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Physical Work in Humid Heat Impairs Postural Balance during Simulated Construction Tasks at Height

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ABSTRACT

TAN, B. W. L., S. B. ALHADAD, G. Z. Y. TAN, P.M. S. TAN, B. LEMKE, and J. K.W. LEE. Physical Work in Humid Heat Impairs Postural Balance during Simulated Construction Tasks at Height. *Med. Sci. Sports Exerc.*, Vol. 57, No. 7, pp. 1579–1592, 2025. **Purpose:** Occupational heat strain can impair construction workers' motor and cognitive functions, potentially leading to accidents, injuries and lowered productivity. We examined the effects of physical work under various warm and humid tropical conditions on performance in virtual reality (VR)–based construction tasks. **Methods:** Eighteen healthy men (age: 29 ± 5 yr) completed three randomized, counterbalanced experimental trials comprising ~2.5 h of exposure to wet-bulb globe temperatures of 24.6°C ± 0.2°C (COOL), 28.1°C ± 0.3°C (WARM), and 32.4°C ± 0.3°C (HOT), representing Singapore's current (COOL and WARM) and projected (HOT) conditions. Participants performed three 30-min bouts of treadmill walking at fixed metabolic heat productions representing light (EX1: 250 W), moderate (EX2: 350 W), and heavy (EX3: 450 W) workloads, each separated by completion of a battery of VR-based construction tasks (welding and plank-walking at height). Task speed and accuracy, postural sway, and gait were recorded during the VR tasks, whereas body core (T_c) and mean skin temperatures (T_{sk}), and heart rate were recorded continuously. **Results:** Posttrial T_c was higher in HOT (38.6°C ± 0.4°C) compared with WARM (38.1°C ± 0.3°C; $P < 0.001$) and COOL (37.9°C ± 0.3°C; $P < 0.001$), whereas mean T_{sk} ($P < 0.001$) and heart rate ($P < 0.001$) differed between all conditions (HOT > WARM > COOL). Task speed and accuracy during welding and plank-walking were similar between conditions (all $P > 0.05$). However, postural sway velocity during welding increased (by 2.08 ± 2.5 mm·s^{-1}; $P < 0.05$) from baseline to posttrial in HOT but not in WARM or COOL (both $P > 0.05$). **Conclusions:** Although task performance was maintained across environments, postural balance during an attention-demanding task (welding) was impaired following physical work in Singapore's projected environmental conditions, which could increase the risk of potentially fatal accidents and injuries (e.g., falling from height). Effective workplace interventions are needed to protect workers' health, safety, and productivity against future warming. **Key Words:** COGNITIVE PERFORMANCE, HUMID HEAT, MOTOR FUNCTION, INJURY PREVENTION

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Workplace heat exposure is increasingly recognized as a serious occupational hazard as it compromises workers' health, safety, and work productivity (1,2). Most affected are workers in occupations (e.g., construction) that involve prolonged or heavy physical labor in hot and/or humid environmental conditions and/or while donning work clothing that restricts heat loss (3). The combination of these factors can impose significant physiological strain (e.g., elevated body temperatures and heart rate, dehydration) that hastens the development of fatigue, reduces physical work capacity and performance, and increases the risk of exertional heat stroke and long-term health complications (e.g., chronic kidney disease, cardiovascular problems) (4–7).

Occupational heat strain can also degrade motor and cognitive functions essential for safety and work performance, such as memory, attention, and concentration (8,9). One study on mining workers found that performance on a working memory test was poorer during summer (30°C wet-bulb globe temperature (WBGT)) compared with winter (20°C WBGT) (10). In another study, foundry plant workers exposed to hot environmental conditions (~33°C WBGT) during a workday displayed slower response speed and made more errors in a complex cognitive test (11). In addition, fine-motor skills, postural balance and gait stability may also be compromised by physical activity in the heat (12–14). Furthermore, these motor and cognitive effects can be exacerbated when workers are directly exposed to the sun (15).

Impaired motor and cognitive functioning can reduce work efficiency and productivity, as well as increase risk-taking behaviors, thereby elevating the risk of workplace accidents and injuries (16). Indeed, an increase in unsafe behaviors during work in hot compared with cool environments has been reported (17). Recent epidemiological data also indicated a positive association between ambient temperature and the occurrence of workplace injuries (18,19). These findings are relevant to the construction industry, where workers often perform skilled tasks (e.g., welding) under hazardous conditions (e.g., working at high elevations) and where rates of work-related injuries and fatalities are especially high (20,21).

A limitation of previous studies is that the traditional neuropsychological tests (e.g., simple reaction time tasks) often used may not adequately capture the actual demands of occupational tasks (22). For instance, standardized tests usually challenge specific cognitive processes in isolation, whereas most occupational and daily activities require the integration of multiple cognitive and motor abilities for successful completion (e.g., performing repairs while standing on scaffoldings, walking while talking). Few studies have attempted to overcome this constraint by using tasks specific to certain occupations (e.g., firefighting, military, manufacturing) (23–25). However, to our knowledge, the effect of exertional heat stress on performance in construction-specific tasks has not been examined. In this regard, virtual reality (VR) can be useful for simulating real-life scenarios with high fidelity and thus provide a more ecologically valid assessment of task performance (26). This is especially valuable for recreating the high-risk situations (e.g., working at high elevations) commonly encountered by construction workers in a safe and controlled manner (i.e., in a laboratory).

As global temperatures and humidity continue to rise due to climate change, more workers will be exposed to potentially dangerous levels of heat stress (2). For tropical cities in Southeast Asia (e.g., Singapore), daily mean temperatures are projected to rise by 0.6°C–2.2°C by mid-century (27). This is concerning as these cities already experience high air temperatures and given that the relationship between heat and cognitive performance is likely nonlinear, additional increases in environmental heat could lead to disproportionately larger performance decrements (28,29). Furthermore, the relationship between heat and cognitive performance is highly dependent on contextual factors (e.g., task type, heat exposure severity) (30). Thus, it is crucial to understand how these evolving conditions might affect performance in occupationally relevant tasks so that context-specific heat adaptation strategies can be developed to protect workers against future warming (8).

Thus, we examined the effects of physical work under current and projected environmental conditions (by 2050) experienced in tropical cities in Southeast Asia (e.g., Singapore, Bangkok, Vietnam) on motor–cognitive function using VR-based construction tasks. We hypothesized that physical work in the projected versus current environmental conditions would lead to higher physiological strain and poorer motor–cognitive performance.

METHODS

Ethical approval. The study procedures were approved by the National University of Singapore Institutional Review Board (NUS-IRB-2021-474) in accordance with the Declaration of Helsinki. All experimental procedures and possible risks were explained to each participant before obtaining their written informed consent.

Participants. Using an effect size (Cohen's d) of 0.86 (Cohen's $f = 0.43$) based on a previous study that investigated the effects of physical work in the heat on task performance (24), along with an α of 0.05 and β of 0.80, a minimum of 15 participants was required (G*Power Version 3.1.9.4). We recruited 18 healthy men (age (mean ± SD): 29.2 ± 4.5 yr; body mass: 72.4 ± 9.2 kg; height: 1.74 ± 0.05 m; percent body fat: 18.9% ± 6.0%) to account for potential dropouts and data loss due to technical issues. Participants were natives of Singapore, self-reported to be exercising regularly, and were certified fit for participation by an independent medical practitioner before continuing with the study.

Experimental design. Participants completed one familiarization session, followed by three experimental trials in a randomized and counterbalanced order. The experimental trials were performed in an environmental chamber (Welltech Human Performance Chamber, Model 3280-10, Mongkok, Hong Kong), under various warm-humid tropical conditions with WBGT of (i) 24.6°C ± 0.2°C (dry-bulb temperature (T_{db}): 26.2°C ± 0.2°C, relative humidity (RH): 79% ± 1%, absolute humidity: 19.5 ± 0.3 g·m^{-3}) (COOL), (ii) 28.1°C ± 0.3°C (T_{db}: 32.0°C ± 0.2°C, RH: 61% ± 1%, absolute humidity: 20.5 ± 0.5 g·m^{-3}) (WARM), or (iii) 32.4°C ± 0.3°C (T_{db}: 40.4°C ± 0.3°C, RH: 40% ± 1%, absolute humidity: 20.6 ± 0.6 g·m^{-3}) (HOT). A wind simulator was placed approximately 1.5 m in front of the treadmill. The measured wind speed averaged 0.5 m·s^{-1} in all trials (see *Experimental Trials*). As solar radiation was not simulated, the reported WBGT values corresponded to indoor WBGT. The conditions in COOL and WARM simulate the mean daily minimum and maximum temperatures currently observed in Singapore, whereas the conditions in HOT simulate the projected annual mean of maximum WBGT in Singapore by 2050 under a high-emission scenario (27). Singapore was chosen as a good test-bed to mimic the environmental conditions and its effects on motor–cognitive performance due to the similarity in current and projected conditions to other tropical cities in Southeast Asia (e.g., Bangkok, Ho Chi Minh City) (27,31). Data collection took place from October 2022 to May 2023, during which the mean monthly WBGT ranged from 25°C to 27°C (31). All trials were separated by at least 4 d to allow adequate recovery and were performed at the same time of day (±1 h) for each participant to minimize circadian influences.

Anthropometric measurements and familiarization. Anthropometric measurements were taken during the familiarization session. Body mass was measured to the nearest 0.01 kg using an electronic precision scale (Mettler-Toledo GmbH Giessen, Germany). Height was measured to the nearest 0.01 m using a stadiometer (Seca, Brooklyn, NY). Skinfold measurements were obtained from four anatomical sites (i.e., biceps, triceps, subscapular, and suprailiac) on the right-hand side of the body using a skinfold caliper (Model HSK-BI-3; Harpenden; Baty International, Burgess Hill, United Kingdom). Body density was calculated according to Durnin and Womersley (32), and percent body fat was estimated using the equation of Siri (33). To ensure familiarity with the testing protocol and minimize learning effects, participants underwent a full familiarization of the experimental procedures and measurements, during which they completed the VR-based construction tasks four times.

Experimental trials. Participants were instructed to refrain from alcohol consumption and strenuous physical activity and to standardize their diet and sleep/wake times in the 24-h period before each trial. Participants were also asked to ingest at least 500 mL of water ~2 h before each trial to ensure a well-hydrated state.

Upon arrival, participants completed a 24-h dietary and lifestyle questionnaire to assess compliance with the pre-experimental controls. Participants provided a midstream urine sample for measurement of urine-specific gravity (USG) using a refractometer (Atago Co., Ltd, Tokyo, Japan) and weighed themselves nude. Euhydration was confirmed with USG <1.025 (34). If USG was ≥1.025, participants were asked to drink ~500 mL of water and to provide a second urine sample 20 min later (35). For all trials, participants wore single-layer work coveralls (65% polyester and 35% viscose; Merchfoundry, Singapore) over a t-shirt or singlet and shorts to mimic the typical clothing worn by construction workers. The estimated insulation of the clothing ensemble was ~1.1 clo (36).

A summary of the experimental procedures is provided in Figure 1. Each trial comprised three 30-min bouts of treadmill walking at fixed rates of metabolic heat production (EX1: 250 W, EX2: 350 W, EX3: 450 W). A similar exercise protocol was previously used and was employed in the present study for time efficiency and practicality (37). These exercise intensities correspond to light (EX1), moderate (EX2), and heavy (EX3) work as defined by the International Organization for Standardization (ISO) 8996:2021 (38) and are similar to the metabolic demands of various construction work activities (e.g., shoveling, moving concrete) (39,40). Participants completed a battery of VR-based construction tasks before the protocol (VR0) and immediately after each exercise bout (VR1, VR2, and VR3). Each set of the VR tasks was followed by 10 min of seated rest. After completing the last set of VR tasks, participants exited the environmental chamber and provided a post-exercise measurement of nude body mass.

To minimize excessive dehydration, participants were given 200 mL of room temperature (~25°C) water every 15 min during each exercise bout and instructed to drink as much (or as little) as they wanted. This drinking pattern mimics the hydration recommendations of the National Institute for Occupational Safety and Health (NIOSH) (i.e., 237 mL every 15 to 20 min) (41). No additional water was provided during the rest periods. The volume of fluid ingested from each bolus, as well as urine output, was recorded using an electronic benchtop scale (OHAUS NV2101, Parsippany, NJ). Whole-body sweat loss and percent body mass loss were estimated from the changes in body mass and corrected for fluid ingested and urine volume.

In each trial, T_{db} and RH were measured at 1-min intervals, and WBGT was derived with a digital weather station (QUESTemp° 44 N; TSI, Shoreview, MN). Wind speed was measured with a digital handheld anemometer (Kestrel 5000 Environmental Meter; Nielsen-Kellerman, Boothwyn, PA) held at the participant's chest every 10 min during each exercise bout. The measured wind speed averaged 0.5 $m{\cdot}s^{-1}$ in all trials. T_c was measured with a telemetric capsule (e-Celsius® temperature sensor) either as a rectal suppository ($n = 16$) or ingested 8–10 h before each trial ($n = 2$). Skin temperature was measured at four sites (i.e., biceps, chest, quadriceps, gastrocnemius) on the right-hand side of the body using iButtons® (DS1923-F5#; Maxim Integrated, Sunnyvale, CA) to derive mean weighted skin temperature (T_{sk}) (42). Heart rate was measured continuously using a chest-based sensor (Polar H10; Polar, Kempele, Finland). The rate of metabolic production (i.e., metabolic rate minus external work) was estimated from oxygen consumption and carbon dioxide production measured every 10 min for 3 min during each exercise bout using a metabolic cart (TrueOne 2400; Parvo Medics, Salt Lake City, UT) (43). Thermal sensation (−3 ("hot") to +3 ("cold")) (44), thermal satisfaction (−3 "very dissatisfied" to +3 "very satisfied" (44)), and ratings of perceived exertion (RPE) (6 "no exertion" to 20 "maximal exertion" (45)) were obtained before and every 10 min during each exercise bout.

VR-based construction tasks. The battery of VR-based construction tasks consisted of welding and plank-walking tasks, performed in the same order. These tasks were simulated at virtual elevation to mimic a hazardous construction scenario that carried a high risk of falling—one of the top contributors to major and fatal injuries at construction sites (46,47). Participants donned a VR headset (Meta Quest 2; Meta Platforms Inc, Menlo Park, CA) to perform these tasks.

Welding task. The welding task was an adapted version of the Hand Steadiness Task described previously (48). This task assessed participants' fine motor skills, such as manual dexterity and hand steadiness. The welding task was simulated at the edge of the 20th floor of a building under construction (Fig. 2A). A virtual welding board was placed in front of

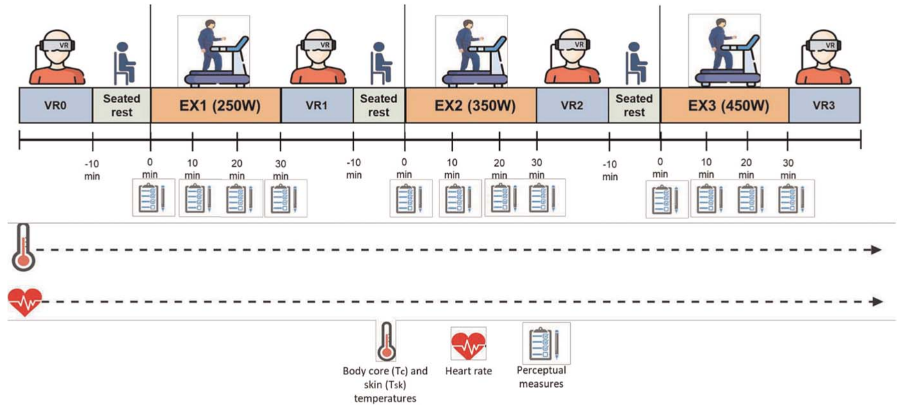

FIGURE 1—Schematic of the experimental procedures. Participants performed three 30-min bouts of treadmill walking at fixed rates of metabolic heat production (EX1: 250 W, EX2, 350 W, EX3: 450 W). A battery of VR-based construction tasks was performed at the start of the trial (VR0) and after each exercise bout (VR1, VR2, VR3), each followed by 10 min of seated rest. Body core and skin temperatures and heart rate were monitored continuously, while perceptual measures were obtained at 10-min intervals.

participants at approximately waist height. Participants were shown two patterns—an upside-down semicircle and a horizontal straight line (Fig. 2A). Participants held the VR controller in their dominant hand, which was presented as a welding torch with an electrode (metal stick) in the virtual environment. Participants used the virtual welding torch to "weld" each pattern from left to right in one smooth, continuous motion while ensuring the electrode tip touched and remained within a predetermined depth (~7.5 mm) of the welding board. Participants' drawings appeared on the virtual welding board in real time, except when the electrode tip did not touch or was too deep into the welding board. The absence of the participant's drawing would be classified as an error. Participants were instructed not to re-trace the missed portions when this happened. Participants always completed the semicircle followed by the horizontal line and were instructed to trace the patterns accurately in the shortest time possible, thus emphasizing the importance of both accuracy and speed. Welding

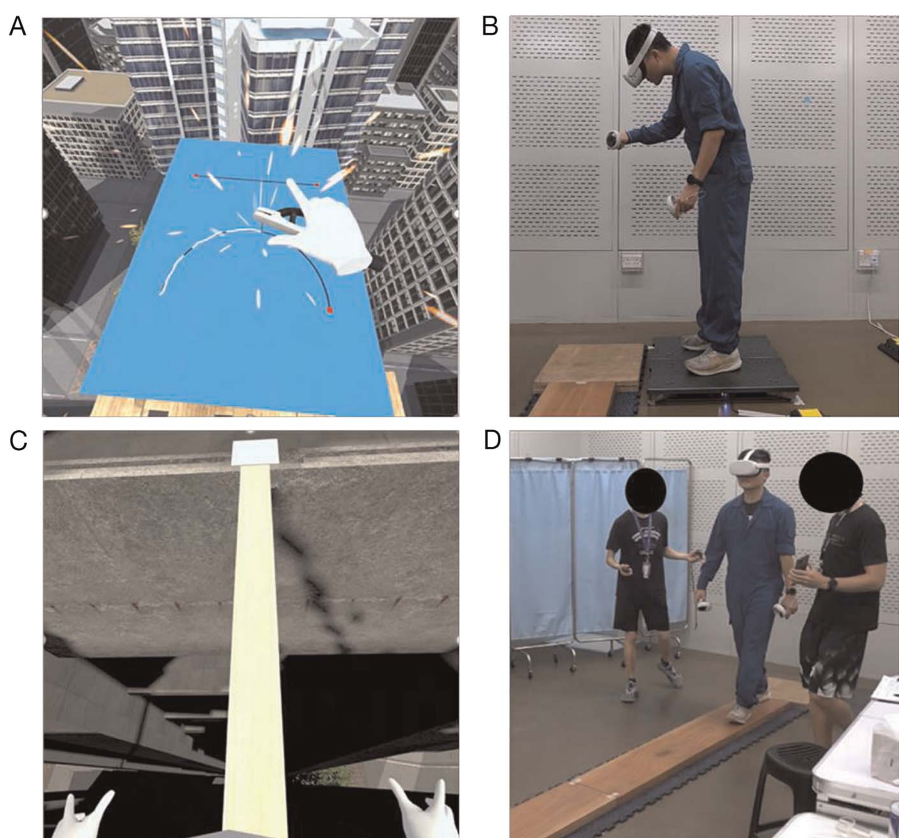

FIGURE 2—First-person views of the welding (A) and plank-walking (C) task in the virtual environment and the setup of each task in the real world (B and D).

performance was assessed based on completion time and welding accuracy. The latter was quantified by the sum of vertical distances between the original pattern and the participant's drawing (i.e., errors in the XY axis; XY DISTANCE) and the total number of times the electrode tip did not touch (TOO FAR) or was too deep (TOO DEEP) into the welding board (i.e., errors in the Z axis) (Fig. 3) (48).

Postural sway during the welding task was assessed by having participants stand on force plates (Force Decks—FDMax; Vald Performance, Brisbane, Australia) (Fig. 2B). Data were sampled at a frequency of 1000 Hz. To ensure consistency in the postural sway measures, participants were instructed to avoid extraneous movement of their lower limbs while performing the welding task (e.g., bending the knees, moving the feet). Center of pressure–based sway measures were derived from the Force Decks software. These included the mean center of pressure velocity (i.e., sway velocity) and the 95% confidence ellipse area (i.e., sway area). An increase in these variables generally suggests poorer postural balance and an increased risk of falling (49,50).

Plank-walking task. The plank-walking task assesses participants' ability to maintain postural balance under dynamic conditions (51). Similar to the welding task, the plank-walking task was simulated on the 20th floor with a virtual plank suspended between two unfinished buildings (Fig. 2C). In the real world, there was a physical plank (length: 4 m, width: 0.3 m, height: 0.05 m) on the ground with a square-shaped wooden board (length: 0.5 m, width: 0.5 m, height: 0.05 m) at each end of the plank (Fig. 2D).

The virtual plank was calibrated to match the actual size of the physical plank. This enabled participants to feel the edge of the plank with their feet, thus enhancing the realism of the virtual elevation (51). Participants walked across the plank to the wooden board at the other end, turned around, and returned to the starting position. Participants were instructed to perform the task as safely as possible and to avoid falling, thus emphasizing task accuracy. To ensure the participants' safety, two researchers walked beside the participant during the task (Fig. 2D). Performance on the plank-walking task was assessed by the completion time and number of times the participant "fell" off the plank in the virtual environment.

Gait patterns during the plank-walking task were assessed using wireless pressure-sensitive insoles (OpenGo Sensor Insoles; Moticon, ReGo AG, Munich, Germany) with a sampling frequency of 100 Hz. Selected plantar pressure distribution and spatiotemporal gait variables were derived from the OpenGo software. These included the mean pressure in each spatial foot region (i.e., toe, metatarsal, arch, and heel) expressed as a percentage of the mean pressure over the whole foot, stride length, gait cycle time, percent of double support, and percent of stance phase and percent of swing phase.

Data and statistical analysis. Data for T_c, mean T_{sk}, and heart rate during exercise were averaged over 5 min, with the average over the last 5 min of each exercise bout used for statistical analysis. These same data obtained during the VR tasks were averaged over the whole duration of each set of tasks. For thermal sensation, thermal satisfaction, and RPE, only values obtained at the end of each exercise bout were used for statistical analysis. For metabolic heat production, the average of the three measurements obtained in each exercise bout was calculated and used for statistical analysis.

All statistical analyses were performed with SPSS software for Windows (IBM SPSS Statistics 28, Armonk, NY). Figures were generated using GraphPad Prism software (Version 9.20; San Diego, CA). Data were reported as means ± SD and, where possible, supplemented with individual values. Statistical significance was set at $P < 0.05$. Data were assessed to ensure they approximated a normal distribution and for sphericity. Greenhouse–Geisser correction was applied when sphericity could not be assumed. T_c, mean T_{sk}, and heart rate obtained during exercise and the VR-based construction tasks were analyzed separately using two-way repeated-measures analysis of variance (ANOVA) with the repeated factors of environment (COOL, WARM, HOT) and time (baseline, EX1, EX2, EX3 or VR0, VR1, VR2, VR3). Thermal sensation, thermal satisfaction, and RPE were also analyzed using two-way repeated-measures ANOVA with the repeated factors of environment and time. Measures of gait patterns (i.e., plantar

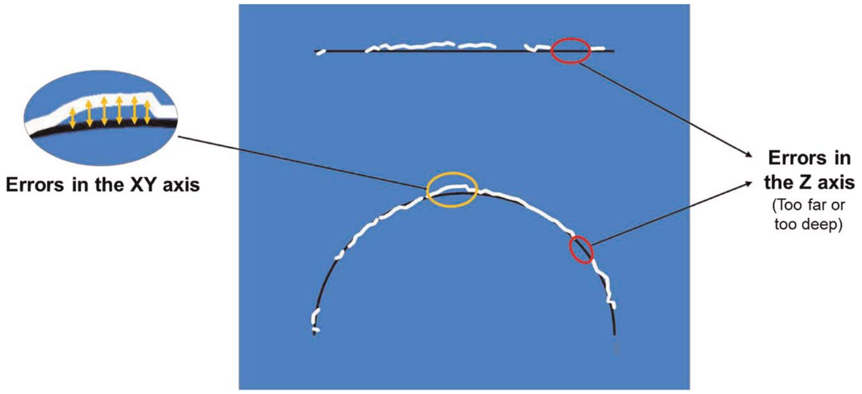

FIGURE 3—Measures of welding accuracy. Errors in the XY axis were defined as the sum of vertical distances between each pattern (black lines) and the participant's drawing (white lines). Errors in the *Z* axis were defined as the number of times the virtual electrode was too far or too deep into the virtual welding board.

pressure and spatiotemporal gait variables) between the left and right feet were compared with paired-sample *t*-tests. As these measures did not differ between both feet (all $P > 0.05$), only data from the right foot were used for statistical analysis. Data from the left foot can be found in Supplemental Table 1 (Supplemental Digital Content, http://links.lww.com/MSS/D177). Subsequently, measures of task performance, postural sway, and gait patterns during the VR tasks were analyzed using two-way repeated-measures ANOVA with the repeated factors of environment and time. USG, metabolic heat production for each exercise bout, ΔT_c across the trial, estimated whole-body sweat rate, percent body mass loss, and volume of fluid ingested were analyzed using one-way repeated-measures ANOVA to compare means between environments. When significant main or interaction effects occurred for the one- or two-way repeated-measures ANOVA, *post hoc* pairwise comparisons with Bonferroni correction were performed. Partial eta-squared (η_p^2) was reported as a measure of effect size with demarcations of small (<0.06), medium (≥0.06 and <0.14), or large (≥0.14) effects, respectively (52). As the changes in T_c, T_{sk}, heart rate, and perceptual measures over time during exercise in the heat are well described, the analysis will focus on the differences between environmental conditions.

RESULTS

Pretrial hydration status and metabolic heat production. Pretrial USG was similar between environmental conditions (COOL: 1.009 ± 0.008, WARM: 1.009 ± 0.007, HOT: 1.010 ± 0.008; $P = 0.89$). Average metabolic heat production during EX1 (COOL: 248 ± 18 W, WARM: 251 ± 19 W, HOT: 262 ± 24 W; $P = 0.06$), EX2 (COOL: 339 ± 33 W, WARM: 349 ± 19 W, HOT: 351 ± 23 W; $P = 0.17$), and EX3 (COOL: 437 ± 27 W, WARM: 449 ± 23 W, HOT: 453 ± 22 W; $P = 0.24$) also did not differ between conditions.

Thermal and cardiovascular responses. Baseline T_c values in COOL, WARM, and HOT were 37.2°C ± 0.2°C, 37.2°C ± 0.2°C, and 37.2°C ± 0.3°C, respectively (all $P > 0.99$) (Fig. 4A). During exercise, absolute T_c differed between environmental conditions and over time (interaction: $P < 0.001$, $\eta_p^2 = 0.61$), such that it was higher in HOT compared with WARM and COOL in EX2 ($P = 0.04$ and $P = 0.03$, respectively) and EX3 (both $P < 0.001$) (Fig. 4A). A similar pattern was observed for absolute T_c during the VR-based construction tasks (interaction: $P < 0.001$, $\eta_p^2 = 0.65$), whereby it was higher in HOT compared with WARM and COOL during VR2 ($P = 0.008$ and $P = 0.007$, respectively) and VR3 (both $P < 0.001$) (Fig. 4B). From baseline to the end of the trial, the rise in T_c was greater in HOT (1.3°C ± 0.4°C) compared with WARM (0.8°C ± 0.2°C; $P < 0.001$) and COOL (0.7°C ± 0.2°C; $P < 0.001$), and greater in WARM compared with COOL ($P = 0.023$).

Mean T_{sk} during exercise differed across environmental conditions and over time (interaction: $P < 0.001$, $\eta_p^2 = 0.51$), such that it was higher in HOT compared with WARM and COOL and higher in WARM compared with COOL in all exercise bouts (all $P < 0.001$) (Fig. 4C). A similar pattern was observed for mean T_{sk} during the VR tasks (interaction: $P < 0.001$, $\eta_p^2 = 0.63$), whereby it was higher in HOT compared with WARM and COOL, and higher in WARM compared with COOL during all sets of the VR tasks (all $P < 0.001$) (Fig. 4D).

Heart rate during exercise differed between environmental conditions and over time (interaction: $P < 0.001$, $\eta_p^2 = 0.56$), such that it was higher in HOT compared with WARM and COOL in all exercise bouts (all $P < 0.001$) and higher in WARM compared with COOL in EX2 ($P < 0.001$) and EX3 ($P < 0.001$) (Fig. 4E). Heart rate during the VR tasks also differed between environmental conditions and over time (interaction: $P < 0.001$, $\eta_p^2 = 0.73$), whereby it was higher in HOT compared with WARM and COOL at VR1 (both $P < 0.001$), VR2 (both $P < 0.001$), and VR3 (both $P < 0.001$), and higher in WARM compared with COOL at VR2 ($P < 0.001$) and VR3 ($P < 0.001$) (Fig. 4F).

Fluid intake, estimated sweat rate and dehydration. Total fluid intake during the trial differed between environmental conditions ($P = 0.001$, $\eta_p^2 = 0.37$), being greater in HOT (0.72 ± 0.32 L) compared with WARM (0.59 ± 0.33 L; $P = 0.02$) and COOL (0.46 ± 0.30 L; $P = 0.03$), with no difference between WARM and COOL ($P = 0.19$). Estimated whole-body sweat rate differed between environmental conditions ($P < 0.001$, $\eta_p^2 = 0.80$), such that it was higher in HOT (0.54 ± 0.12 $L \cdot h^{-1}$) compared with WARM (0.39 ± 0.08 $L \cdot h^{-1}$; $P < 0.001$) and COOL (0.29 ± 0.05 $L \cdot h^{-1}$; $P < 0.001$), and higher in WARM compared with COOL ($P < 0.001$). Percent body mass loss followed an identical pattern ($P < 0.001$, $\eta_p^2 = 0.81$), being greater in HOT (1.91% ± 0.46%) compared with WARM (1.34% ± 0.38%; $P < 0.001$) and COOL (1.03% ± 0.22%; $P < 0.001$), and greater in WARM compared with COOL ($P < 0.001$).

Perceptual measures. Thermal sensation differed between environmental conditions (main effect: $P < 0.001$, $\eta_p^2 = 0.76$), with the difference being independent of time (interaction: $P = 0.78$, $\eta_p^2 = 0.03$). Thermal sensation was lower (i.e., felt warmer) in HOT compared with WARM and COOL, and lower in WARM compared with COOL (all $P < 0.001$) (Fig. 5A). Thermal satisfaction also differed between environmental conditions (main effect: $P < 0.001$, $\eta_p^2 = 0.71$), with the difference being independent of time (interaction: $P = 0.64$, $\eta_p^2 = 0.03$). Thermal satisfaction was lower (i.e., more dissatisfied) in HOT compared with WARM and COOL, and lower in WARM compared with COOL (all $P < 0.001$) (Fig. 5B). RPE also differed between environmental conditions (main effect: $P = 0.006$, $\eta_p^2 = 0.32$), with the difference being independent of time (interaction: $P = 0.07$, $\eta_p^2 = 0.14$). RPE was higher in HOT compared with WARM ($P = 0.04$) and COOL ($P = 0.02$) but was not different between WARM and COOL ($P = 0.33$) (Fig. 5C).

Welding performance and postural sway. Completion time for the semicircle displayed a main effect of time ($P = 0.004$, $\eta_p^2 = 0.28$), such that it generally decreased from

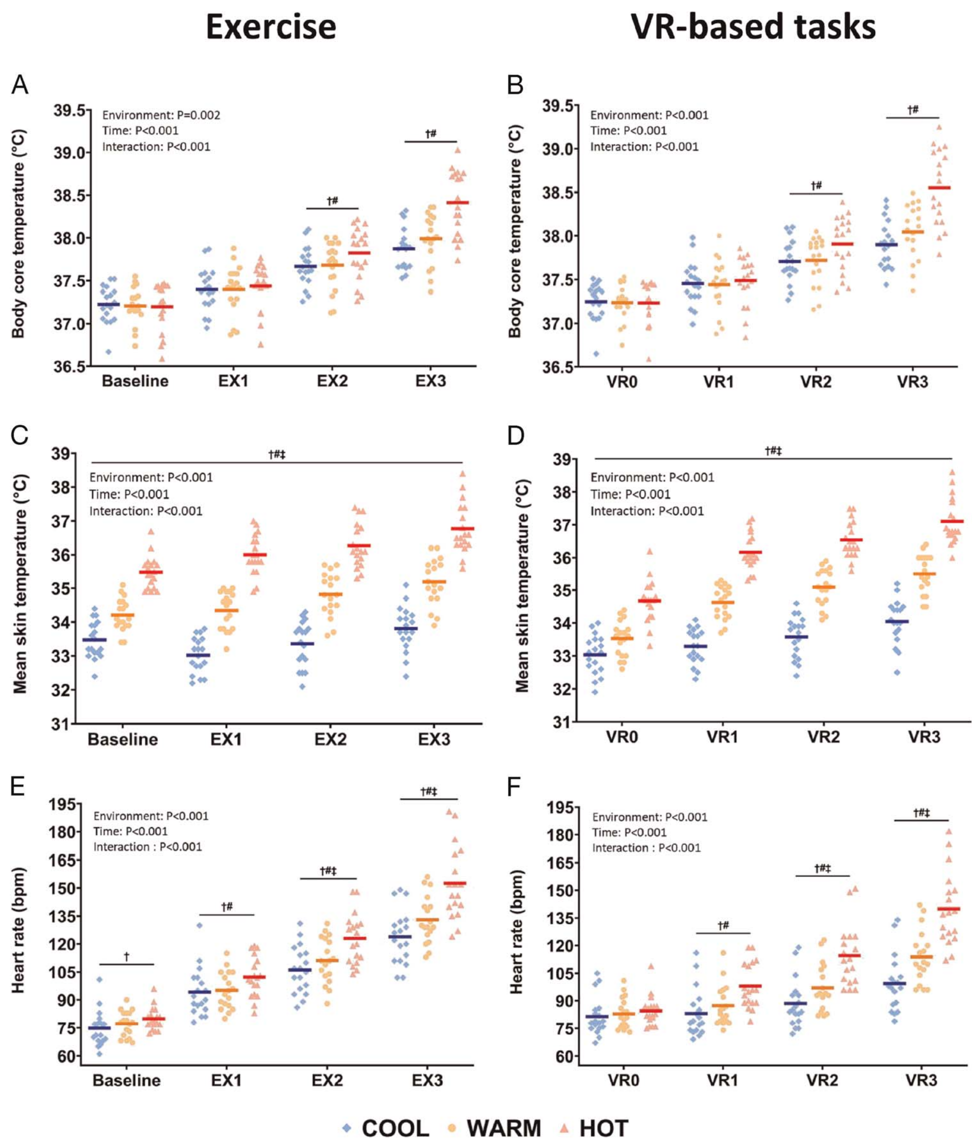

FIGURE 4—Average body core temperature (A and B), mean skin temperature (C and D), and heart rate (E and F) before (Baseline) and at the end of each 30-min exercise bout (EX1, EX2, EX3), and during each set of the VR-based construction tasks performed before (VR0) and after each exercise bout (VR1, VR2, VR3). Data are means ± SD with individual values. Data are mean ± SD with individual values. †#‡Statistical difference between HOT vs COOL (†), HOT vs WARM (#), and WARM vs COOL (‡) ($P < 0.05$).

VR0 to VR3 ($P = 0.03$) (Table 1). However, there was no main effect of environment ($P = 0.80$, $\eta_p^2 = 0.01$) and no interaction effect ($P = 0.56$, $\eta_p^2 = 0.05$) for semicircle completion time. All measures of welding accuracy for the semicircle did not differ between environmental conditions (main effect: all $P > 0.05$) or over time (main effect: all $P > 0.05$), and there were no interaction effects (all $P > 0.05$) (Table 1).

For the horizontal line, completion time and all measures of welding accuracy did not differ between environmental conditions (main effect: all $P > 0.05$) or over time (main effect: all $P > 0.05$), and there were no interaction effects (all $P > 0.05$) (Table 1).

Mean sway velocity during the semicircle differed between environmental conditions and over time (interaction: $P = 0.04$, $\eta_p^2 = 0.12$), such that it increased from VR0 to VR3 (+19.2% ± 20.1%; $P = 0.02$) in HOT, whereas there was no difference across the trial in WARM (+3.3% ± 17.1%; $P > 0.05$) and COOL (+5.8% ± 24.4%; $P > 0.05$) (Fig. 6A). Sway area during the semicircle did not differ between environmental conditions ($P = 0.95$, $\eta_p^2 = 0.001$) or over time ($P = 0.70$, $\eta_p^2 = 0.03$), and there was no interaction effect ($P = 0.30$, $\eta_p^2 = 0.07$) (Fig. 6C). For the horizontal line, both mean sway velocity (Fig. 6B) and sway area (Fig. 6D) did not differ between environmental conditions (all $P > 0.05$) or over time (all $P > 0.05$), and there were no interaction effects (all $P > 0.05$).

Plank-walking performance and gait. Due to a technical error in the pressure-sensitive insoles, gait data for one participant were excluded. The remaining data from 17 participants were analyzed and presented.

Completion time on the plank-walking task showed a main effect of time ($P = 0.004$, $\eta_p^2 = 0.23$), but *post hoc* analysis did not reveal differences between time points (all $P > 0.05$) (Table 2). Moreover, there was no main effect of environmental conditions

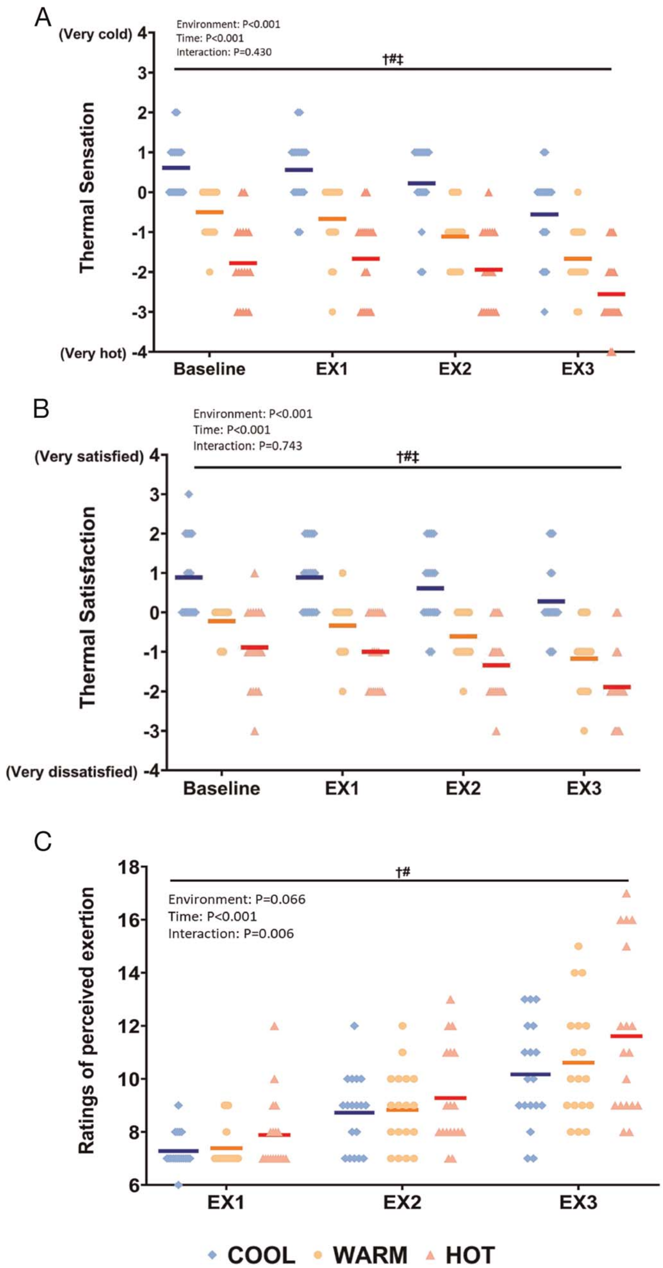

FIGURE 5—Thermal sensation (A), thermal satisfaction (B), and RPE recorded before (thermal sensation and thermal satisfaction only) and at the end of each exercise bout (EX1, EX2, EX3) in each environmental condition. Data are mean ± SD with individual values. †#‡Statistical difference between HOT vs COOL (†), HOT vs WARM (#), and WARM vs COOL (‡) (P < 0.05).

($P = 0.69$, $\eta_p^2 = 0.02$) and no interaction effect ($P = 0.71$, $\eta_p^2 = 0.03$) for plank-walking completion time. Percent mean plantar pressure in each spatial foot region (heel, arch, metatarsal, and toe) during the plank-walking task did not differ between environmental conditions (main effect: all $P > 0.05$) or over time (main effect: all $P > 0.05$), and there were no interaction effects (all $P > 0.05$) (Table 2). For the spatiotemporal gait variables, stride length ($P = 0.001$; $\eta_p^2 = 0.36$) and the percent of double support ($P = 0.001$, $\eta_p^2 = 0.28$) displayed a main effect of time, such that both variables generally increased from VR0 to VR3 ($P = 0.01$ and $P = 0.03$, respectively) (Table 2). However, there was no main effect of environmental conditions ($P = 0.86$, $\eta_p^2 = 0.009$ and $P = 0.50$, $\eta_p^2 = 0.04$, respectively) and no interaction effect ($P = 0.36$, $\eta_p^2 = 0.07$ and $P = 0.15$, $\eta_p^2 = 0.12$, respectively) for either variable (Table 2). All other spatiotemporal gait variables did not differ between environmental conditions (main effect: all $P > 0.05$) or over time (main effect: all $P > 0.05$), and there were no interaction effects (all $P > 0.05$).

DISCUSSION

We compared the effects of physical work in different WBGT representing the current (COOL and WARM) and projected (HOT) environmental conditions in Singapore on

TABLE 1. Welding completion time and accuracy before (VR0) and after each exercise bout (VR1, VR2, VR3) performed in each environmental condition.

		Semicircle				Horizontal Line			
Parameter	Time	COOL	WARM	HOT	ANOVA Output	COOL	WARM	HOT	ANOVA Output
Completion time (s)	VR0	15.6 (9.0)	15.2 (6.3)	16.5 (9.3)	Environment: $P = 0.797$	8.4 (5.7)	8.8 (4.2)	8.8 (5.5)	Environment: $P = 0.971$
	VR1	16.2 (8.8)	15.9 (7.5)	16.3 (8.7)	Time: $P = 0.004$	9.6 (6.0)	8.3 (4.7)	9.0 (5.0)	Time: $P = 0.093$
	VR2*	15.3 (9.2)	14.1 (7.8)	15.4 (7.6)	Interaction: $P = 0.562$	8.5 (5.2)	8.8 (7.8)	8.5 (3.7)	Interaction: $P = 0.411$
	VR3*,**	14.4 (7.8)	14.7 (7.9)	14.3 (7.1)		7.6 (3.5)	8.2 (4.0)	8.3 (4.3)	
Welding accuracy									
XY DISTANCE (cm)	VR0	13.2 (10.0)	11.2 (4.4)	13.3 (9.8)	Environment: $P = 0.493$	8.8 (3.1)	9.6 (6.4)	8.9 (3.6)	Environment: $P = 0.519$
	VR1	12.8 (6.1)	11.3 (4.6)	12.5 (6.2)	Time: $P = 0.625$	8.4 (2.5)	8.2 (3.1)	9.2 (5.1)	Time: $P = 0.479$
	VR2	11.2 (4.1)	19.9 (38.3)	11.4 (3.3)	Interaction: $P = 0.353$	8.8 (3.5)	10.2 (5.7)	8.0 (1.9)	Interaction: $P = 0.433$
	VR3	11.5 (3.0)	13.2 (8.4)	11.6 (2.7)		7.8 (2.0)	8.7 (3.6)	7.9 (2.2)	
Z-axis errors									
b. TOO FAR	VR0	1.8 (2.2)	1.5 (1.9)	2.1 (2.4)	Environment: $P = 0.452$	1.6 (2.1)	0.7 (1.0)	1.0 (1.6)	Environment: $P = 0.699$
	VR1	1.6 (2.1)	1.7 (2.2)	1.7 (1.6)	Time: $P = 0.144$	0.7 (1.5)	0.7 (1.2)	0.9 (1.2)	Time: $P = 0.084$
	VR2	1.3 (2.2)	1.4 (2.1)	2.0 (1.88)	Interaction: $P = 0.814$	1.2 (1.5)	1.1 (1.3)	1.0 (1.7)	Interaction: $P = 0.226$
	VR3	1.9 (2.1)	2.9 (3.2)	2.7 (2.7)		0.8 (1.4)	1.9 (3.0)	2.2 (2.4)	
b. TOO DEEP	VR0	3.2 (3.0)	2.3 (1.9)	2.9 (2.2)	Environment: $P = 0.318$	0.6 (1.2)	0.7 (0.9)	0.4 (0.9)	Environment: $P = 0.576$
	VR1	3.2 (2.2)	3.1 (1.9)	2.7 (2.2)	Time: $P = 0.141$	0.8 (1.4)	0.5 (1.1)	1.1 (1.2)	Time: $P = 0.065$
	VR2	3.7 (2.1)	2.6 (1.9)	3.4 (1.5)	Interaction: $P = 0.625$	0.7 (0.8)	1.5 (1.8)	1.2 (1.9)	Interaction: $P = 0.292$
	VR3	3.5 (2.3)	3.6 (2.4)	3.6 (2.6)		0.8 (1.1)	0.7 (0.8)	0.9 (1.0)	

*Statistically different from VR1. $P < 0.05$.
**Statistically different from VR0, $P < 0.05$.
XY DISTANCE, sum of vertical distance between the displayed pattern the participant's drawing. TOO FAR, number of times the electrode tip did not contact the virtual welding board. TOO DEEP, number of times the electrode tip was too deep into the virtual welding board.

performance in a battery of VR-based construction tasks simulated at height. Our main findings were as follows: (i) welding accuracy did not differ between environmental conditions, although completion time became faster across the trial; (ii) postural sway velocity during welding increased by the end of the trial in HOT only; and (iii) plank-walking performance and gait patterns were unchanged across environmental conditions and across the trial. These findings suggest that physical work in Singapore's projected environmental conditions may compromise postural balance when performing attention-demanding tasks without affecting task performance.

Welding performance and postural sway. Despite differences in physiological and perceptual strain, welding accuracy, and completion time were similar between environmental

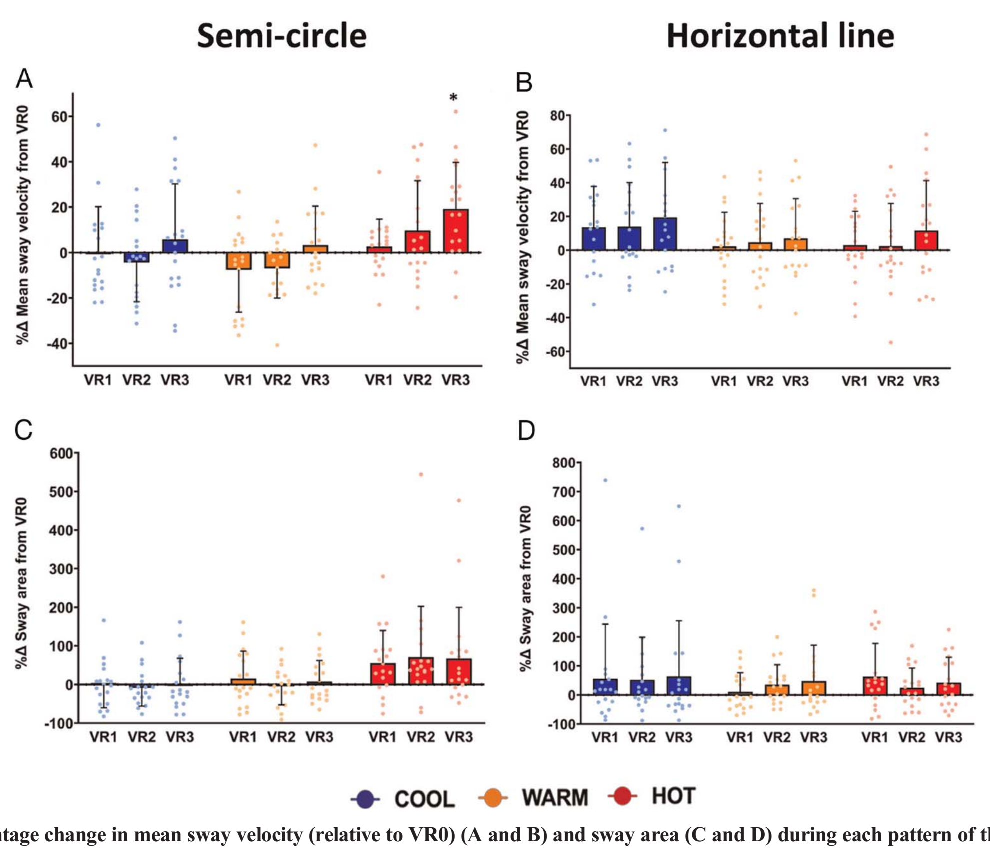

FIGURE 6—Percentage change in mean sway velocity (relative to VR0) (A and B) and sway area (C and D) during each pattern of the welding task performed after each exercise bout (VR1, VR2, VR3). *Statistical difference from VR0.

TABLE 2. Plank-walking completion time, plantar pressure distribution, and spatiotemporal gait variables for the right foot before (VR0) and after each exercise bout (VR1, VR2, VR3) in each environmental condition.

Parameter	Time	COOL	WARM	HOT	ANOVA Output
Completion time (s)	VR0	12.6 (3.2)	12.6 (3.4)	12.4 (2.9)	Environment: $P = 0.692$
	VR1	12.2 (3.2)	12.5 (3.6)	12.4 (2.7)	Time: 0.004
	VR2	11.9 (3.1)	11.7 (2.6)	11.7 (2.7)	Interaction: $P = 0.708$
	VR3	12.2 (3.3)	11.6 (2.5)	11.4 (2.1)	
Plantar pressure distribution					
Heel (%)	VR0	28.8 (8.5)	27.4 (10.6)	29.6 (10.2)	Environment: $P = 0.848$
	VR1	28.9 (10.2)	28.9 (9.5)	28.5 (9.5)	Time: 0.979
	VR2	28.1 (10.1)	29.2 (11.0)	28.3 (9.7)	Interaction: $P = 0.576$
	VR3	27.5 (10.5)	28.5 (11.4)	28.9 (10.6)	
Arch (%)	VR0	18.1 (4.6)	16.7 (5.3)	17.8 (4.7)	Environment: $P = 0.927$
	VR1	17.5 (3.6)	18.2 (3.9)	17.4 (3.6)	Time: 0.873
	VR2	17.4 (4.2)	17.8 (4.0)	17.1 (3.9)	Interaction: $P = 0.210$
	VR3	17.5 (3.4)	17.3 (4.4)	17.7 (4.5)	
Metatarsal (%)	VR0	22.7 (5.9)	24.4 (7.6)	23.6 (5.4)	Environment: $P = 0.662$
	VR1	23.6 (5.8)	23.8 (5.7)	24.3 (5.1)	Time: 0.243
	VR2	24.4 (6.9)	23.9 (6.5)	25.1 (6.2)	Interaction: $P = 0.519$
	VR3	24.9 (6.1)	24.9 (6.2)	25.1 (5.3)	
Toe (%)	VR0	30.7 (7.9)	31.5 (7.7)	29.1 (8.9)	Environment: $P = 0.434$
	VR1	30.2 (8.3)	29.3 (8.0)	29.9 (7.1)	Time: 0.378
	VR2	30.1 (8.2)	29.1 (8.2)	29.5 (6.7)	Interaction: $P = 0.585$
	VR3	29.8 (8.5)	29.4 (8.8)	28.5 (6.3)	
Spatiotemporal gait variables					
Stride length (m)	VR0	1.06 (0.30)	1.06 (0.27)	1.02 (0.26)	Environment: $P = 0.861$
	VR1*	1.11 (0.27)	1.13 (0.27)	1.07 (0.29)	Time: 0.001
	VR2*	1.14 (0.26)	1.14 (0.24)	1.13 (0.24)	Interaction: $P = 0.355$
	VR3*	1.13 (0.28)	1.12 (0.22)	1.18 (0.24)	
Gait cycle time (s)	VR0	1.09 (0.15)	1.08 (0.12)	1.11 (0.23)	Environment: $P = 0.977$
	VR1	1.11 (0.13)	1.11 (0.11)	1.12 (0.15)	Time: 0.445
	VR2	1.11 (0.14)	1.10 (0.14)	1.09 (0.14)	Interaction: $P = 0.737$
	VR3	1.09 (0.17)	1.10 (0.13)	1.09 (0.15)	
% Double support phase	VR0	24.6 (3.1)	26.5 (7.1)	27.6 (7.3)	Environment: $P = 0.497$
	VR1*	24.1 (3.1)	24.7 (8.0)	24.5 (4.4)	Time: 0.001
	VR2	26.0 (7.0)	25.3 (7.4)	22.5 (3.5)	Interaction: $P = 0.146$
	VR3*	25.5 (5.8)	24.4 (5.5)	22.5 (4.0)	
% Stance phase	VR0	62.8 (1.7)	63.0 (5.3)	62.4 (3.3)	Environment: $P = 0.552$
	VR1	61.6 (4.2)	62.4 (3.1)	62.0 (2.3)	Time: 0.241
	VR2	62.2 (2.2)	62.1 (2.8)	61.2 (1.9)	Interaction: $P = 0.656$
	VR3	62.7 (2.5)	61.6 (2.2)	61.6 (2.2)	
% Swing phase	VR0	37.2 (1.7)	37.0 (5.3)	37.6 (3.3)	Environment: $P = 0.552$
	VR1	38.4 (4.2)	37.6 (3.1)	38.0 (2.3)	Time: 0.241
	VR2	37.8 (2.2)	37.9 (2.8)	38.8 (1.9)	Interaction: $P = 0.656$
	VR3	37.3 (2.5)	38.4 (2.2)	38.4 (2.2)	

*Statistically different from VR0, $P < 0.05$.

conditions. Our findings differ from those of a recent study that reported a decrease in performance on a complex visuomotor tracking task from pre- to post-exercise in the heat (40°C) but not in a temperate environment (20°C) (14). Notably, the magnitude of thermal strain in that study (end-exercise $T_c = 39.5°C$) exceeded that observed in the HOT trial in the present study (end-exercise $T_c = 38.6°C$), which may contribute to the different findings. Indeed, recent reviews indicated that heat-induced cognitive impairments were more likely to be observed at $T_c > 39°C$, whereas moderate hyperthermia (~38°C–39°C) had minimal impact (53,54). Furthermore, in other studies where the magnitude of hyperthermia (~38.5°C) was similar to the present study, no performance decrement in fine-motor tasks was observed after exercise in warm-to-hot environments (25,55). Together, these data suggest that the thermal strain experienced by our participants was likely insufficient to challenge their cognitive resources and compromise performance on the welding task (56,57). However, given the relatively short duration of the trial (~2.5 h), it cannot be excluded that prolonged exercise-heat exposures (8–12 h), typical of a work shift, could impair task performance.

Another possibility for the lack of impairment in welding performance could be that to our participants, as tropical natives, are partially heat-acclimatized (58). Wijayanto et al. (59) compared the cognitive responses to passive heat stress between tropical natives and temperate natives and found that the former were better able to withstand the negative effects of heat stress. Although T_c and T_{sk} were similar between groups, cognitive performance remained stable in the tropical natives, whereas it deteriorated in the temperate natives (59). Notably, the tropical natives reported lower thermal sensation ratings, which likely contributed to their better cognitive performance. In addition, heat acclimation has been shown to protect against cognitive declines during exertional heat stress (60). Therefore, the partial heat-acclimatization status of our participants may have mitigated the negative effects of exertional heat stress on their welding performance, although it did not prevent declines in postural balance.

Postural sway was maintained across the trial in WARM and COOL but increased in HOT. Specifically, mean sway velocity increased by 19% from VR0 (before exercise) to VR3 (after EX3) in HOT. At the same time, physiological and perceptual heat strain was higher in HOT compared with WARM and COOL during EX3/VR3, likely mediating this effect. An increase in sway velocity indicates more frequent or faster swaying, suggesting poorer postural control and an increased risk of falling (49,50). Previous research found that higher sway velocity during balance testing was associated with a higher occurrence of lower extremity injuries among athletes (50,61). Our data, therefore, suggest that physical work under Singapore's projected WBGT, along with the associated heat strain, may reduce workers' postural stability during an attention-demanding task (e.g., welding) and thus increase the risk of falls and related injuries. This observation supports the growing body of epidemiological evidence showing a positive association between ambient heat exposure and the risk of occupational injuries (16,19).

Similar to the present study, a recent study observed an increase in sway length and sway area after a strenuous circuit-based exercise regime in a hot environment (40°C) (12). Another study also reported detrimental effects on standing postural balance after exercise in the heat (62). In both studies, however, postural sway was assessed during a quiet-stand task, which may have limited relevance to occupational or daily activities where postural balance is often combined with another task (e.g., walking while talking). Therefore, our findings extend these results by showing that exertional heat stress can also increase postural sway while performing an occupationally relevant fine-motor task (e.g., welding).

The mechanisms underlying the increase in postural sway in HOT cannot be determined from the current data but may be attributed to changes in neuromuscular function, such as altered neural drive and/or sensorimotor feedback (63,64). However, the lack of gait impairments during the plank-walking task (discussed hereinafter) suggests the involvement of additional mechanisms. Alternatively, our observations may be explained by the dual-task interference, which refers to a decrease in the performance of a motor and/or cognitive task when performed together versus separately due to competition for limited attentional resources (65,66). Several studies have observed a decrease in postural stability when performing a cognitive task concurrently, compared with the postural task alone (67,68). The welding task in the current study represented a dual-task condition as participants had to maintain an upright standing balance while simultaneously performing the welding task, thus reducing available resources for postural control. Furthermore, hyperthermia imposes an additional cognitive load that reduces available resources for concurrent tasks (56). Therefore, during VR3 in HOT, the combination of the welding task, maintenance of postural balance, and the magnitude of hyperthermia may have exceeded participants' cognitive resources (56,57). This led to a decrease in postural stability (i.e., increased postural sway), whereas welding performance was undisturbed, suggesting that postural control may be more vulnerable to the effects of exertional heat stress than fine-motor task performance when performed together. On the other hand, the plank-walking task was performed in isolation and may have been less susceptible to task interference, thus explaining the absence of gait impairments.

Plank-walking performance and gait patterns. Performance (completion time and number of "falls") and gait patterns (plantar pressure distribution and spatiotemporal gait variables) during the plank-walking task did not differ between environmental conditions or over time, suggesting that the ability to maintain dynamic balance during tasks involving locomotion may not be affected by exertional heat stress.

In contrast to our findings, some studies found impaired performance on functional-balance tests (e.g., walking across a narrow plank while navigating obstacles) or increased gait instability during exertional heat stress (13,23,69). However, these observations mainly coincided with high levels of fatigue (RPE = "hard" to "very hard") associated with strenuous and/or prolonged physical exertion, often involving the use of heavy personal protective clothing or load carriage. In comparison, the average RPE at the end of the last exercise bout in the HOT trial in our study was rated as "light" (Fig. 5). This suggests that the exercise protocol used in the present study may not be fatiguing enough (in terms of intensity and/or duration) to disturb participants' performance and gait during the plank-walking task. It should be noted, however, that the exercise intensities were chosen based on the metabolic demands observed during common construction work activities (40). Furthermore, as the plank-walking task was performed after the welding task instead of immediately after the exercise bouts, any possible exercise-induced fatigue may have dissipated once the plank-walking task started. Indeed, the effect of exercise-induced fatigue on balance appears to be transient, returning to baseline as soon as within 2 min of exercise cessation (70). This transient effect of exercise-induced fatigue may also explain why impaired postural balance was only observed during the welding task, performed immediately after exercise, but not the plank-walking task, which was performed after a delay.

Experimental considerations and limitations. To our knowledge, this is the first study to investigate the impact of exertional heat stress on motor–cognitive function using VR-based construction tasks to provide a more realistic assessment of occupational task performance. However, several considerations and limitations should be highlighted. First, the mode of exercise (treadmill walking) used in the present study only involved the lower-body musculature, whereas construction workers often perform varying work activities that also engage the upper body (e.g., walking while carrying heavy materials, fixing and bending steel bars) (71,72). Whole-body exercises may elicit different physiological, cognitive, and/or balance responses than those involving only the lower body (73–75). Future studies could therefore seek to incorporate more occupationally relevant exercise modalities. Future studies could also simulate more of the factors (e.g., sun exposure, hypohydration, insufficient sleep) commonly experienced by construction workers or that could further degrade their motor–cognitive performance in the heat (15,76,77).

Second, the relative contributions of exercise intensity and fatigue on the increase in postural sway during the HOT trial could not be determined. This is because the three exercise bouts of low, moderate, and heavy intensities were performed consecutively. Nonetheless, including three exercise intensities, as opposed to a single intensity, is likely more representative of the varied activities performed by construction workers (40). On a related note, the findings of this study are limited to acute exercise-heat exposures lasting ~2.5 h in duration, whereas construction workers are routinely exposed to exertional heat stress for 8–12 $h \cdot d^{-1}$ over multiple consecutive days. Despite this, it appeared sufficient to elicit a decrease in postural stability. Given previous research indicating greater thermal, cardiovascular and perceptual strain during the second of 2 consecutive days of physical work in the heat, further research examining the long-term effects of daily, extended heat exposure (>4 h) on the motor–cognitive performance of construction workers is warranted.

CONCLUSIONS

Compared with current conditions, physical work in Singapore's future environmental conditions led to increased physiological and perceptual strain. Although task performance on the VR-based welding and plank-walking tasks was not negatively impacted, postural balance during welding was compromised following physical work under the projected WBGT. This may subsequently increase the risk of falling and related injuries, which could be fatal when working in high-risk scenarios (e.g., at height). These findings highlight the need for increased awareness among workers and their employers on the health and safety hazards of working in hot weather. Effective strategies to manage workers' heat exposure (e.g., work/rest cycles) are also urgently needed to minimize the heat-related health and safety risks and productivity losses.

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