©Journal of Sports Science and Medicine (2023) **22,** 726-738
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2023.726

Research article

Energetic and Cognitive Demands of Treading Water: Effects of Technique and Expertise

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Abstract

Being able to tread water effectively can improve the likelihood of survival following accidental immersion. People tread water in various ways, ranging from rudimentary 'doggy-paddle' to more elaborate techniques like the eggbeater, but little is known about the energetic and cognitive requirements of treading water. We therefore aimed to measure the demands of treading water techniques for people of different experience levels. Three cohorts, comprising 21 adult water treading experts (water polo players), 15 intermediate swimmers and 16 inexperienced swimmers, treaded water for 3 min each using four different techniques while cognitive and energetic economy measures were taken. For inexperienced swimmers, the flutter kick and breaststroke patterns produced the lowest self-reported physical and task load (rating of perceived exertion, NASA task load index), while cognitive (probe reaction time), cardiac (heart rate) and metabolic (oxygen consumption) load did not differ between techniques. In contrast, for expert water treaders, both breaststroke and eggbeater patterns produced lower cognitive, cardiac and metabolic loads. For intermediate swimmers, breaststroke resulted in the lowest cardiac and metabolic loads, as well as self-reported task load. Probe reaction time was highest while performing the eggbeater technique, indicating that this technique was challenging to coordinate and cognitively demanding. While the energetic demands of antiphase kicking patterns (such as eggbeater in experts or flutter kick in beginners) may be similarly low, the symmetric coordination of upright breaststroke may explain why this pattern's cognitive economy was favourable for all groups. As the eggbeater can be challenging to perform for many people, an upright breaststroke technique is an adequate alternative to adopt in survival situations.

Key words: Water safety, water polo, eggbeater, cognitive load, task load, economy, probe reaction time, physical load, oxygen consumption.

Introduction

As people learn motor skills, the energetic and cognitive demands of performing these skills typically diminish. Beginners tend to move with stiff, poorly coordinated actions and expend considerable energy, whereas more advanced performers tend to move fluidly and expend only the necessary energy. Cognitive economy also improves as we learn. Early learners need to control their movements consciously, explore novel information-movement couplings and organise mechanical degrees of freedom according to the dimensionality of new task demands (see Newell and Vaillancourt, 2001), which leads to a high load on cognitive resources during less skilled performance (Furley and Wood, 2016). Experienced performers, on the other hand, have usually developed automated, subconscious control of their movements. Their focus is on optimising their coordination patterns to best exploit energy flows in their environment, and thus the psycho-motor system becomes more efficient (Sparrow and Newell, 1998; Hatfield and Hillman, 2001). With practice, learners become attuned to informational variables that specify how to move effectively and with efficiency (Button et al., 2020). Highly skilled performers exploit system degeneracy in order to continuously adapt their movement patterns to situational demands, in contrast to early learners who struggle to adapt their movements and consequently waste energy (both mental and physical). However, there is surprisingly little direct research to support the idea that cognitive and energetic demands decrease as a function of expertise (Macnamara and Maitra, 2019). In this exploratory study, we aimed to describe the energetic and cognitive demands placed upon individuals of different skill levels as they attempted to perform different water treading techniques. This research addresses the theoretical question of the link between expertise and economy as well as the significant practical question of the most appropriate survival actions to adopt in an aquatic emergency.

Treading water: economy matters

Learning aquatic movement skills, such as swimming and treading water, has been identified as one of the best protective factors against drowning (World Health Organisation, 2021). Adopting a movement pattern that allows an individual to balance energy conservation, heat exchange and maintenance of an open airway may determine whether they survive or not (Hayward et al., 1975a). Treading water allows the head to be kept out of the water, which reduces the rate of heat loss (Hayward et al., 1973; Hayward et al., 1975b) and allows one to assess the surroundings, which is a key component in effective decision-making (Stallman, 2017). Being able to tread water with the head above the water for a long duration, with minimal cognitive and physical effort, significantly improves chances of survival. Determining water-treading patterns that are energy-efficient and low in cognitive demand is an important step in developing optimal instruction tools for water treading.

Received: 05 April 2023 / Accepted: 01 November 2023 / Published (online): 01 Deecember 2023

Table 1. Treading techniques.

Category in Schnitzler et al. (2015)	Type 1.2	Type 2.1	Type 3.1	Type 4.1
Description	vertical movements of hands and feet	feet flutter kicking and hands sculling	feet and hands sculling synchronously	feet sculling asynchronously, hands sculling
Short description	Running	Flutter kick	Upright Breaststroke	Eggbeater

Many ways to tread water

Staying upright in deep water with the head above the water can be achieved in several ways. While some people seem to naturally prefer a simple "doggy paddle" movement (i.e., pushing the water down with all four limbs), others prefer upright breaststroke, and yet others kick their legs hard and fast. Individual preferences might reflect individual constraints, such as the level of expertise in each pattern, anatomical characteristics, or physical factors (Schnitzler et al., 2015). Schnitzler et al. (2015) identified eight behavioural types of treading water across a range of skill levels, which they distilled into four distinctive movement patterns: 1) vertical movements of hands and feet - 'running' in the water; 2) feet kicking and hand sculling - 'flutter kick'; 3) feet sculling synchronously - 'upright breaststroke'; and 4) feet sculling asynchronously - 'eggbeater' (see Table 1). (Note: a fifth pattern consisted of leg-only eggbeater action. The leg-only eggbeater was not included in the present study as it does not involve the same upper-lower body coordination challenges and it was deemed too difficult for novices to maintain for 3 minutes.)

Physiological demands of treading water

The so-called "eggbeater kick" has established itself as the 'gold-standard' pattern to stay afloat in activities like water polo and artistic swimming. Schnitzler et al. (2014) suggest that the eggbeater technique may be more economical because the sculling movements allow a swimmer to produce continuous lift forces without the need for a recovery phase (as shown by kinematic analyses, e.g., Sanders, 1999). In their study, experts tended to use the eggbeater pattern while less experienced treaders preferred other patterns (Schnitzler et al., 2014). Based on lower ratings of perceived exertion, Schnitzler et al. (2014) inferred that skilled water treaders require less energy than unskilled water treaders. Moreover, skilled treaders may choose to perform more complex, but more economical, patterns.

Some aspects of the physiological demands of eggbeater treading have been studied, including the relationship between force produced during treading and water polo performance (Stirn et al., 2014), the general energetic requirements of a water polo game (Smith, 1998; Platanou, 2009; Stirn et al., 2014), and the effect of fatigue on vertical force and coordination of eggbeater treading (Oliveira and Sanders, 2015; Oliveira et al., 2016). Most studies that investigated water-treading economy relied on time to exhaustion as an outcome measure (Amtmann et al., 2012; Schnitzler et al., 2017), but this depends on fitness, training status and technique, and does not reliably assess energetic economy. Furthermore, time to exhaustion is notoriously difficult to assess accurately (i.e., excluding sources of bias, allowing repeated assessments, excluding other confounding variables). Energetic or physical economy is therefore most accurately and directly represented by metabolic measures, especially rate of oxygen consumption ($\dot{V}O_2$). (Another sensitive indicator of subjective exercise intensity is the Borg Scale, which measures Rating of Perceived Exertion (RPE, see Borg, 1990). However, trained individuals report lower RPE for a given rate of energy expenditure. Consequently, comparisons based on a single variable are difficult (Demello et al., 1987). A combination of measures used in parallel may be the most appropriate assessment to capture absolute as well as relative effort and sustainability.

Only one study to date appears to have compared the physiological and cognitive demands of different water treading techniques against each other (van Duijn et al., 2021). Amongst treading experts, the eggbeater and breaststroke pattern were more economical with respect to both cognitive and energetic variables compared to running and flutter kick patterns. But treading techniques are complex and difficult to master: a novice may require extensive practice to reach a proficient level and many people never reach this level of expertise. Testing only water treading experts may not reflect what is ideal in novices or in good swimmers who don't have specific eggbeater experience, since their preference, body type and endurance may differ greatly. For example, an external rotation of the ankles is necessary for an efficient eggbeater kick. While water polo players may be (self-) selected for this ability, many people struggle to rotate their ankles in this direction (Smith, 1998). Also, there are many fit and experienced swimmers who may not have a water polo background, for whom the preferences and demands may be different yet again. The present study therefore extends upon van Duijn et al.'s (2021) study, by adding comparable data from novices and experienced swimmers without water polo experience. No research has yet explored actual measures of energy usage across the spectrum of experience and techniques. By prescribing the four techniques systematically to treaders of different experience levels, we aimed to identify which is most economical – both cognitively and energetically – for different expertise levels.

Cognitive requirements of executing a movement

To determine which water treading patterns are potentially most economic, it is important to acknowledge there are both physical and cognitive dimensions. In an open water emergency, one may have to make complex decisions under time pressure (Golden and Tipton, 2002). Decision making requires integration of perceptual information with existing knowledge, and is therefore demanding on cognitive resources (Raab, 2003). Because conscious control of a complex movement also depends on the same, limited, cognitive resources (Maxwell et al., 2003; Baddeley, 2012), the demands that result from multiple task requirements (i.e., decision making and movement execution) may overload the performer and disrupt performance

(Poolton et al., 2006). Cognitive load and fatigue can also impair physical endurance (Marcora et al., 2009) as well as skilled motor performance (Fortes et al., 2019).

Cognitive demands of movement control are dependent on the coordination requirements of that movement, but may also be linked to physiological demands (Sparrow et al., 2007). Therefore, being able to tread water with minimal cognitive effort may be as important as being able to do it with minimal physical effort. Button et al. (2019) contrasted participants (ranging from competent to highly skilled) who were treading water during changing task and environmental constraints, and identified that upright breaststroke and the eggbeater technique were most stable when water current, clothing, and additional cognitive demands were manipulated. This could indicate that participants had sufficient cognitive resources to deal with the additional distractors of a changing environment while treading water, which in turn may indicate lower demands on cognitive processing resources. Fatigue has been shown to affect decision making and movement accuracy during water treading (Royal et al., 2006), which also shows that there may be a link between cognitive (here: coordination) and physical load. Van Duijn et al. (2021) showed that experts tended to respond to auditory cues equally quickly while treading with the eggbeater and breaststroke technique; however, they performed slightly worse when employing the flutter kick and running technique. No research has investigated differences in cognitive economy across different expertise levels.

In summary, there is a need to further explore the energy cost of treading water among people of various degrees of competence (van Duijn et al., 2021). We investigated which water-treading patterns may be the most versus least cognitively and energetically demanding, and whether this differs between people of different expertise levels.

Specific research questions:

RQ 1: Which are the most economical water-treading patterns in novices, experienced swimmers, and experienced water treaders?

RQ 2: What combination of factors (e.g., movement preference, movement quality) can best explain an individual's most economical water treading technique?

Methods

To maximise reliability and internal validity, the study was conducted in a lab-based environment (a swimming flume) where other potentially influential factors (such as temperature, water flow, clothing, obstacles) were controlled. The methods were identical to the study by van Duijn et al. (2021). Data from the present study are analysed in combination with data of the expert water treaders in van Duijn et al.'s study to allow direct comparison between groups of learners.

Participants

The total number of participants was 52. A post-hoc G*power analysis (Faul et al., 2007) showed that a total sample size of 51 would be sufficient to show a medium-size effect, $f(V) = .45$, $1-\beta = .80$, $\eta 2=.09$, in a 3 (group) by 4 (pattern) within-between group comparison (with $\alpha = .05$). Additional to existing data from 21 water treading experts (i.e., water polo players and synchronised swimmers who self-identified as treading experts, N = 21, mean age = 24 years, SD = 6, 12 females), we tested a further 31 participants, including experienced swimmers without specific water treading experience (N = 15, mean age = 32, SD = 15, 12 females), and inexperienced swimmers (i.e., basic swimming skills present, N = 16, mean age = 29 years, SD = 11, 7 females). Further descriptive statistics are presented in Table 2. Exclusion criteria included significant motor impairments or existing health conditions (e.g., injuries, severe asthma). Participants reported themselves as sufficiently competent to tread water without support for at least 3 min. The experiment was approved by the human ethics committee of the University of Otago and written informed consent was given prior to commencing the measurements.

Procedure

Testing occurred in a swimming flume (StreamliNZ, Dunedin, New Zealand). The flume depth was 2 m and an area of 6 m × 2 m was available for treading water. For all trials, the water was still (i.e., the flume not operating). The water temperature was consistently set at 27°C to ensure that the data were not influenced by temperature fluctuations (Button et al., 2015; Schnitzler et al., 2017).

The experiment occurred on one occasion, approximately 2 h in duration for each participant, individually. Participants first provided basic demographic information as well as height and weight measurements and self-reported swimming and water treading experience.

They then undertook a static buoyancy measurement procedure as described in previous reports (Button et al., 2019, see also 'wet weight' measures below). After the participants were fitted with a snorkel and heart rate monitor (described in more detail below), they were required to sit quietly for 3 min for collection of baseline respiratory and heart rate data. Participants then carefully entered the flume and rested against a side bar. A note was made of their oxygen consumption during standing at rest in the water, for later reference during recovery intervals.

Table 2. Participant characteristics.

	Overall (n = 52)		Novices (n = 16)		Swimmers (n = 15)		Experts (n = 21)	
# Female	31 (59.6%)		7 (43.8%)		12 (80.0%)		12 (57.1%)	
	Mean	**SD**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**	**SD**
Age [y]	28	11	29	32	24	24	32	15
Wet weight [kg]	5.82	1.51	6.34	4.79	6.16	6.16	4.79	1.17
Swim training [y]	5.4	5.6	1.1	5.1	8.9	8.9	5.1	3.9
WP experience [y]	2.1	5.3	0.00	0.1	5.1	5.1	0.1	0.5

Abbreviations: WP = water polo.

Once they felt comfortable breathing through the snorkel, they moved to the centre of the flume and performed a warm-up trial unsupported in the water using their individual preferred movement pattern. The warm-up trial was uninstructed (i.e., the participants were asked to tread water in their preferred way). The warm-up trial was always conducted first, to ensure that individual preference for water-treading technique would not be influenced by any of the patterns subsequently adopted during the study.

Participants then performed one trial of each of the four water-treading techniques (Table 1) for 3 min. This duration was deemed long enough to achieve steady state, without inducing excessive fatigue. Between each trial, participants rested at the side of the flume until their oxygen consumption had returned to within 20% of $\dot{V}O_2$during standing rest. The order of the remaining techniques was counterbalanced and allocated randomly to participants (i.e., some orders were repeated). Example underwater videos of a water polo player performing the required technique were presented on the screen for as long as the participant wanted to practice the movements. Participants were told to "keep their head above water", and to "move like the person on the screen, as exactly as possible". Participants were allowed to practice each technique until they were sure they could perform it for 3 min continuously, before initiating the test. During the first 2 min of each test, participants performed a concurrent probe reaction time task as described below. The Borg RPE scale was presented to participants on a laminated sheet after 60, 120 and 180 s and they were asked to point to their level of perceived exertion. After each trial, participants completed the NASA Task Load Index (Hart and Staveland, 1988) whilst resting at the side of the flume.

Measures

Wet weight

Given the potential for individual buoyancy to influence energy expenditure (Button et al., 2019), “wet” body weight (i.e., the person’s weight when immersed in the water with their head out) was determined for all participants. A plastic chair was attached via a strain gauge (Futek LCM300 250lb., Futek Advanced Sensor Technology Inc., USA, sample frequency: 100 Hz) to a mechanised winch that could be lowered into the tank. Participants were asked to sit in the chair suspended above water level with a 20-kg barbell in their lap to stabilise their position on the chair when submerged. The chair was then winched into the water until the participant’s chin was just above water level. Once the participant and chair were steady, weight measurements (corrected for weight of the barbell) were recorded for 10 s, while participants held their breath after exhaling maximally (to limit movement, i.e., at residual lung volume). To obtain reliable data, this procedure was undertaken three times with rests permitted between attempts (results were averaged over the three trials). The wet weight data were filtered (Butterworth 4th order, cut-off frequency 0.5 Hz). Since wet weight (with head out of the water) is much lower compared to regular body weight measured out of the water, the relative O_2 values in the present study cannot be directly compared with relative O_2 consumption values reported elsewhere. We have reported the VO_2 values standardised by dry weight as well as wet weight in Table 2 to allow more intuitive understanding of the data; however, only wet weight-standardised data were used for analyses. Spirometry data (i.e., vital capacity) were collected as part of the buoyancy measurement.

Metabolic load

A snorkel was fitted to the face via a rubber band around the head, for measurements of respiratory gases (Button et al., 2019). The snorkel was connected to a respiratory gas sample line and a turbine digital transducer, which measured inspired and expired volume, and fractions of O_2 and CO_2 in the expired air via an automated gas analysis system (CPET, Cosmed, Italy).

Participants wore a nose clip to prevent extraneous ventilation. Before and after each test, the volume transducer was calibrated using a manual 3-L syringe (Hans Rudolph, Kansas City, MO) and the gas analysers were calibrated using room air and a gas mixture of known composition (5% CO_2, 16% O_2, atmospheric Nitrogen). Inspired and expired gas volume and gas concentration signals were continuously sampled (breath-by-breath) from the mask using an analogue-to-digital converter (Omnia suite, version 1.0, COSMED, Rome, Italy) and stored for offline analysis in Microsoft Excel. The accepted range for breaths was defined as: tidal volume (VT) > 0.2 L, respiratory frequency between 2 and 80 breaths/min, $\dot{V}O_2$ between 5 and 7500 mL/min, and respiratory exchange ratio between 0.50 and 2.00. Invalid breaths were discarded. Baseline for respiratory, metabolic and physiological data was calculated as the mean of the last 120 s of baseline data. During treading, it was presumed that a steady-state in oxygen consumption would have been reached within 180 s, as shown in previous studies comparing the four swim strokes (Capelli et al., 1998) and in water treading (Von Dobeln and Holmer, 1974). Producing a vocal noise when using a snorkel (as required when completing a probe reaction time task) introduces artefacts in the measurements, so respiratory data were not analysed for the first two minutes of the trial. For analysis, $\dot{V}O_2$ was standardised by participants' wet weight (i.e., buoyancy measurement) to produce a variable representing relative $\dot{V}O_2$ [mL/min/kg] because this better reflects movement economy in water.

Heart Rate

Heart rate was continuously recorded from the heart’s electrical activity via a chest strap (H10; Polar Electro Inc, Kempele, Finland) and digitised using an ANT+ port.

Perceived exertion

The Borg RPE linear scale was used to assess perceived exertion (Borg, 1990). The scale ranges from 6 (no exertion at all) to 20 (maximal exertion).

Probe reaction time

A probe reaction time task provided an objective measure of cognitive load of each treading technique. Response time during this task has been shown to reflect cognitive demand of a concurrently performed motor task (Brisswalter et al., 1995; Wulf et al., 2001). A visual signal (black, large dot) was presented on the screen at random intervals, accompanied by a beep, upon which the participant was asked to respond with a vocal noise (“yes” or similar) through the snorkel as quickly as possible. Pilot tests showed that participants were able to respond with a vocally produced noise without disrupting their breathing through the snorkel. The stimulus was presented 11 times during 120 s, the first measurement was discarded as participants were familiarising with the technique.

Total task load

Self-perceived effort was assessed using a NASA-Task Load Index (Hart and Staveland, 1988), at the conclusion of each trial. TLX raw is based on NASA TLX, a weighted rating scale that assesses six aspects of task load, including the mental, physical and temporal demands, as well as effort, frustration and perceived performance. Each scale was presented as a 12-cm line with a title (e.g., MENTAL EFFORT) and bipolar descriptors at each end (e.g., HIGH/LOW). Numerical values were not displayed, but values ranging from 1 to 100 were assigned to scale positions during data analysis. To compute a summary estimate of overall workload, TLX raw was calculated by summing the raw scores of each subscale (Hart, 2006; Bustamante and Spain, 2008; Colligan et al., 2015). Additionally, the three cognitive items on the scale (i.e., mental demand, performance and frustration) were further analysed separately as an indication of subjective cognitive load (TLX cog).

Ratings of movement pattern and quality

Participants’ behaviours were recorded by three HD video cameras (Sony, Tokyo, Japan): one from behind the participant (below water level), and two from the left and right diagonal (above water level). The under-water camera was the principal camera for qualitative analysis of technique, the front-left camera was used for audio-based assessment of probe reaction time, and the front-right camera was mainly used as back-up in case of equipment malfunction or to help confirm pattern classification. Participants were positioned to face a screen suspended over the pool edge, approximately 0.5 m away from the pool side. A ladder as well as bars at the side of the flume channel were available for support while entering or exiting the water, and during breaks.

To check whether participants performed the instructed techniques correctly, two analysts were trained to perform qualitative analysis of treading water according to the method developed by Schnitzler and colleagues (Schnitzler et al., 2014). Both analysts independently identified the coordination pattern in a random sample of the data while blinded to the technique that was instructed. The variable “performed pattern” was analysed only for the uninstructed trial, where it reflects the participant’s preferred treading technique. Analysts also rated the quality of movement execution on a scale ranging from 1 (low / novice quality) to 10 (high / expert quality), considering fluidity, compatibility of movements with experts' movements and whether all limbs were moving in the way that the pattern required (Table 2). An intraclass correlation coefficient (Koo and Li, 2016) was calculated for quality, for n = 50 cases (i.e., 10 participants x 5 techniques). ICC estimates and their 95% confident intervals were calculated based on a 2-way mixed effects model for consistency, and revealed good reliability (ICC = 0.834, 95% CI [0.708, 0.906], F(49,49) = 6.031 $p < 0.001$). Technique ratings, being on a nominal scale, were analysed for agreement and showed a 98% agreement between analysts.

Statistical analysis

A Shapiro-Wilk test showed no departure from normality for: PRTs, W(48) = 0.98, p = 0.50; TLX raw, W(48) = 0.97, p = 0.20; RPEs, W(48) = 0.97, p = 0.24; or $\dot{V}O_2$, W(48) = 0.97, p = 0.22. However, a significant departure from normality was evident for HR, W(48) = 0.93, p = 0.005. Hence, for each variable (i.e., HR, $\dot{V}O_2$, RPE, TLX raw, TLX cog, PRT), a separate 4 Technique (running, flutter kick, ‘upright breaststroke’, eggbeater) by 3 Group (Novice, Expert, Swimmer) Analysis of Variance (ANOVA) with repeated measures on the first factor was conducted. Analysis of Variance has been reported to be robust to violations of the normality assumption (Rasch and Guiard, 2004). Greenhouse-Geisser correction was used in cases where data was non-spherical. Post-hoc comparisons were conducted with a Bonferroni correction. To check whether groups differed in swim and water polo experience, separate independent samples t-tests were conducted for water polo experience (Novice vs. Expert and Expert vs. Swimmer) and for deliberate swim experience (Novice vs. Swimmer). Pearson-product-moment correlation coefficients were calculated between movement quality and each variable of economy. We conducted a linear regression analysis (backward method) on a long data set, in which variables were collapsed over all treading patterns. This enabled prediction of a single variable “technique preference” from all economy variables. A Pearson Chi-Square test was used to compare preferred pattern (as executed in uninstructed warm-up trial) with the most efficient pattern (based on $\dot{V}O_2$). The threshold for statistical significance was set to p = 0.05. All analyses were conducted using SPSS Statistics Version 28 (Armonk, NY: IBM Corp).

Results

Participant characteristics

Table 2 shows that swim training and water polo experience clearly differed between the three groups: the novices showed low values in both, treading experts showed high water treading and swimming experience, and swimmers showed high swimming experience but no water polo experience. Direct t-test comparisons showed that experts had significantly more experience in water polo compared to novices (t(20.268) = -3.068, p = 0.003) and experienced swimmers (t(20) = -2.749, p = 0.002), and that experienced swimmers had significantly more deliberate swim practice compared to novices (t(20.657) = -3.610, $p < 0.001$).

Economy of treading water techniques

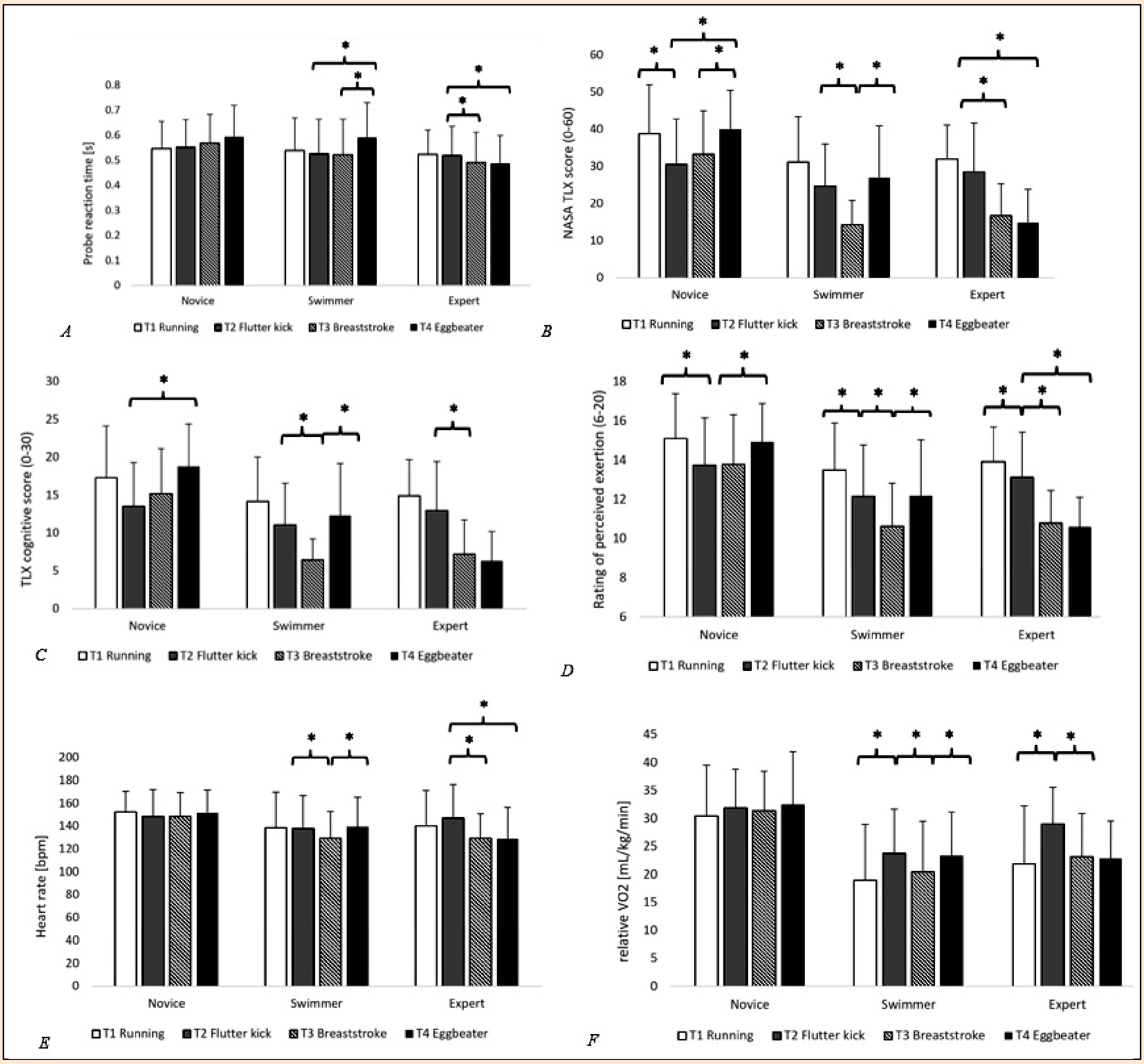
A significant Group x Technique interaction was found for each variable. Post-hoc comparisons (Bonferroni corrected) were conducted to compare Techniques within each Group (see Table 3 and Figures 1a-f). In Novices, flutter kick and breaststroke were lowest for self-reported physical and task load (RPE, TLX), while cognitive (PRT), cardiac (HR) and metabolic load ($\dot{V}O_2$) did not differ between techniques. In Experts, both breaststroke and eggbeater were linked to lower self-reported physical load, self-reported task load, cognitive load, cardiac and metabolic load. In experienced swimmers, breaststroke led to lowest RPE, TLX, HR and $\dot{V}O_2$ (Figure 1). PRT was highest while performing the eggbeater technique, but not significantly different between the other techniques.

Figures 1 a-f. Mean values in main variables for each group and treading pattern. Error bars indicate one standard deviation.

Movement quality

A significant interaction between Technique x Experience was found (for details, see Table 4). Post-hoc analyses with Bonferroni correction showed that pattern quality was significantly higher in Experts compared to both Novices and Swimmers, and was significantly higher in Swimmers compared to Novices, in each technique (As a reminder, movement quality was assessed by trained expert analysts who rated the quality of movement execution on a scale ranging from 1 (low / novice quality) to 10 (high / expert quality), considering fluidity, apparent economy and similarity of movements with experts' movements.).

Upon visual inspection, the difference in movement quality between groups is greatest in the eggbeater technique and smallest in running technique (see Figure 2). Negative correlations were evident between pattern quality and three of the variables during breaststroke as well as with each variable during eggbeater techniques, but no significant correlations were found during running or flutter kick techniques (see Table 4).



Figures 1. a-f. Mean values in main variables for each group and treading pattern. Variables presented: a) probe reaction time, b) NASA TLX raw, c) TLX cognitive score, d) rating of perceived exertion, e) heart rate, f) relative $\dot{V}O_2$. Error bars indicate one standard deviation. Note: The $\dot{V}O_2$ values presented in this graph were standardised by dry weight to allow more intuitive understanding of the data; however, the wet weight-standardised data were used for analyses.

Table 3. Effects and interaction of Group and Technique on variables of economy.

		ANOVA results					Direct comparisons		
		df	F	*p*	Partial η^2	Obs. power	Novices	Swimmers	Experts
PRT	Group	2, 49	1.314	.278	.051	.271	1=2=3=4 and 2(=)4	1=2=3<4 and 2<4	1=2>3=4 and 2>4
	Technique	3, 147	3.715	.013	.070	.798	All equally economic	4 least economic	3 and 4 most economic
	Group x Technique	6, 96	5.057	.000	.171	.992			
TLX raw	Group	2, 49	11.065	.000	.311	.988	1>2=3<4 and 2<4	1(=)2>3<4 and 2=4	1=2>3=4 and 2>4
	Technique	2.6, 127.3	20.423	.000	.294	1.00	2 and 3 most economic	3 most economic	3 and 4 most economic
	Group x Technique	5.2, 83.2	9.001	.000	.269	1.00			
TLX cog.	Group	2,49	10.484	<.001	.907	1.00			
	Technique	3,147	15.952	<.001	.246	1.00	1=2=3=4 and 2<4	1=2>3<4 1>3	1=2>3=4 and 1>3, 1>4, 2>4
	Group x Technique	6,96	8.529	<.001	.258	1.00	T4 less economic than T2	T3 most economic	T3 and T4 most economic
RPE	Group	2, 49	8.513	.001	.258	.957	1>2=3<4, 2<4	1>2>3<4 and 2=4	1>2>3=4 and 2>4
	Technique	2.5, 122.2	26.964	.000	.355	1.00	2 and 3 most economic	3 most economic	3 and 4 most economic
	Group x Technique	5.0, 80	7.511	.000	.235	.999			
HR	Group	2, 49	1.891	.162	.072	.374	1=2=3=4 and 2=4	1=2>3<4 and 2=4	1=2>3=4 and 2>4
	Technique	2.3, 110.3	7.143	.001	.127	.946	All equally economic	3 most economic	3 and 4 most economic
	Group x Technique	4.5, 72	4.304	.002	.149	.979			Experts
$\dot{V}O_2$	Group	2,49	6.683	.003	.214	.898			1=2>3=4 and 2>4
	Technique	2.5, 120.7	24.27	<.001	.330	1.00	1=2=3=4	1<2>3<4	3 and 4 most economic
	Group x Technique	4.9, 78.8	6.97	<.001	.222	.998	All equally economic	T3 lowest	
Movement Quality	Group	2, 49	35.114	<.001	.589	1.00			1=2>3=4 and 2>4
	Technique	3, 147	10.365	<.001	.175	.998	1=2=3>4 and 2>4	1=2=3>4 and 2>4	3 and 4 most economic
	Group x Technique	6, 96	6.978	<.001	.222	1.00	4 worst	4 worst	

Abbreviations: HR = heart rate, RPE = rating of perceived exertion, PRT = probe reaction time, $\dot{V}O_2$ = oxygen consumption relative to head-out immersed body weight (mL/min/kg), TLXcog = cognitive subscale of NASA TLX. Techniques: 1 running, 2 flutter kick, 3 breaststroke, 4 eggbeater. Note: Bonferroni corrections used for post-hoc comparisons.

Table 4. Pearson product-moment correlation coefficients between movement quality and each of the five economy variables during each pattern.

Variables	Correlation of variable with movement quality rating of the same pattern							
	running		flutter kick		breaststroke		eggbeater	
	r	p	r	p	r	p	r	p
HR	-.12	.40	-.07	.60	-.29	.035	-.42	.002
$\dot{V}O_2$	-.13	.35	-.08	.59	-.27	.058	-.38	.006
PRT	-.09	.55	-.22	.12	-.37	.007	-.39	.004
RPE	-.08	.56	-.27	.05	-.44	.001	-.70	.001
TLX raw	-.05	.72	-.24	.09	-.42	.002	-.66	.001
TLX cog	-.02	.90	-.234	.10	-.446	.001	-.75	.001

Abbreviations: HR = heart rate, RPE = rating of perceived exertion, PRT = probe reaction time, $\dot{V}$ O2= oxygen consumption relative to body weight, TLXcog = cognitive subscale of NASA TLX.

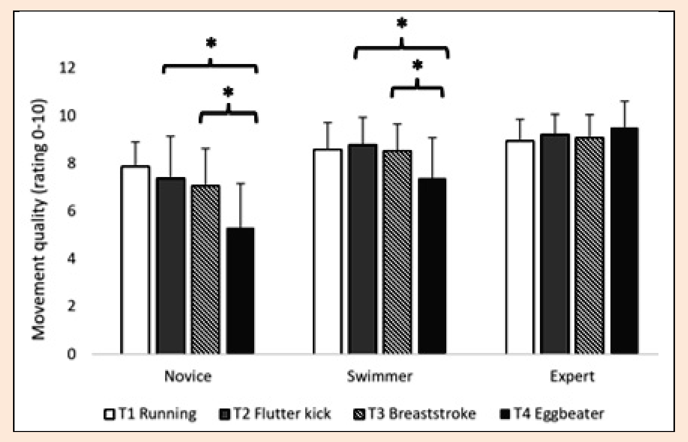


Figure 2. Means and SD of movement quality during each pattern.

Preferred treading pattern

A Pearson Chi-Square test comparing preferred pattern (as executed in uninstructed warm-up trial) with the most efficient pattern (based on $\dot{V}O_2$) revealed that preference and efficiency were independent (i.e., not related, $\chi2$ (9) = 14.57, p = 0.104). The preferred pattern matched the most economical pattern in 38% of participants (Novices 43%, Experts 47%, Swimmers 20% - see Table 5). For the most efficient pattern based on PRT, a similar result was found, $\chi2$ (12) = 12.68, p = 0.392.

A regression analysis was conducted to determine whether age or sex influenced preferred pattern. Sex was not a significant predictor of preferred pattern, R^2(adjusted) = -0.005, F(1,206) = 0.001, p = 1.00, and was therefore not included as a predictor variable in the subsequent analysis. Collinearity was evident (condition index 35.547 on 7th dimension, variance proportions 0.71 (TLX raw), 0.53 (RPE) and 0.38 (TLX cog). Therefore, raw TLX was excluded from the regression analysis. Movement quality was excluded as it was deemed to be a consequence rather than a potential cause of pattern preference.

Stepwise regression analysis (backward method) was used to determine which combination of factors predicted pattern preference. The predictor variables included TLXcog, PRT, RPE, HR and $\dot{V}O_2$. The threshold value for the predictor variables was p = 0.05 for inclusion and p = .10 for exclusion. Results of the regression analysis are presented in Table 5. Model 1, including all variables, was significant. In subsequent steps, HR, which had a p-value greater than .10, was removed to leave a significant model (Model 2). Removal of RPE and PRT (p > 0.10) further refined the model (Models 3 and 4). Finally, removal of $\dot{V}O_2$ (p > 0.10) yielded a model (Model 5) in which TLXcog was the only significant predictor of pattern preference, accounting for one third (31%) of the variance in pattern preference (see Table 6).

Discussion

RQ 1: Which are the most economical water-treading patterns in novices, experienced swimmers, and experienced water treaders?

This study is the first to combine psychological, physiological and technical data for treading water, which provides ideal grounds for the discussion of the relationship between skill level and workload. In Novices, flutter kick and breaststroke resulted in the lowest self-reported physical load and task load (RPE, TLX raw), while cognitive (PRT), cardiac (HR) and metabolic load ($\dot{V}O_2$) did not differ between techniques. In Experts, both breaststroke and eggbeater led to lower RPE, TLX, PRT, HR and relative $\dot{V}O_2$ compared to the other techniques. In experienced swimmers, breaststroke led to lowest RPE, TLX, HR and $\dot{V}O_2$. PRT was highest while performing the eggbeater technique, but not different between the other techniques.

Table 5. Matchings between preferred pattern and most economical pattern.

Experience group	Pattern with lowest $\dot{V}O_2$	Preferred pattern				
		T1	T2	T3	T4	Total
Novices	1	0	1	1	0	2
	2	3	2	1	0	6
	3	0	2	2	0	4
	4	1	2	0	1	4
	Total	4	7	4	1	16
Swimmers	1	1	1	1	2	5
	2	0	0	0	0	0
	3	1	3	3	2	9
	4	1	0	0	0	1
	Total	3	4	4	4	15
Experts	1	0	0	0	0	0
	2		0	0	1	1
	3		3	1	4	8
	4		0	2	10	12
	Total		3	3	15	21

Table 6. Backward regression analysis to predict pattern preference.

	Model 1		Model 2		Model 3		Model 4		Model 5	
R^2	.101		0.101		0.100		0.098		.095	
p	<.001		<.001		<.001		<.001		<.001	
Sig. F change	<.001		.884		.602		.532		.392	
Variables	**β**	**p**	**β**	**p**	**β**	**p**	**β**	**p**	**β**	**p**
HR	.015	.884	—	—	—	—	—	—	—	—
RPE	-.065	.592	-.063	.602	—	—	—	—	—	—
PRT	.049	.506	.046	.516	.044	.532	—	—	—	—
$\dot{V}O_2$	.079	.413	.087	0.277	.070	.308	.061	.392	—	—
TLXcog	-.304	0.007	-.302	0.007	-.345	<.001	-0.330	<.001	-.308	<.001

Beta and P-values for predictor variables, and R^2_{adj} values and P-values for each model. Abbreviations: HR = heart rate, RPE = rating of perceived exertion, PRT = probe reaction time, $\dot{V}$O2 = oxygen consumption relative to body weight, TLXcog = cognitive subscale of NASA TLX.

While energetic demands of other patterns (e.g., eggbeater in experts or flutter kick in beginners) may be similarly low, the bilateral symmetric coordination of upright breaststroke may explain why this pattern was cognitively economical in all groups. With increasing task demands, humans tend to synchronise their movements, a synergetic solution that reduces degrees of freedom (Schöner and Kelso, 1988). Especially novices show a global tendency to synchronise the limbs rather than to exhibit asynchrony, as documented in rhythmic movements (Oullier et al., 2006). Synchronised movements require less attentional effort, and also less physical effort to coordinate (Sparrow and Newell, 1998; Sparrow et al., 2007; Seifert et al., 2013). In water treading, however, this has not been shown thus far. On the contrary, it has been suggested that asynchronous movements might provide a physical benefit due to the lack of a recovery phase (which may be costly in terms of energy). It thus seems that the task constraints of the most economical patterns (asynchronous, antiphase movements) are likely to be a mismatch with most learners' intrinsic dynamics (which favour synchronous coordination patterns), making water treading an extremely complex skill to perform (Kostrubiec et al., 2012).

In this study, experienced swimmers showed a clear preference for breaststroke technique when treading without instruction, indicating that intrinsic dynamics may favour minimising the cognitive effort of coordinating bilateral movements over minimising physiological economy. The fact that the upright breaststroke pattern has a recovery phase and still came out as superior in cognitive and physical load to the eggbeater technique underlines how strongly coordination requirements may influence the total demand on a person treading water.

Another factor that may explain the low cognitive load of upright breaststroke is movement automaticity due to extensive practice. Breaststroke is often the first swimming technique that is taught, so a person may therefore have been using the movement for significantly more time compared to other (theoretically more economical) water treading techniques. As well as developing an economical movement pattern by fine-tuning the patterns of coordination, this is likely to lead to automated motor control and less motor planning demands (Fitts and Posner, 1967). According to the psychomotor efficiency hypothesis (Hatfield and Hillman, 2001), improvement in motor control through practice is accompanied by the suppression of task-irrelevant processes (e.g., diverting resources away from brain regions that have limited relevance for the task) and the enhancement of task-relevant processes (e.g., redirecting resources to the most important cortical regions for task performance, see e.g., Hatfield et al., 2004; Cooke, 2013; Gallicchio et al., 2017).

It is likely that cognitive and physical economy are not completely separable, but rather influence one another. Sparrow and Newell (1998) found that attentional cost of a coordination task was influenced not only by the information-processing demands of coordination itself, but also by the metabolic energy demands of performing the tasks. Our findings could be interpreted via the Haken, Kelso, and Bunz model (HKB, see Haken et al., 1985) in terms of metabolic energy and attentional cost: the HKB model suggests that movement behaviour arises from self-organisation, and that control parameters regulate the stability of a system's (read: learner's) behaviour: At a critical value of the control parameter an initially stable coordination state may lose stability and the system switches to a different coordination pattern (Kelso, 2021). When applying this to water treading, the energy required by the central nervous system to stabilise a coordination pattern may be seen as a control parameter for coordination patterns (Zanone et al., 2001). This means, at some intensities, certain coordination patterns may be more stable than at others. More experienced treaders may exhibit lower heterogeneity and stronger preferences in their coordination patterns, which makes these patterns inherently more stable. A similar proposition has previously been investigated in water treading. Button et al., (2019) found that expert patterns were generally more robust to changing constraints (such as the wearing of clothing or the presence of a water current). Experts' coordination patterns likely form a more stable attractor in a person's perceptual-motor landscape and may therefore be less easily disrupted by changing demands (Zanone et al., 2001). However, when thinking about the energetic demands we would deem it necessary for novices to prioritise one technique. Under ecological dynamics theories, it is conceivable that people with less experience may be more focused on stabilising a single movement pattern (perhaps visible in experienced swimmers preferring Breaststroke), and only with increased experience and exposure to different constraints would they be triggered to explore and stabilise other movement patterns and widening their movement repertoire (as seen in treading experts who mostly have water polo experience).

Breaststroke caused lower demands overall for novices and experienced swimmers in this study, while eggbeater was most economical overall in those who had practiced it over a long time (i.e., water polo experts). In beginners, the cognitive effort of coordinating alternate movements probably led to high cognitive load of performing the eggbeater technique, while that of upright breaststroke was low. With expertise, this attentional/coordination load is lowered, until it may be compensated for by the more consistent hydrodynamic lift that is created by alternating movements. This results in reduced physiological demands of this technique in experts.

RQ2: What combination of factors best predicts an individual's most economical water treading technique?

Movement quality was lower in novices compared to experts, especially when using the eggbeater technique. This was expected, as novices had less experience of performing the movement patterns. Across all participants, movement quality was inversely related to heart rate and oxygen consumption during upright breaststroke as well as eggbeater. This indicates that how well a skill is executed seems to affect the energetic costs associated with it (Sparrow and Newell, 1998).

Novices showed no common preference for a treading pattern, and even in experienced treaders, the preferred technique of each individual participant did not match the technique that required the least energy (based on oxygen consumption) for them. This means that people may not be very adept at self-selecting the most economical treading pattern, or that preference is trumped by yet other factors in promoting economical movement coordination. Self-reported cognitive task load (TLX cog) was the only variable that predicted pattern preference in a significant regression model. There may be a potential link between preferred pattern and cognitive load, or in other words, that people self-select a technique that feels easier to coordinate.

Explorative observations

The preferred treading pattern, as well as cognitive and energetic load differed among novices, to the extent that no consistent differences between techniques could be found. This suggests that either the treading pattern didn't matter for novices, or that there were large individual differences, with some participants being more economical at one technique and others in another. As this group was very diverse in terms of age, preferences, fitness level and body composition (see Table 2), the second explanation is more likely. Preferred pattern differed greatly within this group, further supporting this explanation. There may be factors that can predict these individual differences, such as experience in each treading pattern, joint flexibility, and movement preferences, but a larger cohort is needed for a fully powered regression analysis. Furthermore, no clear connection between anthropometric factors and sinking force in different body postures has been established to date, which could play a role in the relationship between technique and economy as well.

Treading patterns of novices were inconsistent over time as well. We observed many changes in movement patterns during the three minutes of treading (Note: this is observational only, data are not reported in this paper.) This is not surprising when one considers aquatic behaviour from a constraints-led approach. The same goal may be reached by a variety of movement solutions (Newell, 1986; Davids et al., 2004). In the light of open water survival, this "noise" in movement output may actually be beneficial as it may delay the onset of fatigue and cramping (Nelson and Churilla, 2016). Indeed, a potential ideal protocol for long-term behaviour when immersed in cold water might consist of rotating between different modes of locomotion (Golden and Tipton, 2002).

Overall, novices used a lot (>40%) more energy to stay afloat compared to the other two groups (Figure 1e). Since fitness level differed between these groups, this finding may not be indicative of economy only, but may be reflective of a total (rather than relative) increase in demands. Lower treading experience and therefore lower economy of all treading techniques is likely an explanation. This means that inexperienced people are at higher risk of reaching exhaustion before being rescued in immersion incidents. In fact, inexperienced and less fit swimmers are compromised in multiple ways in a potential water emergency: 1) they require more energy as their movements are less economical, 2) they have a lower fitness and therefore less energy available and 3) as time to exhaustion is disproportionately more affected by fitness level than power output (Hopkins et al., 2001), novices will fatigue much more quickly than fit swimmers or experienced treaders.

Implications for water safety and potential future research

Drowning has been the cause of over 2.5 million preventable deaths in the past decade (UN General Assembly, 2021). Maintaining an upright posture in the water with minimal cognitive and energetic effort is an important skill, especially when immersed in cold water: Survival is contingent upon the delicate balance between conserving energy levels and body heat, versus expending energy in order to remain afloat until rescue arrives (see Moran, 2019). For a comprehensive discussion of hypothermia and survival techniques in open water, refer to Golden and Tipton (2002).

In the event of an emergency, we suggest that a person should pick whichever movement pattern they find easiest to coordinate – it is the "safest bet" as it is likely to be most efficient. When deciding on the water treading technique that should be taught to promote survivability, the findings of the present study indicate that first the breaststroke, and second the eggbeater patterns should be practiced extensively. This would facilitate these patterns to become economic and easy to coordinate, or even to become the most stable movement solution for the learner (Zanone et al., 2001). Thus, a short-term aim should be to learn how to produce an efficient breaststroke technique, but in the long run it is worth trying to learn an efficient eggbeater treading pattern.

In water treading, there seems to be a trade-off between the cognitive effort of coordinating movements (which is expected to be high in alternate limb movements) and the physiological demands of performing the movement pattern (which is expected to be low when eggbeater pattern allows continuous lift). A study might directly test which of these explanations holds and how this may change with expertise, for example by comparing fatigue vs. energetic and cognitive economy over time and with practice. Aside from energy conservation, heat loss during treading water should also be considered when deciding on the optimal technique. Some studies have shown that using the arms leads to quicker heat loss / drop in body temperature, as more blood perfuses more superficial tissue, causing cooling. It might be worth investigating treading patterns that can work with minimal arm movements, and compare energy consumption, heat loss and cognitive functioning during performance of these. For example, Schnitzler et al. (2015) initially identified a fifth movement pattern, which was leg-only eggbeater kicks. Such movement solutions may be especially useful in cold water.

Limitations

The present study was an exploratory, multidisciplinary study, powered for medium-sized effects. The authors are aware that sex and body weight as well as aerobic fitness were not matched between groups and were significantly different between the three experience groups, hence not all between-group differences may be directly attributed to experience only.

Conclusion

This multidisciplinary study showed ‘remarkable’ consistency between physiological, psychological, and qualitative data. The fact that the eggbeater technique was associated with a higher workload in all dimensions for novice and swimmers, but not for experts, shows that this technique may be an efficient solution when it has been practiced extensively. If there is not enough time to practice a more physically economical skill, such as the eggbeater, to proficiency, an upright breaststroke technique may be the safest bet to teach, and to adopt in an emergency.

Acknowledgements

We thank Nigel Barrett and Dr Chris Harvey for their valuable input with the set-up and design of the experiment. This study was funded by the Swiss National Science Foundation (P2SKP1_187632). The study complies with the current laws of the country in which they were performed and conforms the Declaration of Helsinki. The authors have no conflict of interest to declare. The datasets generated and analyzed during the current study are available under the following link: https://osf.io/bruxa/?view_only=ea5c8f5ee0cb44e695649e57264818e2.

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Key points

- The physical and cognitive load of water treading varies for different treading techniques and between levels of expertise.
- In experienced treaders, the energetic demands of continuous, asynchronous patterns are generally lower.
- In less experienced swimmers, the cognitive load of performing synchronous movements is lower compared to antiphase patterns.

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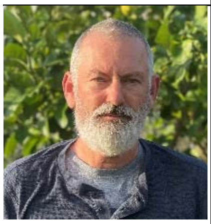

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