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Influence of acute and chronic therapeutic cooling on cognitive performance and well-being

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ABSTRACT

Purpose: Research regarding the effect cold-water immersion (CWI) has on cognitive performance often uses excessive cooling protocols (>1-hour) to measure the detrimental impact prolonged cold exposure has on cognition. Previous studies have not considered shorter CWI protocols, similar to that used in recovery and wellness practices (~10 min).

Aims: To investigate a more ecologically valid CWI protocol on cognition, well-being and sleep in an acute and chronic manner. It was hypothesised that a therapeutic CWI protocol would improve well-being, and sleep and have no detrimental effect on cognition.

Methods: Thirteen healthy participants (20.85±2.15 years), (169.96±7.77 cm), (72.03±14.92 kg), (27.67±9.55 BF%) volunteered to complete a 4-week CWI protocol. Participants were immersed in cold water (10.42±0.59 °C) 3-times a week for 4-weeks. Cognitive performance (Stroop & TMT), well-being (WEMWBS, PSWQ, GAD-7, SHS) and sleep (PSQI) were measured acutely and chronically over the 4-week protocol along with thermoregulatory measures (Tsk, Tco, thermal comfort).

Results: Results show that CWI had no detrimental impact on cognitive performance, with Stroop performance & well-being seeing no differences acutely or chronically. Alternatively, the trail making test showed significant improvement from baseline (TMT-A 15.17±4.81-seconds, TMT-B 39.68±15.12-seconds) to week-3 (TMT-A 11.06±3.29-seconds, TMT-B 26.18±10.23-seconds). A reduction in sleep disturbances was seen from baseline scores of 7.85±3.44 AU to the end of week-3 measures 5.75±3.77 AU.

Conclusion: Therapeutic cooling can improve sleep quality when utilised in short frequent doses (3 times per week, for 4-weeks) and is not detrimental to cognitive performance, improving certain aspects of executive function.

1. Introduction

Cold therapies have long been utilised for medicinal and therapeutic purposes due to their efficacy in promoting recovery, alleviating pain, and improving overall well-being [3,19]. In sporting contexts, cold-water immersion (CWI) has gained much attention for its promise in facilitating recovery from intense [21] or muscle damaging [1] exercise. While empirical research has predominantly been focused towards establishing CWI's influence on performance and muscle recovery enhancements, the cognitive aspects of recovery have received less attention. This can provide additional insight into an athlete's ability to optimise subsequent performance, with psychophysiological monitoring and cognitive performance considered important metrics for assessing readiness [40]. Therefore, examining how CWI affects cognitive function alongside physiological recovery is implicated in athlete performance and holistic well-being.

Previous research investigating the impact of cooling on cognitive performance, using various cognitive tests, suggests that prolonged exposure to cold temperatures can have detrimental effects on various cognitive functions [13]. These effects encompass executive functioning, attention and processing speed, memory, reasoning, and visuospatial abilities [6,13]. While an impairment in working memory (WM) has been associated with cold exposure, there is evidence that individuals acclimatised to cold temperatures may experience

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improvements in WM [13], suggesting an adaptive cognitive response to repeated cold exposures. The negative effects on cognitive functioning seen in previous studies may be related to the protocols employed, with many studies including a wide range of durations (60-minutes up to 180-minutes) and temperatures (4.7 °C to 15 °C), with the goal to induce mild hypothermia [13]. Such cold temperatures for extended durations do not align with what is used in practice for sporting recovery and health applications; whereby 10–15 min at 10–15 °C is suggested to be sufficient [3,4,19,39,41]. As such, data assessing cognitive performance following a more ecologically valid protocol is lacking.

Away from sports performance and recovery, cold therapies have been shown to be beneficial to perceived mood and well-being. Individuals who participate in regular cold-water swimming often report a decrease in tension, fatigue and negative mood states, with an improvement in positive mood states noted [18,40] and beneficial effects seen even after the very first immersion [25]. Mechanisms underpinning improved mood scores are associated with associated changes in brain connectivity [42] and biochemical changes following CWI [40], with immersion in cold water triggering the fight or flight response [27] which in turn affects neurotransmitters important for emotional regulation. Neurotransmitters play a significant role in mental health, as evidenced by their involvement in psychiatric disorders such as depression and anxiety [28,40]. Consequently, it becomes clear that regular application of CWI holds potential benefits for improving mental health.

Another area where cold therapies might have a significant impact is on sleep quality. Any disturbances in sleep can have adverse health effects, which can result in reduced well-being [24], affecting not only the general population but also sports performance [9]. Research suggests that having a maximal rate of decline in core temperature before bedtime can be beneficial, with cold water immersion showing improvements in sleep architecture whereby users experience improved quality and quantity of sleep [10]. Thus, cold therapies can lead to improvements in subjective sleep quality [31,38].

It is well established that prolonged cold exposure is detrimental to cognitive function, therefore, this study aims to use a shorter, more ecologically valid dose of cold exposure, more in keeping with its use for therapeutic purposes, recovery, and general health and wellbeing. Specifically, the aim of the present investigation was to assess the effect of acute and chronic cold-water immersion on cognitive performance measures. Secondary aims include investigation of the effect of regular cold application on overall well-being and quality of sleep. It is hypothesised that after the cooling protocol, well-being and sleep will be improved with no decrement in cognitive performance.

2. Methods

2.1. Participants

Thirteen (8 males, 5 females) healthy participants (age, 20.85 ± 2.15 years; height, 169.96 ± 7.77 cm; mass, 72.03 ± 14 kg) voluntarily provided their written informed consent to participate in this study. All participants completed a Physical Activity Readiness Questionnaire (PAR-*Q*+) and a cold sensitivity questionnaire to screen for any known cold related conditions (e.g., Raynaud's syndrome). Prior to experimental testing, ethical approval was granted by the University's School Ethics committee (XS39002022_8979).

2.2. Experimental protocol

One week before testing, subjects were familiarised with all cognitive tasks by completing the cognitive battery three times sequentially, which was previously deemed sufficient to mitigate any confounding learning effect [8,22]. Participants were also given the opportunity to experience the cold-water immersion protocol, if unfamiliar. Prior to experimental testing, participants were instructed to refrain from caffeine and alcohol for 24 h [14,35].

The study implemented a 4-week cooling protocol with 3 cold-water immersions per week (between Monday-Friday, 9.00–17.00) (Fig. 1). Participants were immersed in water with a temperature of 10.47±0.46 °C for 10-minutes while seated and submerged to a level between the naval and arm pit in a temperature-controlled ice bath (The Ice Bath Co, Northamptonshire, UK); arms and hands were encouraged to be submerged. This target depth was based on evidence previously presented showing 43 % of users immerse to waist depth, 33 % of users immerse full-body head out, whilst 24 % of users do not control for immersion depth [3]. Measurements were assessed at six time points: Baseline, post-immersion-1, end-week-1, end-week-2, end-week-3 and

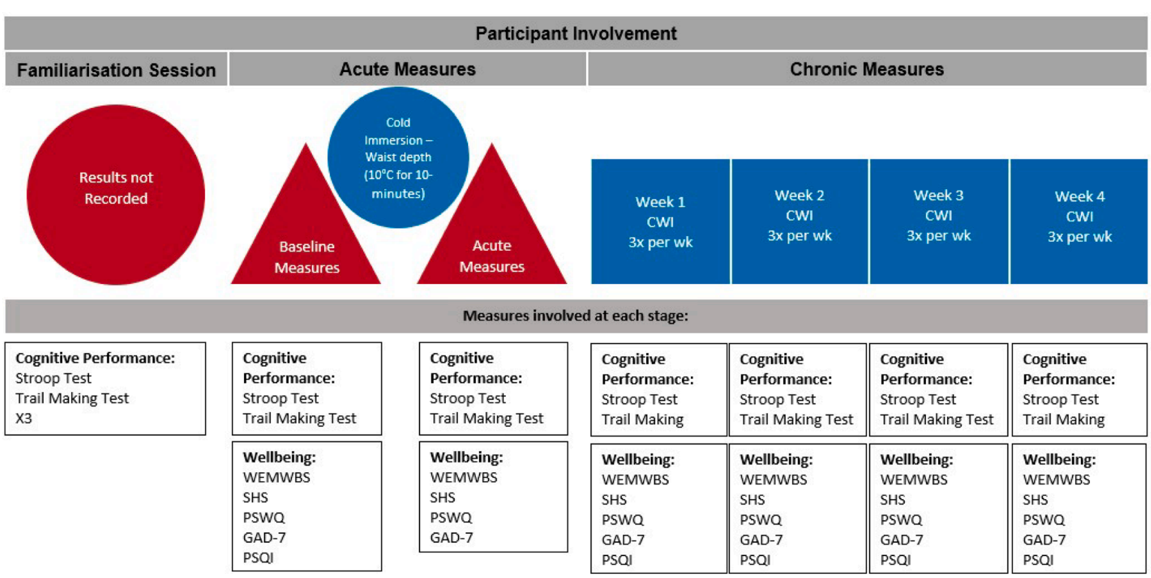

Fig. 1. Diagram of the experimental protocol designed to assess **cognitive performance** and **well-being** following both **acute** and **chronic** cold-water immersion. Participants first familiarised themselves with the **cognitive tasks**, after which baseline measurements were taken. Participants were then immersed in cold water (∼10 °C) for 10-minutes at waist depth. Subsequent acute measures were then recorded for **cognition** and **well-being**. After the initial immersion, participants were tested using the cognitive and wellbeing battery at the end of each week. **WEBWMS** *–The Warwick-Edinburgh Mental Wellbeing Scale*, **SHS** *–Subjective Happiness Questionnaire*, **PSWQ -** *Penn State Worry Questionnaire*, **GAD-7** *–Generalised Anxiety Disorder Assessment*, **PSQI** *–Pittsburgh Sleep Quality Index.*

end-week-4. At baseline, the participants stature was measured using a stadiometer (Seca 213, Hamburg, Germany), with body mass recorded using bioelectrical impedance scales (Omorn BF511, Kyoto, Japan). Acute effects of CWI were assessed by recording baseline measurements of cognitive performance, well-being, sleep and stress, immediately before the first immersion. Post-immersion measurements were taken within 15-minutes of exiting the bath, allowing for acclimation to the lab temperature, with participants allowed to change into dry clothes. Surface water on the skin was removed, and participants were instructed to "pat-dry" their skin with a towel and avoid rubbing to prevent unnecessary warming of the skin [34]. Chronic effects were evaluated by assessing cognitive performance, well-being, sleep, and stress measurements at the end of each week of immersion (i.e., following immersion number 3, 6, 9 and 12, respectively).

2.3. Experimental measures

Core temperature (Tco) and skin temperature (Tsk) were measured using the Braun Thermoscan and Flir E5 thermal camera (Teledyne FLIR LLC), respectively. Following a 15-minute acclimation to the laboratory conditions (centrally controlled at 21 °C), skin temperature was assessed at a 90° angle to the limb [32] at a fixed distance of 30 cm, with a focus area over the belly of the vastus lateralis at the midpoint of the femur; measured as the midpoint between the head of the femur at the hip and the lateral condyle of the knee. Infrared thermography has previously been reported to be a reliable and valid measure with clinical utility and sensitivity [30]. Thermal comfort was measured using the perceived thermal comfort scale, which operated on a scale of 1–9 with 1 being very cold, 5 being neutral and 9 being very hot. Sleep quality and quantity was measured using the Pittsburgh Sleep Quality Index (PSQI) [7], a questionnaire comprising of 7 components. Each component had an individual scoring system, with the global PSQI scores being calculated from the sum of each of the 7 components. Higher scores indicate a worse sleep quality whereas lower scores indicate a better sleep quality. Stress was measured using the Penn State Worry Questionnaire (PSWQ) [26], a 16-item questionnaire rating statements 1–5, which are summed up to produce a total score. The lower the score indicating participants exhibit less worry, with higher scores indicating participants exhibit more worry.

Anxiety measures were taken using the Generalised Anxiety Disorder 7 (GAD-7) [36], which is a 7-item questionnaire rating statements 0–3, which are summed up to produce a total score. Lower scores indicate lower anxiety levels, and higher scores indicate higher anxiety levels. Wellbeing was measured using two questionnaires: The Subjective Happiness Scale (SHS, [23]) to measure hedonic well-being, and the Warwick-Edinburgh Mental Well-being Scale (WEBWBS, [39]) to measure both hedonic and eudaimonia wellbeing. The former of which has 4-items rated on a Likert scale of 1 –7 (1 =not at all, 7 = *a* great deal), which are summed up and divided by 4 to reach a total score. Higher scores reflecting a better state of well-being and lower scores reflecting a worse state of well-being. The latter has a 14-items rated on a Likert scale of 1–5 (1=none of the time, 5=all of the time), which are summed up to produce a total score, with higher scores reflecting greater happiness.

In accordance with Hurst et al. [17], cognitive performance was measured using the EncephalApp –Stroop test, and the trail making test, respectively. The Stroop test measures psychomotor speed and areas of executive functioning such as selective attention, while the rate and trail making test measures behavioural regulation and motor speed (part TMT-A) along with mental flexibility (part TMT-B). The Stroop test was measured using time of completion for two conditions (Stroop-ON and Stroop-OFF), in addition to the number of errors made during 5-successful runs. Before timing the participants, each were allowed 2 trial runs. The Stroop-OFF trial consisted of 10 different coloured hashtags (red, green or blue) displayed on screen one after the other as the participant selected which colour, they observed. The Stroop-ON trial consisted of the words 'RED', 'GREEN', and 'BLUE' coloured in either red, green, or blue. The participant had to select the colour of the word, rather than the meaning of the word.

The trail making test (TMT) has two components, TMT-A and TMT-B. This is a paper based exercise that avoids any lag associated with electronic devices. TMT-A consists of randomly scattered circles containing the numbers 1–25, the participant starts with their pen on the first circle and is timed as they connect all the numbers in ascending order until the pen hits the final circle at which point the timer stops. TMT-B consists of 25 circles with the numbers 1–13 and letters A-L, the participant starts with their pen on the first circle which contains the number 1, and draws a line to the corresponding letter (e.g., 1-A-2-B-3-C., etc.). The timer is stopped once their pen reaches the final circle containing the number 13. If an error is made for either of the trail making tests, participants were guided back to the last correct entry.

Immediately post-immersion, thermal comfort, Tsk, and Tco were recorded following the final immersion of each week. Cognitive performance tasks were performed within 15-minutes after immersion in a climate controlled (21 °C), quiet, darkened room to reduce external distractions.

2.4. Statistical analysis

The normality of the data was checked using Shapiro-Wilk tests and visual inspection of Quantile-Quantile (Q-Q) plots. The data were subsequently analysed using a one-way (Time) repeated measures analysis of variance (ANOVA). If the assumption of sphericity was violated, a Greenhouse-Geisser correction was employed when epsilon (ε) was $\leq$ 0.75, and a Huynh-Feldt correction was used when ε was $>$ 0.75. Where a significant main effect for time was identified, a post hoc test with a least significant difference (LSD) correction was employed to locate differences between time-points. Specifically, comparisons were made between baseline and post-immersion, representing the response to acute immersion, and between baseline (and post-immersion) and the weekly time-points, representing the response to chronic immersion. Hedges *g* effect sizes are reported to show the magnitude of the difference between the selected time-points and interpreted using [15]: < 0.20 = trivial; 0.20 - 0.60 = small; 0.61 –1.20 = moderate; 1.21 - 2.0 = large; 2.01 - 4.0 = very large. The Statistical Package for the Social Sciences (SPSS, Version 28.0.1.1, IBM, UK) was used for all statistical analyses. The alpha level of significance was set as $P < .05$. Data are presented as mean ± SD unless otherwise stated.

3. Results

3.1. Cognition

There was no significant main effect of time for the Stroop-OFF times ($F_{3.24,32.35} = 0.564$, $p > .05$, $g = 0.03$ to 0.58) (Table 1). There was also no

Table 1
Stroop-ON, Stroop-OFF, trail making-a (TMT-A) and trail making-B (TMT-B) over 6-time points for a 4-week cooling protocol (mean±SD).

	Baseline	Post-Immersion	Week-1	Week-2	Week-3	Week-4
Stroop-OFF (Seconds)	57.36s ±9.45	56.08 ±7.99	53.39 ±9.21	57.05 ±11.08	53.63 ±8.48	55.66 ±14.94
Stroop-ON (Seconds)	58.96 ±10.16	56.39 ±7.85	58.25 ±10.75	58.67 ±8.16	55.82 ±9.29	56.37 ±7.76
TMT-A (Seconds)	15.17 ±4.81	13.51 ±4.82	12.32 ±4.27*	11.71 ±3.28*	11.11 ±2.75*	11.06 ±3.29*
TMT-B (Seconds)	39.68 ±15.12	29.20 ±11.18*	34.92 ±17.79	30.70 ±14.04 *	26.18 ±10.23 *#	27.77 ±14.37 *#

* Denotes significance from baseline # Denotes significance from Week 1.

significant main effect of time for Stroop-OFF errors ($F_{3.08,30.75} = 1.227$, $p>.05$, $g = 0.00$ -to 0.72) acutely (baseline: 0.77±1.30 errors vs post-immersion: 0.62±1.04 errors) or chronically (week-1: 0.31±0.85 errors vs week-4: 0.73±0.79 errors). Similarly, no significant main effect of time was found for Stroop-ON completion times ($F_{3.27,32.74} = 0.239$, $p>.05$, $g = 0.01$ to 0.31) (Table 1). In addition, no significant main effect of time was found for the Stroop-ON errors ($F_{3.15,31.45} = 0.25$, $p>.05$, $g =$ 0.00 to 0.27) acutely (baseline: 0.46±0.66 errors vs post-immersion: 0.31±0.85 errors) or chronically (week-1: 0.46±0.78 errors vs. week-4: 0.45±0.52 errors).

A significant main effect of time was found for TMT-A ($F_{2.29,22.935} =$ 7.894, P=.002). LSD pairwise comparisons showed a significant reduction in completion time in weeks 1–4 when compared against baseline (all $p<.05$, $g = 1.0$ to 1.35; Table 1). Additionally, a significantly lower TMT-A completion time was noted between the post-immersion and week-4 time-points (p=.034, $g = 0.71$; Table 1). However, there was no significant difference in completion time found acutely between the baseline and post-immersion time-points ($p>.05$, $g = 0.65$, Table 1). Similarly, no other significant differences were found between any of the other time-points (all $p>.05$, $g = 0.16$ to 0.69, Table 1).

A significant main effect of time was found for TMT-B ($F_{2.67,26.64} =$ 5.32, p=.007). LSD pairwise comparisons showed a significant reduction in completion times versus baseline in the acute phase (post-immersion; p=.01, $g = 1.04$) and in weeks 2–4 (all $p<.05$, $g = 1.06$ to 2.32; Table 1). Significant reduction were also seen between Week 1 and Weeks 3 ($p =$ .17, $g = 0.84$) and 4 ($p = .18$, $g = 0.82$). There were no significant differences found between any other time points (all $p>.05$, $g = 0.12$ to 0.45, Table 1).

3.2. Wellbeing

There was no significant main effect of time found for WEMWBS ($F_{2.46,24.57} = 0.31$, $p>.05$, $g = 0.03$ to 0.61) and SHS ($F_{2.03,20.31} = 0.51$, $p>.05$, $g = 0.00$ to 0.54) (Table 2). A significant main effect of time was found for the PSWQ ($F_{2.1,21.05} = 4.09$, p=.030) with lower worry scores recorded post-immersion versus baseline (p=.002, $g = 0.70$) and at weeks 2–4 compared with post-immersion (all $p<.05$, $g = 0.58$ to 0.94; Table 2). For the GAD-7 variable, there was no significant main effect of time ($F_{2.84,28.35} = 1.19$, $p>.05$), with anxiety scores remaining similar across the study protocol ($g = 0.00$ to 0.50) (Table 2).

3.3. Sleep

There was a significant main effect of time found for the PSQI variable ($F_{2.35,23.49} = 4.84$, p=.014) with LSD pairwise comparisons showing subjective sleep scores were significantly improved from baseline at weeks 2–4 (all $p<.05$, $g = 0.78$ to 0.90; Table 2). No other significant differences were found between the other time points (all $p>.05$, $g =$ 0.20 to 0.64; Table 2).

3.4. Temperature

A significant main effect of time was found for Tsk ($F_{2.31,23.12} =$ 288.25, $p<.001$) with lower Tsk temperature recorded at all measurement time-points compared with baseline across the study protocol (all $p<.001$; $g > 5.0$; Fig. 2). However, no significant main effect of time was observed for Tco ($F_{5,50} = 1.78$, $p>.05$, $g = 0.02$ to 1.14) (Fig. 2). A significant main effect of time was found for TC ($F_{3.29,32.93} = 16.325$ $p<.01$) with LSD pairwise comparisons demonstrating TC scores were significantly reduced at each weekly time-point compared with baseline (all $p<.01$, $g = 0.10$ to 1.89; Fig. 3). In addition, significant differences in TC were found at weeks 2–4 compared with ratings provided at post-immersion (all $p<.05$, $g = 0.76$ to 0.80; Fig. 3).

3.5. Discussion

This study aimed to investigate the effects of acute and chronic CWI upon cognition, well-being, and sleep quality using short frequent immersion at 10 °C for 10-minutes. It was hypothesised that well-being and sleep quality would improve following CWI, whilst cognition would remain unaffected by the cooling protocol. Our findings demonstrate that a short ~10 °C immersion for 10-minutes improved subjective worry scores, both acutely and chronically, improved subject sleep quality after 2 weeks, and was not detrimental to well-being and cognition, even improving certain aspects of executive function.

3.6. Cognition

The results herein, suggest an ecologically valid, therapeutic CWI protocol of 10 °C for 10-minutes has no detrimental impact on cognition. Previous research examining cognition following a more prolonged exposure (60–180 min) to cold water (~4.7 –15 °C) has reported detrimental effects on cognitive performance [13]. However, using a much shorter, ecologically valid protocol we observed a marked reduction, and therefore improved cognition, in TMT-A and TMT-B performance from baseline times at each weekly time-point, over 4 consecutive weeks (Table 1). Our present findings contrast with previous work by [29], who reported divers fully submerged in 7.2 °C waters for 2-hours showed no significant effect in TMT-A (25.8 ± 6.6-seconds) or TMT-B (50.2 ± 21.5-seconds) times when wearing heated diving suits. The obvious methodological differences between our studies make direct comparisons in the cognitive performance challenging; however, our study employing short frequent cold immersions, as typically used for recovery and therapeutic purposes, suggests CWI may benefit certain aspects of cognition, such as executive function. The underlying mechanisms behind this improvement in cognitive performance is not clear, although it has been suggested that improvements in cognition following CWI may be related to increases in sympathetic activity [13]. Alternatively, repeated immersions may reduce thermal discomfort via

Table 2
Warwick Edinburgh Mental Well-Being Scale (WEMWBS), Penn State Worry Questionnaire (PSWQ), Generalised Anxiety Disorder 7 (GAD-7), Subjective Happiness Scale (SHS) and the Pittsburgh Sleep Quality Index (PSQI) scores over the 4-week protocol (mean±SD). Post-immersion PSQI not available as measures were taken on the same day as baseline measures.

	Baseline	Post-immersion	Week-1	Week-2	Week-3	Week-4
WEMWBS (AU)	50.31±8.28	50.54±9.85	52.31±10.20	51.08±9.51	51.42±12.52	48.55±12.52
PSWQ (AU)	50.23±15.51	52.38±15.98*	51.69±15.33	49.62±15.05#	50.25±12.76#	51.18±10.48#
GAD-7 (AU)	8.23±5.13	9.46±5.91	8.23±5.48	7.31±6.05	7.75±5.80	8.55±5.57
SHS (AU)	4.23±0.59	4.38±1.13	4.60±0.73	4.60±0.65	4.46±0.53	4.39±0.73
PSQI (AU)	7.85±3.44	N/A	7.15±3.36	6.38±3.38*	5.75±3.77*	6 ± 3.44*

* Denotes significance from baseline scores.
# Denotes significance from post-immersion scores.

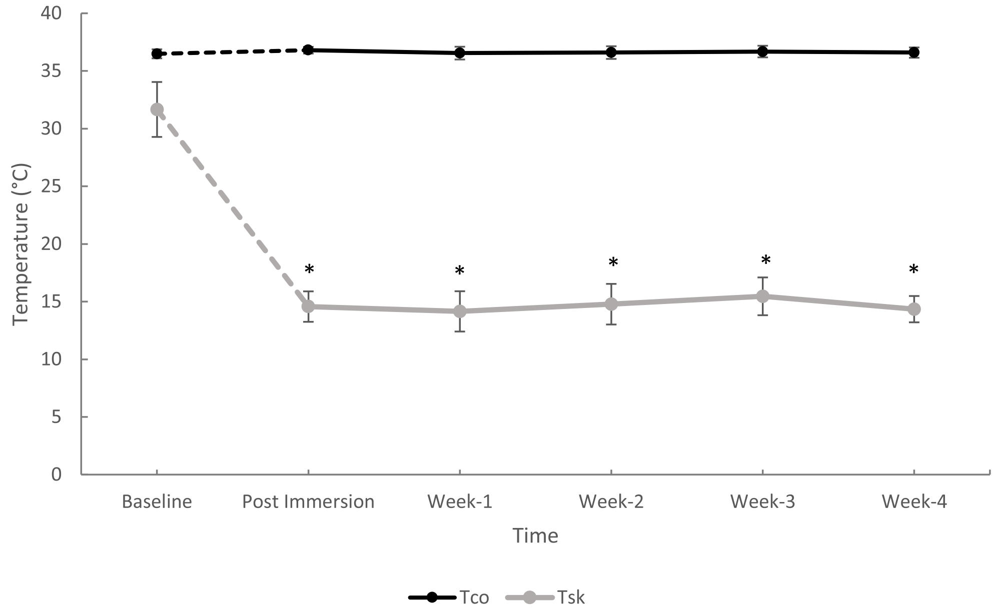

Fig. 2. Core (Tco) and skin (Tsk) temperature over the course of the 4-week protocol (mean±SD). Dotted line indicates the acute measures. *Denotes significance from baseline measurement.

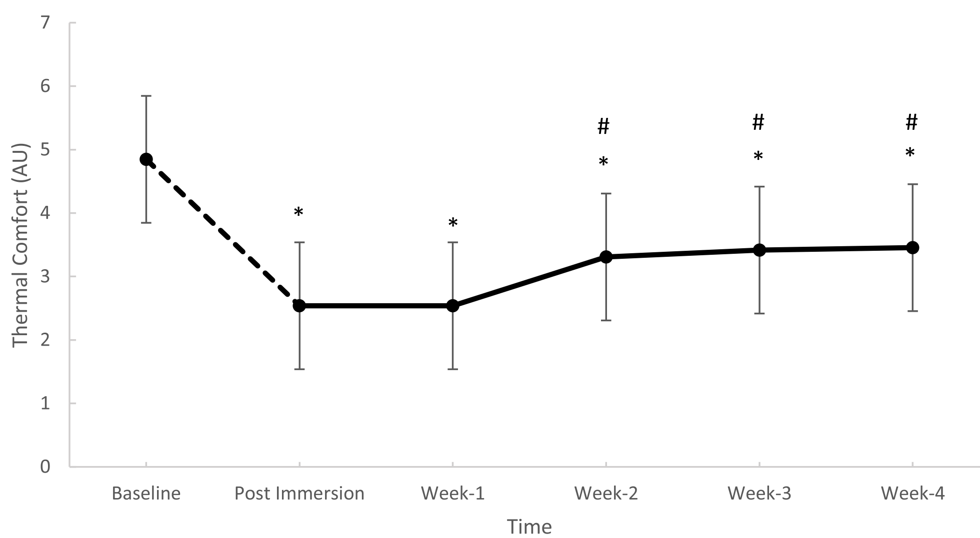

Fig. 3. Thermal comfort (TC) over the 6-time points of the 4-week protocol (mean±SD). Dotted line indicates the acute measures. *Denotes significance from baseline measurements. #Denotes significance from post-immersion measurements.

thermal adaptation, resulting in changes in cognitive performance [13]. Indeed, in our study, a higher TC was perceived at weeks 2–4 compared with post-immersion TC ratings (Fig. 3), suggesting thermal adaptation occurred.

Despite finding an improvement in the TMT-A and TMT-B performance, we did not observe any change in Stroop-OFF or Stroop-ON completion times across time-points (Table 1). Our data supports previous work from Seo et al. [33] who found no significant difference in Stroop performance from pre-immersion levels to all time points measured while immersed. Nevertheless, it is important to note, that in contrast to Seo et al. [33], we found no significant detriment in Stroop performance after any immersion. Differences between our results are likely explained by differences in protocol as Seo et al. [33] immersed participants for 60-minutes (13.0 ± 1.0 °C) compared to our protocol of 10-minutes at 10 °C. Additionally, the present investigation allowed participants to change into dry clothes following immersion, allowing a sense of rewarming. This approach mirrors real-world practices, unlike the method utilised by Seo et al. [33], where testing occurred at pre-determined intervals throughout the 60-minute immersion.

In combination, the results of the cognitive assessments suggest a short, single bout of CWI (10 °C for 10-minutes) does not impair measures of cognition, and when completed regularly over 4 weeks, may even improve certain aspects of cognition. Future research is needed to build upon such results, utilising a more comprehensive cognitive battery, which will help provide a wider view on the overall effect CWI has on cognition with short frequent immersions.

3.7. *Wellbeing*

Acute CWI reduced subjective worry scores (PSWQ) after a single immersion. We also observed reduced PSWQ scores from 2 weeks of regular immersions (versus post-immersion time point) (Table 2). Interestingly, previous work has shown positive effects of CWI upon mood states, even after the very first immersion [25]. Our data is in agreement with such a timeframe, with an acute CWI protocol significantly reducing worry scores immediately post-immersion. Mechanisms of action have been suggested to be related to biochemical and nor-/epinephrine alterations in response to cold temperatures [27,40]. Indeed, previous work where cold-water immersion was conducted in similar temperatures for similar durations to the protocol used herein have consistently shown an upregulation of epinephrine and norepinephrine [5,20] in the acute post-immersion timeframe. Further work is required to determine the physiological mechanisms responsible for reduced worry scores following acute and chronic CWI.

The WEMWBS scores demonstrated that there were no changes in perceived mood either acutely or chronically after CWI (Table 2). The absence of a change in well-being contradicts Massey and colleagues (2020) findings who reported significant increases in mood over the course of an introductory sea swim programme. This would also suggest that subjective mood and worry scores change independently of each other, with positive results seen for worry herein. Discord between our results and those of Massey et al. [25] may be a result of different immersion protocols. Massey and colleagues utilised sea-swims in a natural setting with group participation and physical exertion, whilst our investigation conducted repeated immersions in a controlled laboratory environment, with limited social interaction and no physical activity. This setting minimized social interaction and lacked physical activity, aiming to isolate the cold stimulus. The social and environmental differences could explain the disparity between our studies, with absence of proximity to a 'blue space' (natural water-based aquatic environments) [11,12] a potential explanation for the lack of improved mood scores seen herein. While we also noted no marked differences in GAD-7 and SHS scores over the course of the 4-week protocol (Table 2), neutral results do not suggest a negative impact. Therefore, it is important to identify that the results show chronic exposure to cold water in frequent short doses is not detrimental to subjective wellbeing.

3.8. Sleep

Our hypothesis regarding the enhancement of subjective sleep quality over the 4-week cooling protocol was confirmed by observing higher PSQI scores during weeks 2–4 compared to baseline, indicating less sleep disturbance over the course of the study. These findings are corroborated by previous research employing subjective sleep measures (Hooper index), which demonstrated a significant improvement in sleep from pre-exercise values (−2.04 to −0.68) at 24-hour after CWI (~10 °C for 15 min) [38]. Alternatively, Qu and colleagues (2012) found no significant improvement in subjective sleep quality measures when utilising a CWI protocol of 15 °C for 12-minutes. However, a noticeable improvement was reported when employing colder temperatures (−110 °C to −140 °C for 3-minutes) using whole body cryotherapy (WBC). Taken together, this would suggest that a colder stimulus is needed to elicit favourable changes in subjective sleep quality [10]. Moreover, it highlights the importance of the 1:1.1 temperature: duration ratio promoted for use in CWI protocols to provide a suitable cold stimulus for reductions in muscle tissue temperature ([41]. An important point of note is that as baseline measures of sleep were worse (higher scores) in our study (7.85±3.44AU) compared to those of Qu et al. [31] (5.42 ±2.02AU), thus it could be speculated that the benefits of CWI are more pronounced in those with a markedly lower quality of sleep.

Extrapolating the findings of fewer sleep disturbances with chronic application of CWI, it could be suggested that greater benefits of CWI upon subjective measures of sleep might further promote athletic recovery during times of high training loads and frequency, offering a greater potential for recovery practices. Many proposed mechanisms behind cooling modalities resulting in a positive effect on sleep have been suggested, such as increased parasympathetic activity, blunting of sympathetic activity, the analgesic effect of cold, or even hormonal changes (norepinephrine) [2,31]. Our results suggest regular CWI has the potential to assist in improved subjective sleep quality. Therefore, future investigations should look to combine subjective and objective measures (i.e., polysomnography) of sleep using an ecologically valid protocol to measure the effect that a cold stimulus in isolation has on sleep.

3.9. Temperature

Thermal comfort was observed to acutely decrease from baseline levels immediately post-immersion; however, TC was rated significantly higher between weeks 2–4 compared with both baseline and post-immersion values (Fig. 3). Our results indicate that once acclimated to the cold, participants perceptions of the cold reduce; providing a likely explanation for the improvement seen in TMT performance and subjective sleep quality scores across the same times points. Nevertheless, such a suggestion contradicts the synthesis findings from Falla et al. [13] who found limited evidence supporting cold acclimation improving cognitive performance. While our present study does not confirm that acclimation to the cold improves cognition, it does suggest that frequent short immersions does improve one's perception of cold exposure.

What isn't clear in our data is the lack of agreement seen in Tco with previously published work. Following cold-water immersion protocols of a similar temperature and duration it is expected that core temperature might decrease [37]. However, the lack of decrease seen in core temperature herein might be explained by the peak difference in Tco change occurring at 60 min post-intervention [37]. Thus, perhaps the drop in temperature herein was missed due to the nature of the experimental design. In contrast, aural thermometry has been shown to underestimate changes in core temperature when compared to rectal core temperature measurements [16] and the lack of change seen herein might be explained by such an underestimation.

4. Conclusion

In conclusion, short frequent immersions have no detrimental impact on cognition, even improving certain aspects of executive function, while subjective measures of sleep improved after regular immersions spanning 4-weeks. Additionally, no detrimental impact was found on well-being over the 4-week protocol, with positive effects seen with reduced worry scores both in acute and chronic timeframes.

5. Practical implications

- Cold water immersions at 10 °C for 10 min, 3 times per week for 4 weeks, have no detrimental impact on cognition.
- These short, frequent immersions might even improve certain aspects of cognitive function whilst improving subjective measures of sleep and worry.
- Positive effects on subjective worry are seen after the first immersion.
- Regular therapeutic CWI in a laboratory environment has a neutral impact on mood. It is suggested improvements in mood seen elsewhere may be implicated by access to blue and green space.
- Two weeks of regular therapeutic CWI improved sleep, with fewer sleep disturbances reported.
- CWI to assist with sleep may be more efficient at times when sleep disturbances are more pronounced.

CRediT authorship contribution statement

Joseph Knill-Jones: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gareth Shadwell:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation. **Howard T. Hurst:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Chris Mawhinney:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Jonathan K. Sinclair:** Writing – review & editing, Visualization, Validation, Project administration, Formal analysis, Data curation. **Robert Allan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Ethical Approval

Ethical approval was granted by the University's School Ethics committee.

Consent to Participate & Publish

Participants provided written informed consent to participate, which included consent to publish findings.

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