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Integrative physiological and behavioural responses to sudden cold-water immersion are similar in skilled and less-skilled swimmers

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HIGHLIGHTS

• Severity of cold shock whilst treading water not influenced by swimming skill
• Treading water increased brain blood flow despite cold shock-induced hypocapnia.
• Cold-water swimming capacity was at least one third lower than in temperate water.

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ABSTRACT

We examined the initial physiological responses and subsequent capacity to swim following cold-water immersion. An ecologically-valid model was used whereby immersion was sudden (<2 s) and participants had to actively remain afloat. Participants (15 skilled swimmers, 17 less-skilled swimmers) undertook four experimental test sessions: a physiological test and a swimming test in both cold (10 °C) water and temperate (27 °C) water in a swimming flume (temperature order counter-balanced). For physiological testing, measures of brain perfusion [flow velocity (MCAv, Doppler) and oxygenation (NIRS)] and cardiorespiratory function [ventilation parameters and end-tidal PCO_2 ($P_{ET}CO_2$)] were recorded whilst treading water for 150 s. The swimming test involved treading water (150 s) before swimming at 60% (up to 120 s) and 90% (to intolerance) of pre-determined maximum velocity. Multifactorial analysis revealed that swimming duration was influenced most heavily by water temperature, followed by respiratory variables and MCAv in the first 30 s of immersion. The time course and severity of cold shock were similar in both groups ($p = 0.99$), in terms of initial physiological changes (MCAv down ~20 ± 11%, respiratory frequency increased to 58 ± 18 breaths·min^{-1}, $P_{ET}CO_2$ dropped to 12 ± 9 mm Hg). Treading water following cold-water immersion increased MCAv by 30% above resting values despite maintained cold-shock-induced hyperventilation. In comparison to temperate water, swimming capacity was also reduced similarly between groups in the cold (i.e., distance decreased by 34 ± 26% skilled; 41 ± 33% less-skilled, $p = 0.99$). These integrative findings verify that sudden cold-water immersion followed by physical activity leads to similar physiological responses in humans when contrasting between skilled and less-skilled swimmers.

1. Introduction

Drowning is responsible for at least 388,000 accidental deaths worldwide per year [1], many of which are associated with sudden cold-water immersion (CWI). When humans are immersed suddenly in cold water up to their neck they typically exhibit a set of physiological responses commonly referred to as the cold-shock response [2], characterised by an inspiratory gasp and 1–3 min of hyperventilation and tachycardia. The usual experimental protocol for investigating cold shock involves lowering a seated participant into cold water with a mechanical winch [e.g., 3–5]. Whilst this immersion technique affords experimental control in a laboratory setting it may not be representative of many aquatic emergency situations — where the immersion is sudden and actively treading water may be the only option to stay afloat (i.e., <2 s vs. controlled immersions in ~28 s [3]). Thus, despite there being a substantial amount of research on CWI, much has utilised a slow, staged immersion protocol, and few studies have included treading water, thereby considering its potential effect on the physiological responses and subsequent behaviour. In one exception to this trend, Golden & Tipton [6] found that dynamic immersions over-rode or masked the adaptive benefits gained from repeated static immersions in cold water. Hence, there is some evidence that dynamic immersions have the capacity to alter how humans respond to sudden CWI.

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An important, yet less examined element of cold shock is the effect that hyperventilation-induced hypocapnia has on cerebral perfusion and how this may affect behaviour. Mantoni et al. [5] reported that cerebral blood flow dropped by 43% following a 30-s immersion in 0 °C ice water and resulted in symptoms of imminent syncope (i.e., drowsiness, blurred vision, loss of responsiveness) for those with the greatest drop (>60%), likely as a consequence of the severe cerebral hypoperfusion [7]. Whilst Datta and Tipton [8] have also reported reduced cerebral blood flow (CBF) during 12 °C water immersion (CBF down 25%), no study to date has included physical activity (e.g., treading water) during the cold-water immersion or examined the initial response (i.e., <60 s) during realistic sudden immersion conditions. Given that moderate intensity exercise increases CBF by 10–20% [9], it seems likely that the action of treading water whilst immersed will influence CBF, via exercise-induced increases in neural activity as well as the concomitant increases in cardiac output and arterial blood pressure. Therefore, the physiological response experienced whilst actively staying afloat may well differ to that reported to date from passive, slow-onset immersions [6].

Previous work has considered how cold shock can be reduced in humans via staged entry into the water [10], mental preparation [3], and habituation [4]. Whilst it is known that individual variation exists in the extent of cold-shock response [11], the factors influencing this variation are still unclear. For example, it is possible that the cold-shock reflex and swimming skill level are interrelated. Skilled swimmers may have already developed partial habituation to cold-water immersion, thereby resulting in a less severe response than less-experienced swimmers [12,13]. Relatedly, experience of cold shock amongst surf swimmers in comparison to swimmers without surf experience contributes to better swimming performance in surf conditions [14]. Furthermore, skilled swimmers should be able to support themselves in the water more effectively (and efficiently) than less-skilled swimmers [15], and hence exhibit a relatively lower ventilation rate during the first few minutes of immersion. Further verification of whether swimming skill can influence the severity and duration of cold shock upon CWI is required.

The present study was developed to extend the ecological validity of previous work concerning cold shock. The testing protocol was devised to examine the initial physiological responses following immersion and subsequent swimming capacity whilst participants were required to actively float (i.e., tread water) and then swim rather than being supported passively in the water. It was of particular interest to determine if the cold-shock response was influenced by swimming skill. We predicted that the severity and duration of cold shock may be less in skilled swimmers than in less-skilled swimmers, due to prior partial habituation over time. We also predicted that the typical decrease in CBF velocity associated with static cold-water immersion would be less pronounced whilst participants tread water. This was an exploratory, multidisciplinary study and as such our testing procedure focussed initially upon the physiological responses to sudden cold-water immersion (1st day) followed by subsequent swimming capacity (2nd day).

2. Material and methods

2.1. Participants

Thirty eight participants aged between 18 and 45 years were recruited through advertisements placed on notice boards around the participating institution at local aquatics/leisure clubs and via a web-based job recruitment facility. Informed consent was obtained prior to any testing. Participants were excluded if they failed a health and fitness-screening questionnaire (PAR-Q) to demonstrate their competency to carry out the physical tests. Individuals with prior experience of lifesaving or water survival techniques were also excluded. Part of the testing involved wearing a facemask which needed to remain dry, so if participants were unable to tread water or float sufficiently well to keep their head above water for at least 30 s, they were also excluded from the study. Based on these criteria, 6 participants were excluded. The swimming skill of the remaining 32 participants was determined by measuring maximal swimming speed, and the duration of a 200-m swim performed at a self-selected speed (Table 1). If participants completed the 200-m swim in 300 s they were assigned to the skilled group (N = 17, 7 males and 10 females); if they were unable to swim 200 m or they required longer than 300 s to complete the distance they were assigned to the less-skilled group (N = 15, 9 males and 6 females). The 300 s time-limit was determined based on pilot work identifying it as a reliable criterion that distinguished between recreational and competitive swimmers. The participants in the two groups were well matched in terms of physical and anthropometric characteristics (Table 1).

2.2. Equipment

All testing sessions occurred in a swimming flume (StreamLiNZ, Invercargill, New Zealand). This flume is a 10-m long × 2.5-m wide channel through which the flow and temperature of water can be manipulated. Participants wore a full body harness (Delta™ Repel™ Technology Riggers Harness, Capital Safety, Red Wing, MN) so they could be lowered rapidly into the water using a compressed-air powered hydraulic winch. The lightweight harness (<1 kg) did not interfere with arm or leg movements in the water. The rate of descent was fixed for all participants and took 1–2 s from the start of immersion to full immersion up to neck level. Once in the water the winch rope was slack so that they were unsupported. Following each testing session, or in the potential case of an emergency, it was also possible to remove participants rapidly from the water using the winch.

A 2-MHz Doppler ultrasound system (DWL Doppler, Compumedics, Germany) was used to measure blood flow velocity through the middle cerebral artery (MCAv; which supplies ~80% of total brain blood flow). The flow signal was obtained and refined using search techniques described elsewhere [16,17] before the Doppler probe was maintained in position, at a fixed angle, within a commercially-available fixation headframe (Marc 600; Spencer Technologies, USA). Prefrontal cortical oxygenation was measured noninvasively using near-infrared spectroscopy (NIRS; NIRO-200, Hamamatsu Photonics, Hamamatsu, Japan). A probe holder containing an emission and detection probe 4.5 cm apart was attached at the right side of the forehead using cloth tape (which also assisted with exclusion of light contamination). The methodology of this system has been described previously [18,19]. All data from the ultrasound and spectrophotometer were recorded using LabChart® software (Version 7.0, ADInstruments, Dunedin, NZ).

Respiratory flow profiles, breathing rate and minute ventilation, rates of oxygen usage and carbon dioxide (CO_2) production, and end-tidal CO_2 partial pressure ($P_{ET}CO_2$) were measured using a MetaLyzer 3B gas analysis system (Cortex, Leipzig, Germany).

2.3. Procedure

The following procedures were approved by the participating institution's human ethics committee. All participants completed five

Table 1
Group means and standard deviations of participant characteristics and swimming skill measures for each group. Swim duration refers to the initial 200 m assessment which some of the less-skilled group did not complete (hence the duration is less in this group).

	Less-skilled (n = 15)	Skilled (n = 17)	Total (n = 32)
Age (y)	22.8 ± 5.5	22.7 ± 6.9	22.8 ± 6.2
Height (m)	171.4 ± 6.0	172.6 ± 7.1	172.0 ± 6.5
Mass (kg)	72.9 ± 11.2	70.2 ± 9.3	71.5 ± 10.2
Skeletal muscle mass (kg)	33.6 ± 6.8	32.0 ± 5.5	32.8 ± 6.1
Fat mass (kg)	14.0 ± 7.4	13.0 ± 5.8	13.5 ± 6.6
Swim duration (s)	227 ± 163	255 ± 32	242 ± 113
Max. swim speed ($m \cdot s^{-1}$)	1.0 ± 0.3	1.4 ± 0.4	1.2 ± 0.4