humidity, minimally clothed conditions.

These differences in infant heat exchange pathways are consistent with fundamental thermoregulatory principles. Dry heat exchange depends mainly on the temperature gradient between skin and the surrounding air, which decreases as ambient temperature approaches skin temperature, reducing heat loss by radiation and convection. At 34 °C, mean skin temperature (34.5 °C) was close to ambient temperature, and differences among local skin sites were smaller (Fig. 2), which is consistent with literature describing the greater uniformity of skin temperatures in warmer conditions (Cravello and Ferri, 2008; Frim et al., 1990).

As the ability to lose heat through dry heat pathways decreases with increasing temperatures, wet heat loss (primarily via evaporation of sweat) becomes the main pathway for heat dissipation in infants (Fig. 4). Interestingly, wet heat loss at 23 °C accounted for a larger share of total heat loss in infants (28%) when compared to adults in similar conditions (~18%) (Wang et al., 2016). This greater proportion likely reflects the relatively high rates of transepidermal water loss (also known as insensible perspiration) in infants (Mack et al., 2016; Nikolovski et al., 2008) and possibly, differences in physical activity level during trials.

An interaction effect between age and trial was observed for wet heat loss; at 34 °C, older infants showed higher losses than younger infants, whereas no age effect was seen at 23 °C (Fig. 5). Term infants are born with all eccrine sweat glands, and thus have the highest gland density at birth (Foster et al., 1969). The sweat output per gland is lower in infants than in adults, yet their WBSR can be higher during heat exposure (Tsuzuki-Hayakawa et al., 1995). Although Tsuzuki (2023) reported no age differences in WBSR between age groups ranging from <1 to 8 years, our findings suggest that in dry heat, an age effect can emerge within the age group of 3–13 months. Differences in the observed age effect between these two studies may be related to the higher humidity conditions in Tsuzuki (2023), which could have restricted overall sweat evaporation, whereas the potential higher physical activity levels in older infants in our study may have contributed to their greater wet heat loss.

Both tympanic and temporal temperature were on average 0.4 °C higher at 34 °C than at 23 °C. Yet, after the 30-min familiarization period, the calculated heat storage at 34 °C did not significantly differ from zero. Therefore, differences in core temperature between environmental conditions do not necessarily indicate a loss of heat balance,

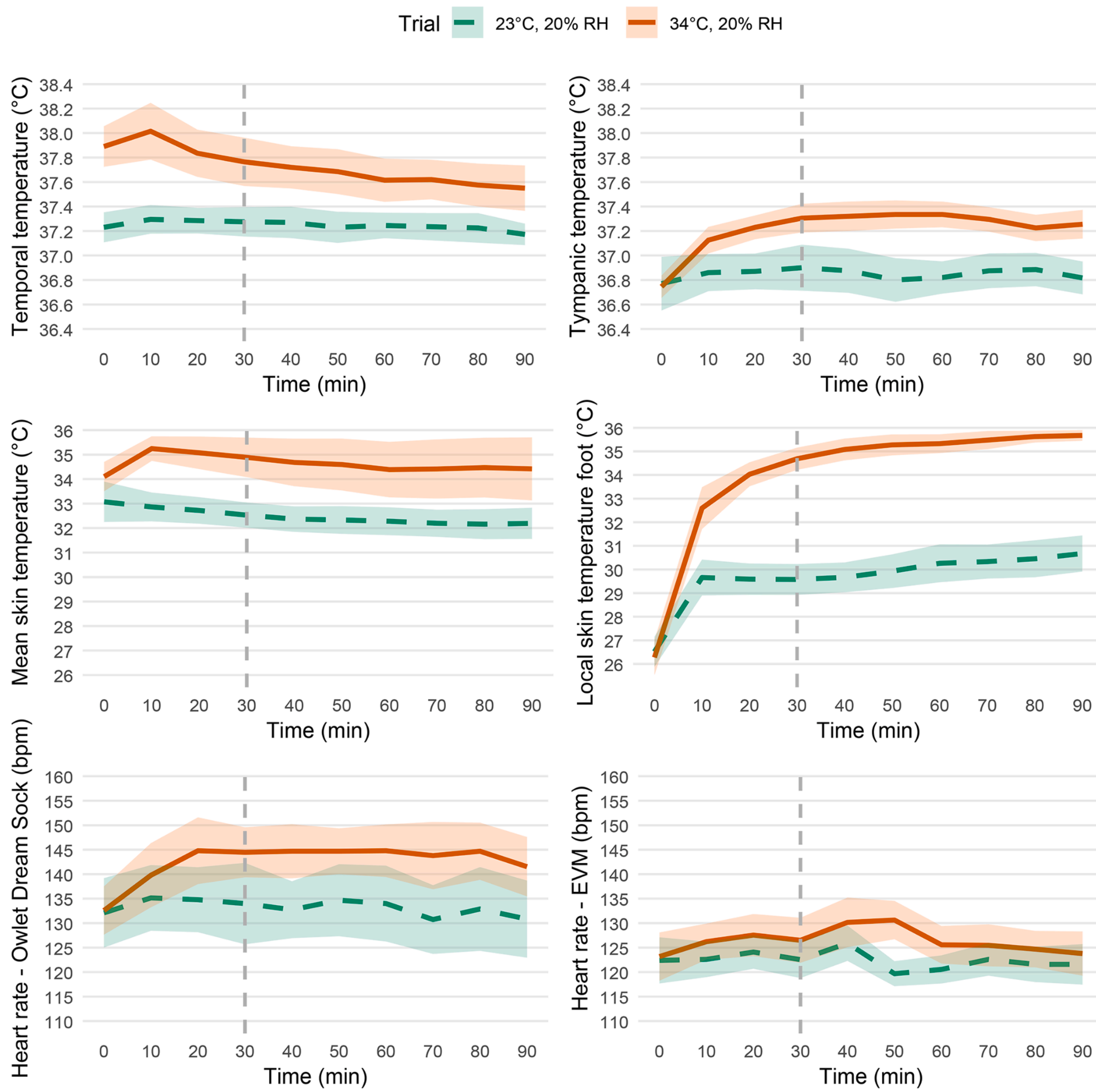

Fig. 1. Thermophysiological responses of infants over time measured across two trials (23 °C, 20% RH and 34 °C, 20% RH). The lines indicate mean values (solid line: 34 °C; dashed line: 23 °C), with the shaded ribbon showing the 95% confidence interval. The dashed vertical line at 30 min. marks the end of the familiarization period. The visualized local skin temperature of the foot is derived from measurements by iButton. EVM: Eulerian Video Magnification; bpm: beats per minute; RH: relative humidity.
Body core temperature was estimated using both temporal and tympanic temperature measurements. After the 30-min familiarization period, the mean temporal temperature was 37.2 ± 0.2 °C in the 23 °C trial and 37.6 ± 0.4 °C in the 34 °C trial, with the difference being statistically significant ($p < 0.001$). Tympanic temperature showed a difference of the same magnitude: 36.9 ± 0.3 °C at 23 °C and 37.3 ± 0.2 °C at 34 °C ($p < 0.001$).

as core temperature may restabilize to a higher steady value rather than it reflecting continuous heat storage (Mitchell et al., 2025).

Compared to the heat balance of adults in similar environmental conditions (Wang et al., 2016), infants relied more heavily on wet heat loss at 34 °C (89%vs. ~85% of total heat loss). This deviation can be partly explained by the lower relative humidity utilized in this study (20%vs. 31%). Yet, relying on wet heat loss also means that conditions may quickly become dangerous when evaporation is limited by high humidity. Increased risk also arises when ambient temperature exceeds skin temperature and the dry heat flux reverses, causing dry heat gain – a process likely accelerated in infants due to their high body surface area-to-mass ratio (Van de Kamp and Daanen, 2025). Yet, the exact environmental thresholds at which external ambient conditions become dangerous to infants, and their risk for heat-related illnesses increases, remain uncertain.

Cardiovascular strain was assessed using two techniques: the Owlet Dream Sock and Eulerian Video Magnification (EVM). The methods showed different absolute heart rate values, reflecting their distinct measurement principles. EVM is based on short video segments with minimal movement, possibly explaining the lower heart rate values. The Owlet sock provides continuous measurements but may be influenced by foot movement. At 34 °C, EVM showed an increase in heart rate between minutes 40 to 60. The Owlet sock did not show this increase midway, which suggests that this variability in EVM values is caused by methodological sensitivity, such as to movement or lighting, rather than actual changes in cardiovascular strain. Given the methodological differences, a conservative approach was taken when interpreting heart rate data.

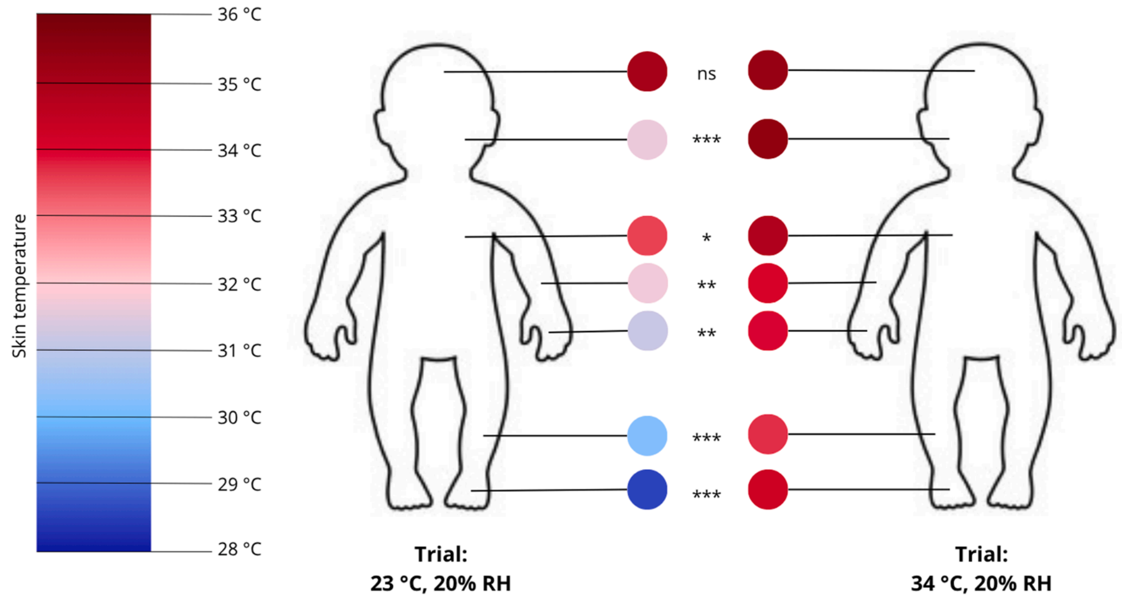

Fig. 2. Local skin temperature of infants across two trials (23 °C, 20% RH and 34 °C, 20% RH). Values represent means, calculated from T ≥ 30 min (after familiarization period). Statistical comparisons between trials were performed using paired t-tests, with p-values adjusted for multiple comparisons with Benjamini-Hochberg corrections. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: nonsignificant. Values are obtained through thermal imaging. RH: relative humidity.

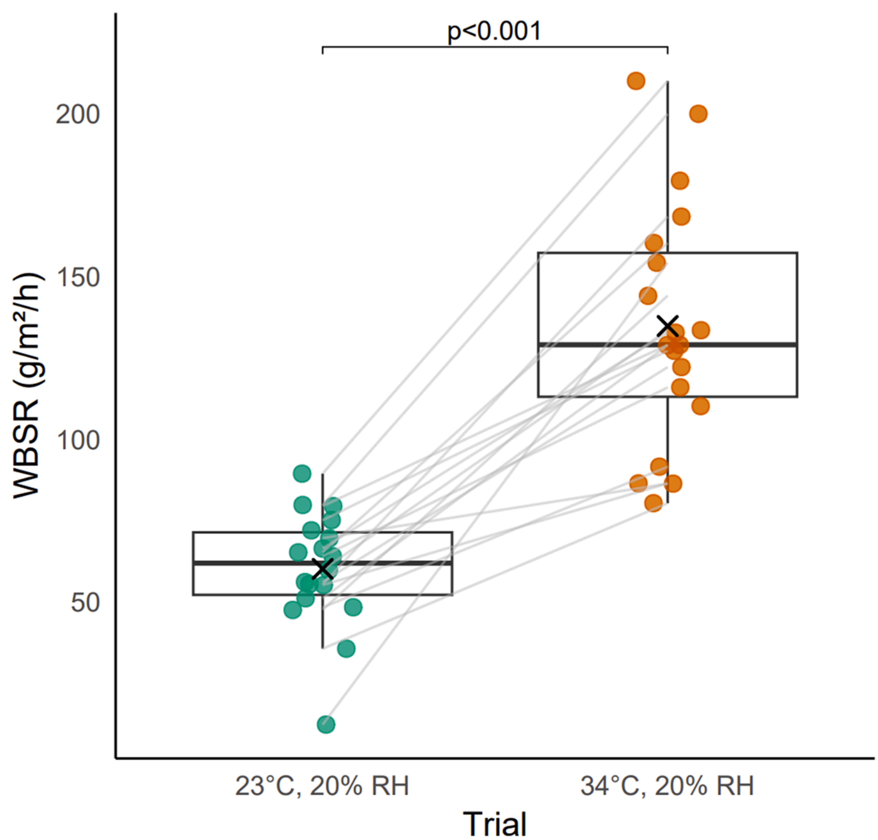

Fig. 3. Whole-body sweat rate (WBSR) by trial. The dots indicate individual values with the lines between both trials connecting the values of one participant. Mean values are visualized by crosses. Statistical comparisons between trials were performed using paired t-tests, with p-values adjusted with Benjamini-Hochberg correction. RH: relative humidity.

4.1. Public health implications

Under the specific conditions tested (34 °C, 20% RH, diaper-only, minimal airflow), the infants did not show clear signs of physiological heat strain during the 60-min time period. Yet, their overall vulnerability is strongly influenced by caregiver behavior, which determines exposure to external factors that affect their heat balance. Since infants rely primarily on wet heat loss in hot, dry conditions, ensuring adequate

Table 3
Heat balance of infants across two trials (23 °C, 20% RH and 34 °C, 20% RH), with power expressed in watts (W). Values represent mean ± SD. Statistical comparisons between trials were performed using paired t-tests, with p-values adjusted for multiple comparisons with Benjamini-Hochberg corrections. RH: Relative humidity.

	23 °C, 20% RH	34 °C, 20% RH	
	Mean ± SD (W)	**Mean ± SD (W)**	**P-value**
Dry heat loss	34 ± 6	4 ± 9	<0.001
Wet heat loss	13 ± 5	32 ± 12	<0.001
Heat storage	−1 ± 2	−1 ± 3	0.844
Metabolic heat production	47 ± 9	35 ± 15	0.007

opportunities for sweat evaporation is critical, even more so when infants become increasingly physically active – through crawling or walking – and metabolic heat production rises dramatically.

Practical measures for caregivers to consider when infants are exposed to heat include dressing them in light, breathable clothing and ensuring adequate hydration. Current guidelines recommend exclusive breastfeeding in infants up to six months of age, regardless of weather conditions (World Health Organization, 2019). A systematic review found that exclusively breastfed infants maintained normal hydration status in hot conditions, and that supplementary water was generally not required (Edney et al., 2022). While hydration status and urine output were not measured in the present study, caregivers should pay attention to signs of dehydration, such as fewer wet diapers and darker urine color, particularly due to the wet heat losses observed at 34 °C in the current study. In addition to clothing and hydration, it is important to keep indoor spaces cool and ventilated. Outdoors, providing shade and avoiding direct sunlight are essential.

Caregivers should also be aware of microclimates that infants may experience, like the inside of strollers or vehicles, where temperatures can exceed ambient levels by several degrees. Experimental studies have shown that combining a moist cloth with fan airflow can lower stroller temperatures (Bin Maideen et al., 2023). However, improper use of cloth covers also carries potential risks, since fully covering a stroller with a dry cloth during hot weather can restrict airflow and increase internal stroller temperatures. To avoid blocking ventilation, shade can be provided by closing the stroller canopy or using a parasol attached to the frame instead (Bin Maideen et al., 2023).

Public health campaigns should raise awareness of infants' heightened vulnerability to heat, highlight early signs of overheating (e.g., flushed skin or rapid breathing), and promote simple, safe, and evidence-based cooling practices.

4.2. Strengths and limitations

Key strengths of this study include the direct measurement of thermophysiological responses of a vulnerable age group (3–13 months) and the comprehensive assessment of infants' heat balance under controlled conditions. The use of innovative, non-invasive techniques, such as the

Table 4
Bootstrapped 95% confidence intervals for predictors of infants' heat balance from linear mixed-effects models. Significant effects (95% CI excluding zero) are indicated with an asterisk (*).

Predictor	Dry heat loss (95% CI)	Wet heat loss (95% CI)	Heat storage (95% CI)	Metabolic heat production (95% CI)
Trial (34 °C)	−33.9 [−40.8, −27.2] *	18.9 [13.8, 23.3] *	−1.5 [−3.6, 0.5]	−16.5 [−26.6, −6.1] *
Age	0.8 [−2.9, 4.7]	−0.3 [−3.4, 2.9]	−0.5 [−1.6, 0.7]	1.6 [−5.7, 8.8]
Sex (female)	−2.5 [−9.7, 5.7]	−6.2 [−12.9, 0.7]	−2.0 [−4.1, 0.5]	−7.0 [−22.8, 8.6]
BSA/Mass	−1.8 [−5.3, 1.7]	−1.2 [−3.9, 1.5]	0.2 [−0.8, 1.3]	−3.1 [−9.0, 2.7]
Trial (34 °C) * Age	−0.8 [−6.4, 4.5]	6.4 [2.2, 10.3] *	0.7 [−1.0, 2.3]	4.1 [−4.6, 13.5]
Trial (34 °C) * Sex (female)	6.3 [−5.6, 17.5]	−1.2 [−9.9, 7.8]	3.5 [−0.1, 6.9]	10.5 [−10.7, 30.5]
Trial (34 °C) * BSA/Mass	3.2 [−2.0, 8.8]	0.5 [−4.1, 2.9]	−0.5 [−2.1, 1.2]	1.3 [−6.8, 8.9]

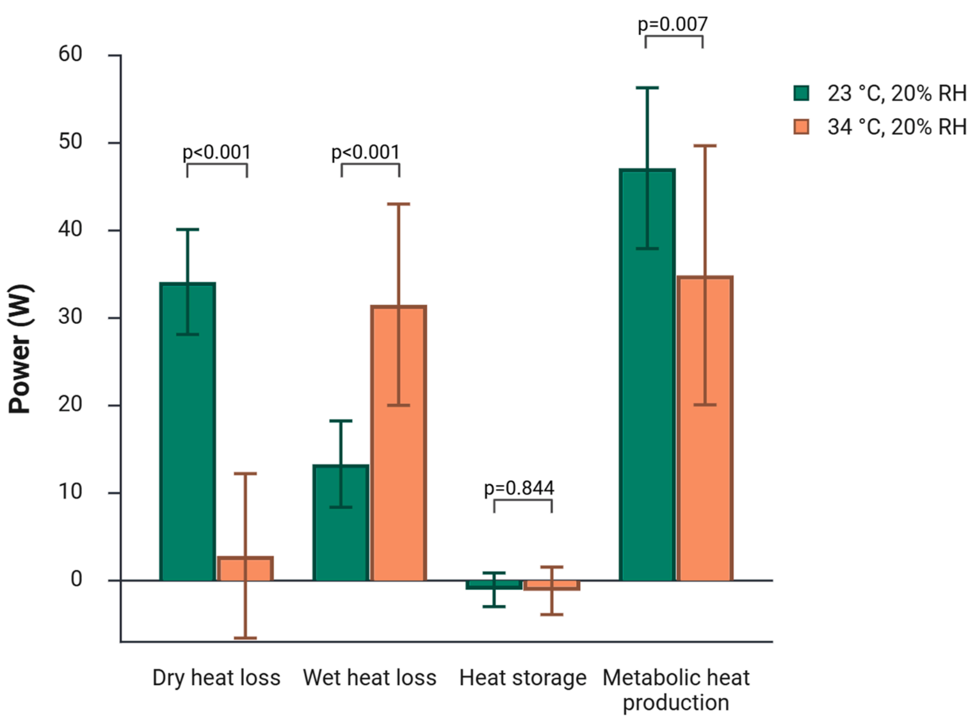

Fig. 4. Heat balance of infants across two trials (23 °C, 20% RH and 34 °C, 20% RH). Values represent mean ± SD.

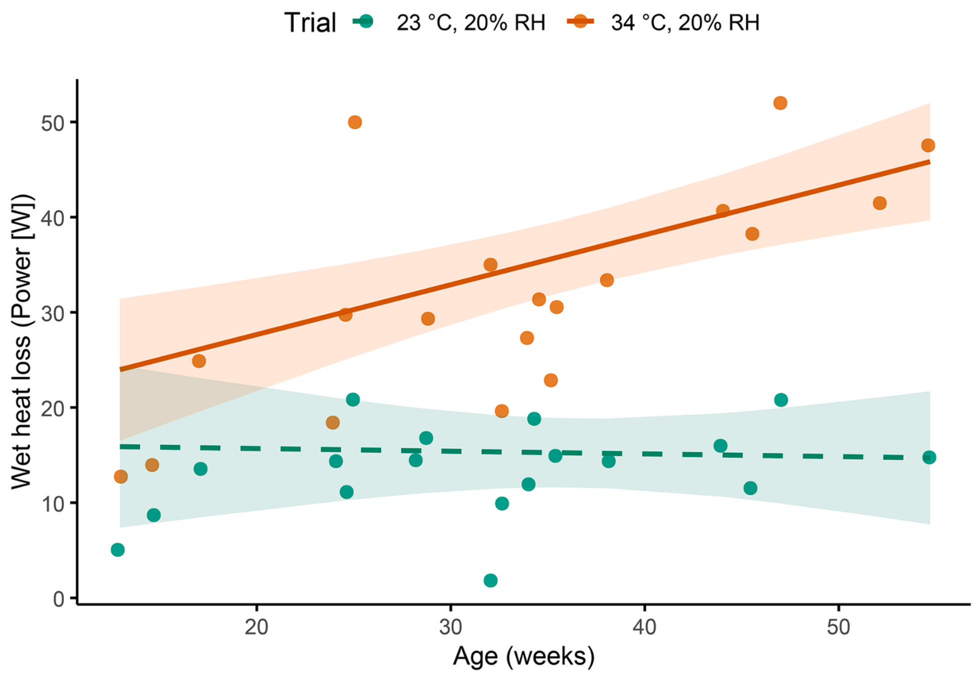

Fig. 5. Relationship between age and wet heat loss in infants across two trials (23 °C, 20% RH and 34 °C, 20% RH). Each point represents an individual raw measurement. Lines show the model-predicted mean wet heat loss for each trial derived from the linear mixed-effects model and adjusted for covariates, with shaded bands indicating bootstrapped 95% confidence intervals. RH: relative humidity.

Owlet Dream Sock and EVM, allowed continuous monitoring of heart rate without disturbing the infants. Limitations include challenges in standardizing infant physical activity, which may have influenced their metabolic heat production. Metabolic heat production was higher at 23 °C than at 34 °C (47.8 ± 9.2 W vs. 34.9 ± 16.1 W, $p = 0.006$), possibly due to increased levels of activity in cooler conditions, or a thermoregulatory response to counteract heat loss, as suggested by Garcia-Souto and Dabnichki (2016). Furthermore, as body mass change could only be measured over the full duration of the trials, wet heat loss was estimated by assuming a constant sweat rate over time. This assumption may have led to an underestimation of the sweat rate if sweating increased over time. Additionally, while infants maintained thermal balance during the 60-min exposure at 34 °C, as indicated by no discernible net heat storage, this state may not reflect longer-term thermal equilibrium beyond those experienced within the study period. Nevertheless, given the scarcity of experimental data on infant thermoregulation during heat exposure, this study offers valuable insights into the heat balance of infants under controlled heat exposure.

4.3. Future directions

Future research should systematically vary humidity, temperature, airflow, and clothing to determine thresholds for net heat gain and the limits of evaporative capacity. Keeping in mind the ethical constraints that restrict the possibilities in infant thermoregulation research, alternative approaches should be considered, including computational models, infant thermal manikins, or assessments during naturally-occurring heat events. Moreover, future research could focus on local heat losses, in addition to the total heat balance calculations performed in the present study. For example, mapping local sweat rates, as done in prepubertal children by Arlegui et al. (2021), could help inform clothing recommendations for infants.

While this study focused on infants in the Netherlands, the researchers recognize that infants in other parts of the world are exposed to more extreme and frequent heat events, and are projected to face even greater increases in the future (UNICEF, 2024). Exploring the adaptability of infants to heat, and whether infants' thermoregulatory responses vary regionally, will therefore be essential to future adaptation and mitigation strategies to the effects of global warming.

5. Conclusion

Under our specific experimental conditions (34 °C, 20% RH, diaper-only, minimal airflow), healthy term-born infants were able to maintain heat balance over a 60-min exposure by shifting from dry to wet heat loss pathways. This suggests an effective thermoregulatory capacity under hot, dry controlled conditions, but does not exclude the possibility of heat strain under different environmental or clothing conditions. Particularly, the reliance on sweat evaporation may become a concern when evaporation is restricted or made redundant by high humidity or excess clothing. Moreover, at higher ambient temperatures above skin temperature, infants may experience dry heat gain, which is particularly concerning due to their high body surface area-to-mass ratio. The findings of this study contribute to a better understanding of infant thermoregulation and highlight the importance of maintaining conditions that allow for evaporative cooling in order to protect infants in a warming world.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used OpenAI's ChatGPT-5 in order to improve the readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Eline van de Kamp: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Amber Klomp:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Shawnda A. Morrison:** Writing – review & editing, Investigation, Conceptualization. **Hein Daanen:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heha.2026.100194.

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