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Swimming obstructed by dead-water

Sander P. M. Ganzevles · Fons S. W. van Nuland ·
Leo R. M. Maas · Huub M. Toussaint

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Abstract In nautical literature, 'dead-water' refers to the obstructive effect encountered by ships moving in stratified water due to the ship generating waves on an interface that separates different water masses. To investigate the hypothesis that open water swimming may also be obstructed by an encounter of dead-water, possibly causing drowning, we performed two experiments that assess the impact of stratified water on swimming. In the first experiment, subjects made a single front-crawl stroke while lying on a carriage that was rolling just above the water surface. The gain in kinetic energy, as a result of the stroke, was far less in stratified than in homogeneous water. In the second experiment, four subjects swam a short distance (5 m) in homogeneous and in two different settings of stratified water. At the same stroke frequency, swimming in stratified conditions was slower by 15%, implying a loss in propulsive power by 40%. Although in nature stratification will be less strong, extrapolation of the results suggests that dead-water might indeed obstruct swimming in open water as well. This effect will be most pronounced during fair weather, when stratification of a shallow surface layer is most easily established. Our findings indicate that swimmers' anecdotal evidence on 'water behaving strangely' may have to be taken more seriously than previously thought.

Keywords Drowning · Swimming · Dead-water · Stratified water · Internal waves

Introduction

Drowning is a major cause of death worldwide, with an estimated 400,000 people drowning annually (WHO 2002; Peden and McGee 2003). Recently, it was proposed that enigmatic drowning cases in open water, occurring under fair-weather conditions, might be caused by 'dead-water', a typical effect of the water's stratification (Maas and Van Haren 2006).

Dead-water was first encountered in Norwegian fjords and referred to ships suddenly losing speed, up to a factor five (Nansen 1897). The obstructive effect occurred in water stratified in salinity (i.e. density) and appeared to be caused by the ship generating interfacial gravity waves (Ekman 1904; Miloh et al. 1993; Tulin et al. 2000; Walker 1991). The phenomenon was coined dead-water because the water surrounding the ship had a glassy appearance and seemed motionless. Ekman (1904) quotes a sailor who described that when his ship encountered dead-water 'it was as if we swept the whole sea along with us'. This was due to the absence of any relative motion between water and ship as the interfacial wave, generated by the ship, propagated at ship speed. Interfacial waves are similar to surface gravity waves, except they arise on the interface between layers of water of different density, rendering them nearly invisible at the surface. They extract energy intended

S. P. M. Ganzevles · F. S. W. van Nuland · H. M. Toussaint
Research Institute MOVE,
Faculty of Human Movement Sciences, VU University,
Van der Boechorststraat 9,
1081 BT Amsterdam, The Netherlands

L. R. M. Maas (✉)
Royal Netherlands Institute for Sea Research,
PO Box 59, 1790 AB Den Burg, The Netherlands
e-mail: maas@nioz.nl

L. R. M. Maas
Institute for Marine and Atmospheric Research Utrecht,
Utrecht University,
Utrecht, The Netherlands

for propulsion, especially when the object's draft is comparable to the upper layer depth and when its speed approaches the interfacial long wave (or critical) speed, c' (Ekman 1904):

$$c' = \sqrt{g'h'} \text{ with } h' = h_1 \cdot h_2/(h_1 + h_2) \text{ and } g' = g(\rho_1 - \rho_2)/\rho_1 \tag{1}$$

Here, $h_{1,2}$ are lower and upper layer depths, $\rho_{1,2}$ corresponding densities and g' is gravity acceleration, g (9.81 $\text{m}\cdot\text{s}^{-2}$), reduced by the relative density difference between the two layers.

It is known that this type of interfacial wave drag also affects drifting ice keels (Pite et al. 1995), hence it is conceivable that swimmers, crossing a relatively deep, temperature-stratified lake, might be obstructed by deadwater as well. This is what we want to examine here. For such lakes (Padisák and Reynolds 2003), e.g., ρ_1= 999.1 $\text{kg}\cdot\text{m}^{-3}$ (fresh water at 15°C), ρ_2=997.0 $\text{kg}\cdot\text{m}^{-3}$ (fresh water at 25°C), h_1=30 m, the upper layer depth can be as thin as h_2=1 m, and one finds an interfacial long wave speed, c'=0.14 $\text{m}\cdot\text{s}^{-1}$. Swimming speed, however, is often much higher than c', ranging from 0.75 $\text{m}\cdot\text{s}^{-1}$ for recreational up to 2 $\text{m}\cdot\text{s}^{-1}$ for competitive swimmers (Toussaint and Truijens 2005). This discrepancy in speeds makes it unlikely that the swimmer's body, seen as a displacement hull, experiences additional drag by generating interfacial waves, due to lack of coupling (Esler et al. 2007). This might explain the absence of any measurable effect in a genuine swimming pool experiment, where the upper layer was less than 0.40 m (Maas and van Haren 2006), despite the fact that the swimmer's body (chest depth approximately 0.3 m (Vennell et al. 2006)) was well within the 0.7-m distance over which a surface or interface might be disturbed by a moving object in its vicinity (Vennell et al. 2006; Costill et al. 1992).

However, as swimmers propel themselves by upper limb-movement mainly (Toussaint et al. 1990), is stratification perhaps limiting propulsion? During stratified conditions, the path of the propelling surface (mainly hands) can be near the interface, while its speed, in order to generate forward propulsion, changes from positive to negative. Thus, during every single stroke, absolute hand speed will pass critical speed, c', twice. When the hand speed approaches c', and the hand moves close to the interface, the hand itself might generate interfacial waves, possibly affecting propulsion. Alternatively, at supercritical speed, the non-stationary motion of the moving hand may directly mix fluid.

To elucidate these effects of stratification on propulsion, we will interpret swimming as drag-based paddling (Fish 1996). When the hand moves backwards through the water (leftwards, in Fig. 1a), the pressure on the palmar side of the hand increases and pressure on the dorsal (*i.e.* back) side decreases (indicated by plus and minus symbols in Fig. 1a,b respectively). This creates a pressure difference, a representative of the propulsive force (Takagi and Wilson 1999), which allows the swimmer to propel. In stratified water, when the hand speed approaches c', we expect pressure anomalies on the palmar and dorsal side of the

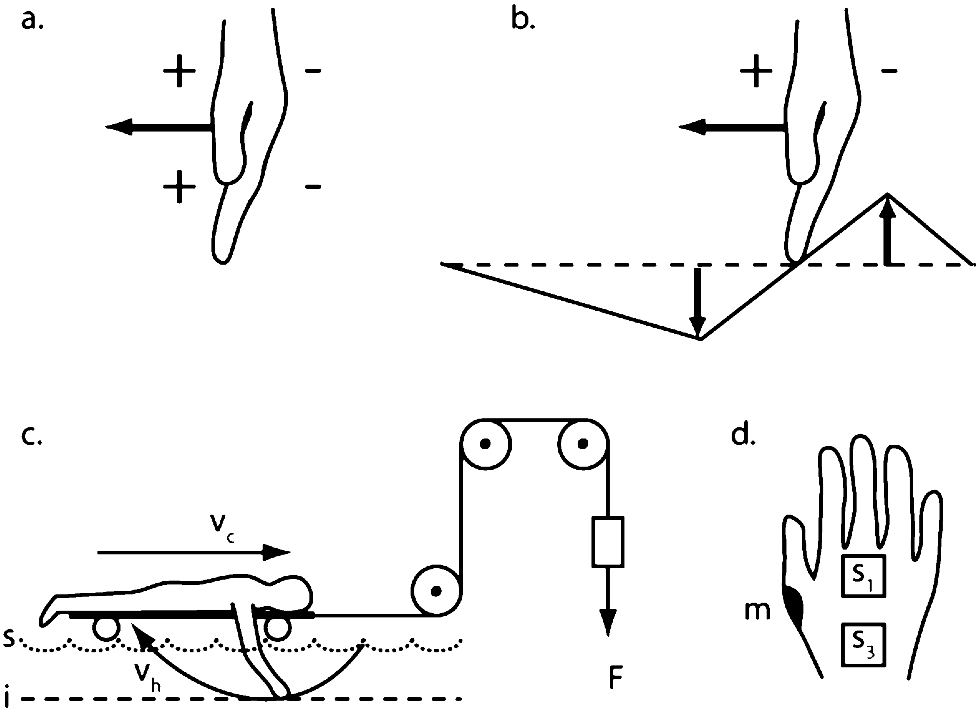

Fig. 1 Hypothetical effect of stratified water (**a–b**) and setup of experiment 1 (**c–d**). **a–b** Schematic of propelling hand moving in direction of *arrow* and resulting increase/decrease in pressure (+/−) in homogeneous (**a**) and stratified case (**b**) (Maas and van Haren 2006). In **b** interface is indicated before (*dashed line*) and after (*solid line*) displacement due to a stroke. **c** Side view of set-up in experiment 1, with F propelling force, v_c carriage speed, v_h hand speed, s water surface (*dotted line*), i interface (*dashed line*). **d** Placement of pressure sensors, S_1 and S_3, on the hand (*back side*) with m marker. Sensors S_2 and S_4 were placed on similar locations on the palm of the hand

hand to relax instantaneously due to the elastic properties of the interface, diminishing the pressure difference (Fig. 1b). However, in contrast to the regular wave train generated by a steadily moving ship, each stroke likely acts as an individual impulse. This generates either a packet of dispersive waves (having speeds that are maximized by the critical speed), when the hand velocity is subcritical, or a wave structure that is trapped to the hand, as schematically represented in Fig. 1b, at supercritical speed (Tulin et al. 2000). This wave will deepen and likely become unstable and mix fluid. Because the pressure difference across the hand thus relaxes rapidly near the interface, the fluid's resistance to hand motion decreases, leading to a higher speed of this propelling surface relative to the rest frame. At the same mechanical power output, a larger part of the work is spent in displacing fluid, both horizontally as well as vertically, against gravity, raising the fluid's potential energy. This leaves less propulsive power for overcoming body drag and thus reduces the propelling efficiency (Toussaint et al. 1988).

To investigate the validity of these arguments, two experiments were performed that compared swimming in stratified water to that in homogeneous water. To entirely remove the displacement effect of the body, in the first experiment the 'swimmer' was lying on a carriage, rolling above the water. The impact of a single stroke, performed in the vicinity of the interface, was examined. In the second, regular swimming experiment, the time was measured that a swimmer needed to cover a preset distance. Effects of interface depth and swimming frequency were also investigated.

Materials and methods

General Four subjects (see Table 1) participated in this study. Subject 1 was the only subject without competitive swimming experience. Both experiments were conducted in a water tank of length, width, and height: 9.5×2.3×1.3 m. The homogeneous water had a uniform salinity of 26‰, a temperature of 19°C, and thus possessed a uniformly constant density of 1,018 kg/m^3. Vertical stratification was created by carefully dropping fresh water (salinity of 0.3‰, a temperature of 14°C and a density of 999 kg/m^3) on top of this homogeneous salt water layer. Stratification profiles were monitored at the beginning and end of each set of similar trials (together referred to as a sample) by measuring temperature and salinity at 0.05-m depth increments at a single point near the center channel's edge.

Experiment 1 In experiment 1, subjects 1 and 2 (of mass M_1, see Table 1) made a single stroke while lying on a small carriage (of mass M_2=18 kg) that was rolling above the water surface. Carriage plus subject were propelled by gravity acting on a counterweight of mass M_3, with a force $F=M_3\ g$ (Fig. 1c). By changing the propelling counter weight M_3 (from 11 to 14 kg), the (nearly) steady speed that the carriage obtained after about 2 s covered a range of 1.2–1.7 m·s^{-1}, emulating a swimming speed at the start of the stroke. The carriage position was tracked by a camera (25 Hz) looking top-down, and placed perpendicular to the direction of motion of the carriage. The rate of change in position provided the speed of the carriage over time, v_c. Two underwater cameras (25 Hz) presented side-views, perpendicular to v_c, and enabled measurement of the instantaneous position of the marker on the hand (Fig. 1d). Horizontal hand speed (v_h) was retrieved from the low-passed video data (cut-off frequency 10 Hz).

Up to twenty successive trials were performed per sample, both in homogeneous and stratified water. As 0.3 m of the arm was above the water, the lower/upper layer heights were taken 0.55/0.45 m, giving c'=0.218 m·s^{-1}. This set-up guaranteed that the hand of both subjects (Table 1) was in the vicinity of the interface, where coupling to interfacial waves is expected to be strongest. The stroke began (t_0) and ended (t_{end}) with the arm above the water surface. To evaluate the propulsion generated by the hand, four pressure sensors (Honeywell 26PCBFA6D), sampling at a rate of 100 Hz, were attached to both sides of the hand (Fig. 1d). From these, cross-hand pressure differences ($\Delta P_{1,2}$ and $\Delta P_{3,4}$) were obtained. Work, W, produced by the hand during one stroke, was calculated as a weighted sum:

$$W = \int_{t_0}^{t_{\mathrm{end}}} \left(\frac{2}{3} \Delta P_{1,2} + \frac{1}{3} \Delta P_{3,4} \right) v_h A_h dt \tag{2}$$

Table 1 Subject characteristics

Subject	Gender (M/F)	Age (years)	Mass (kg)	Length (m)	Hand surface (x10^{-2} m^2)	Arm length (m)[a]
1	M	23	70	1.73	1.52	0.74
2	M	24	78	1.84	1.80	0.84
3	F	24	63	1.70	1.48	0.76
4	F	26	60	1.73	1.47	0.76

[a] From acromion to fingertips

Here A_{h} is the hand surface area (Table 1) and weight factors 2/3 and 1/3 represent relative hand surface areas corresponding to placement of differential pressure sensors labeled $S_{1\text{–}2}$ and $S_{3\text{–}4}$ respectively (see Fig. 1d).

Total mass $M=M_1+M_2+M_3$ is the sum of subject, carriage, and forcing masses. Since M was equal in homogeneous and stratified conditions, the velocities at start ($v_{\mathrm{c},0}$) and end of a stroke ($v_{\mathrm{c,end}}$) sufficed to calculate the gain in kinetic energy of the carriage plus subject, ΔE:

$$\Delta E = \frac{1}{2} M \left(v_{\mathrm{c,end}}^2 - v_{\mathrm{c},0}^2 \right) \qquad (3)$$

Experiment 2 In experiment 2, subjects 2, 3, and 4 (see Table 1) swam 5 m front-crawl at two successive stroke frequencies (40 and 50 strokes·min^{-1}). The stroke frequency was presented to the swimmers by an acoustic cue. For both stroke frequencies, each subject performed five trials per sample. Samples were obtained both in homogeneous water and in two different settings of stratified water (lower/upper layer heights h_1/h_2=0.30/0.70 m and 0.40/0.60 m, leading to c'=0.201/0.215 m·s^{-1} respectively). On a countdown signal (in view of the camera), the swimmers started out of a horizontal start-position. A camera (25 Hz) was placed above the swimming pool at 5 m from the starting point. The time between the start and the moment the head of the subjects crossed the 5 m line was measured, enabling computation of average swimming speed. Subjects 3 and 4 each used fresh (0.30/0.70 and 0.40/0.60) stratifications. Continuing with the same stratification as used by subject 4, subject 2 performed the same protocol, albeit with a weaker initial stratification.

Statistics Unpaired data from different conditions and sample size were compared and the null hypothesis, the absence of any difference in sample means between stratified and homogeneous conditions, was tested by use of a two-tailed t test of the difference between these two means. As subjects differed both physically, as well as in swimming skill, we compared sample means for each individual separately. The t test statistic for this comparison (t_ν), having ν degrees of freedom, was computed from Table 2 and the null hypothesis was rejected when probability p was less than the significance level α (0.01, except when stated differently, see Sokal and Rohlf (1995)).

Results

In experiment 1, cross-hand differential pressures were surprisingly similar in stratified and homogeneous conditions (not shown). This indicates that the same amount of work was delivered per stroke. However, propelling efficiency did show substantial differences. For a single trial of subject 2, for instance, Fig. 2a shows carriage speed as a function of time (after t_0) due to propelling mass M_3= 12 kg and a single stroke in homogeneous (thick solid line) and stratified water (thick dashed line). The stroke performed in homogeneous water continued to accelerate the carriage, even during out-sweep. While this was

Table 2 Descriptive statistics (means±SD)

Experiment 1					
Subject	Condition	n	ΔE (J)	W (J)	
1	Homogeneous	19	31.7±6.0	32.56±9.52	
	0.55/0.45	21	**13.1±6.5**$^{+}$	32.16±7.85	
2	Homogeneous	20	45.0±8.1	56.81±14.49	
	0.55/0.45	20	**17.9±13.0**$^{+}$	47.21±16.92	
Experiment 2					
Subject	Condition	n_{40}	u_{40} (m·s^{-1})	n_{50}	u_{50} (m·s^{-1})
2	Homogeneous	5	0.71±0.03	4	0.86±0.02
	0.30/0.70	5	0.70±0.03	2	0.83±0.004
	0.40/0.60	5	0.70±0.03	3	**0.76±0.01***
3	Homogeneous	5	0.78±0.06	4	0.80±0.04
	0.40/0.60	5	**0.66±0.02***	5	0.77±0.02
4	Homogeneous	4	0.64±0.02	5	0.75±0.01
	0.30/0.70	5	0.64±0.03	5	**0.70±0.03***
	0.40/0.60	5	**0.55±0.02***	5	**0.66±0.02***

Sample mean and standard deviation (SD) of kinetic energy gain of carriage plus subject, ΔE, and work delivered by hand, W (experiment 1), and swimming speed, u (experiment 2). Sample size, n, is the number of trials performed. Comparing stratified to homogeneous fluids, the t test statistics in experiments 1 and 2 are the differences in (1) mean kinetic energy gain of carriage plus subject and (2) swimming speed, respectively. Subscripts 40 and 50 indicate stroke frequency (strokes·min^{-1}) at which the variable was measured. An asterisk (*)/plus (+) and bold face letters indicate that these differences are significant at α=0.05/0.01, respectively

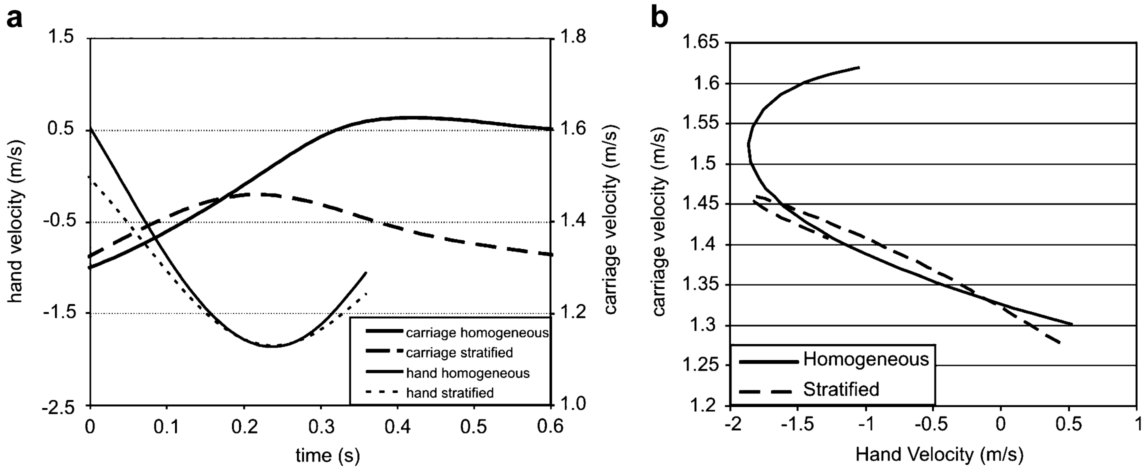

Fig. 2 **a** Example of observed hand (*thin lines*, *left axis*) and carriage velocity (*thick lines*, *right axis*) versus time (t_0–t_{end}) for subject 2, propelled by a mass M_3=12 kg, when a single stroke is performed in a homogeneous (*solid*) and stratified fluid (*dashed*). Velocities are positive in carriage propagation direction. **b** Observed carriage velocity versus observed horizontal hand velocity, performing a single stroke in homogeneous (*solid line*) and stratified fluid (*dashed*). Both velocities are measured relative to the laboratory frame of rest. Upon immersion, the hand still has a positive velocity, into the carriage propagation direction (lower right-hand side of figure), before turning negative, when the 'swimmer' pushes backwards

initially also the case in stratified water, remarkably, after about 0.25 s, the carriage decelerated strongly; energy was evidently lost to the fluid. This reversal coincided with the moment the hand (thin lines, Fig. 2a) started to decelerate (Fig. 2b), a phenomenon that was also observed in other trials. The response of the interface to time-varying hand motion is reminiscent of the response of a stratified, time-varying (tidal) flow over a sill. This shows development of a 'massive' lee wave behind the sill, occasional mixing within the lee wave and the release of the lee-wave at slackening tide, propagating against the tide in the form of a sequence of solitary waves (Farmer and Smith 1980). We speculate on the role this lee wave has in retarding the carriage in the "Discussion" section.

The reduced propulsion was also visible in the net gain in kinetic energy ΔE over time interval $t_0 - t_{\mathrm{end}}$. Averaged over 20 trials, a significant difference between homogeneous and stratified conditions was found for both subjects (*t* test, subject 1, t_{38}=9.4, p<0.001; subject 2, t_{32}=7.9, p< 0.001), see Table 2 for descriptive statistics and Fig. 3a,b. This difference decreased at higher work values for subject 2, but not for subject 1. Different hand size or swimming experience might have an effect. But, in agreement with the hypothesis of coupling with interfacial waves, it is also possible that there was less effect of stratified water at higher hand velocities.

Comparing the stratified with the homogeneous conditions, we observed a drop of several tens of Joules in kinetic energy gain (Fig. 3a,b). This may, however, still be a conservative estimate as we were not able to correct for the reference state (without stroke) that varied somewhat from one realization to the next. Given that the same work was performed, the remaining energy might have been used to mix fluid, raising its center of gravity. The fluid's gain in potential energy is estimated as $\int_{-h}^{h} \rho gz dzA = \frac{1}{2}(\rho_1 - \rho_2) gh^2 A$, where h is the depth over which water on either side of the interface (at z=0) is mixed upwards or downwards and A is the horizontal area involved. Taking A to be equal to the hand area (Table 1) and h a distance of 0.1 m (consistent with observed changes in stratification), this would lead to an insignificant gain in potential energy of just 1.5×10^{-2} J. However, the fact that a change in density profile was measured at the tank edge, at least 1.5 m away from the position where the stroke was performed, suggests that the affected horizontal area may be grossly underestimated. Nonetheless, a substantial part of the energy may also have gone into bringing fluid into horizontal (vertical) motion, parallel to the stratification, which is ultimately released as heat.

The obstructive effect of stratification did not depend crucially on initial carriage speed (or weight M_3). There was a weak (20%) decrease (increase) in the gain in kinetic energy when the weight increased from 11 to 14 kg for subject 1 (2).

In experiment 2, all subjects showed one or more differences between homogeneous and stratified water. As a result of stratification, the average swimming speed dropped by an amount up to 15% (Table 2 and Fig. 3c,d). The equivalent loss in propulsive power, proportional to speed cubed (Toussaint et al. 1988), reached up to 40%. It is important to note that the stratification declined over time as a result of upper and lower layer water mixing induced

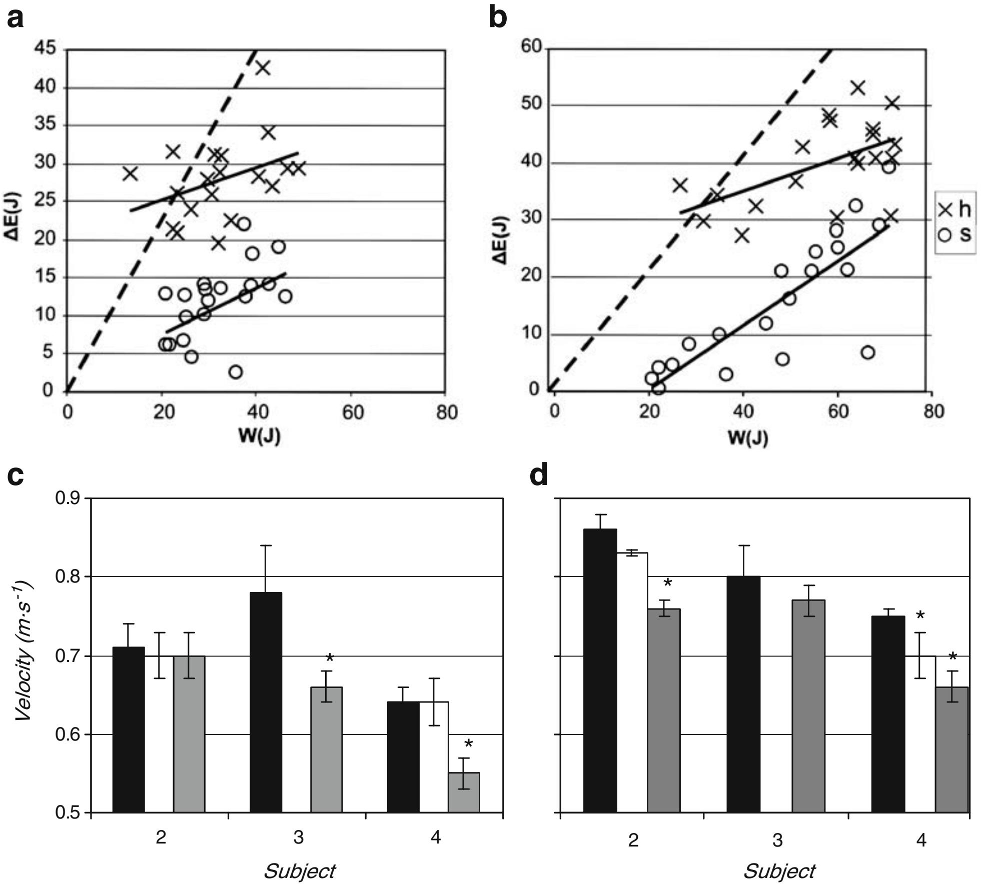

Fig. 3 Results. **a–b** Experiment 1: change in kinetic energy, *ΔE,* against work delivered by the hand, *W,* for subject 1 (**a**) and 2 (**b**). Crosses (*circles*) depict measurements in homogeneous (stratified) water. *Lines* indicate best linear fits. Note the difference in work delivered by subjects 1 and 2. Also note that *W* does not contain the work performed by gravity, explaining why paradoxically the net energy gain sometimes appears greater than *W* (above bisectrix, the *dashed line*). For the *lines* in (**a**), R^2 is 0.15 for the homogeneous and 0.19 for the stratified condition. In **b** R^2 is 0.31 for the homogeneous and 0.68 for the stratified condition. Although R^2 is low, we stress that it pertains to the fit of the data to a linear relationship between work and gain in kinetic energy, not to the difference between the homogeneous and stratified condition, which corresponds to the average difference reported in Table 2, first column. **c–d** Experiment 2: average swimming speed over 5 m stretch at (**c**) 40 strokes·min^{-1} and (**d**) 50 strokes·min^{-1}. *Black* indicates homogeneous, *white* 0.30/0.70 and grey 0.40/0.60-stratification. Note there is no 0.30/0.70 observation for subject 3. *Error bars* indicate plus and minus one standard deviation. An *asterisk* (*) indicates a significant difference with the homogeneous condition

by the swimmers, see Fig. 4. This might have especially affected results of subject 2, whose initial stratification at the measurement point near the side wall, arguably, fitted neither the 0.30/0.70 nor 0.40/0.60 classification, although it was not known how the stratification was affected throughout the tank. The gradual degradation of the stratification did not, however, lead to a gradual drift in swimming speed over subsequent trials.

Figure 3c,d shows that the obstructive effect of stratification on swimming was greater in the 0.40/0.60-stratification, where the hand seemed to spend more time in the vicinity of the interface than in the 0.30/0.70-stratification. Considering that the swimmer's chest was submersed at a depth of about 0.3 m, this occurred despite the fact that the arm extended in all cases well into the lower layer.

A higher stroke frequency led to a higher swimming speed (Table 2). However, the obstructive effect of stratification on swimming was in general independent of the employed stroke frequency (Fig. 3c,d), although differences in stratification and in arm length may have led to different results. For example, although the stratification in the 0.30/0.70-condition was very strict to begin with (see Fig. 4), subject 4 did not show any significant difference in swimming speed between homogeneous and stratified water performing a stroke at a frequency of 40 strokes·min^{-1}, but when the frequency was increased to 50 strokes·min^{-1} the difference was significant (*t* test, $t_{4.8}$=3.5, p=0.02). Similarly, while the stratification encountered by subject 2 was quite gradual, a significant decrease in speed occurred at 50 strokes·min^{-1} (*t* test, $t_{4.6}$=8.66, p=0.0006).

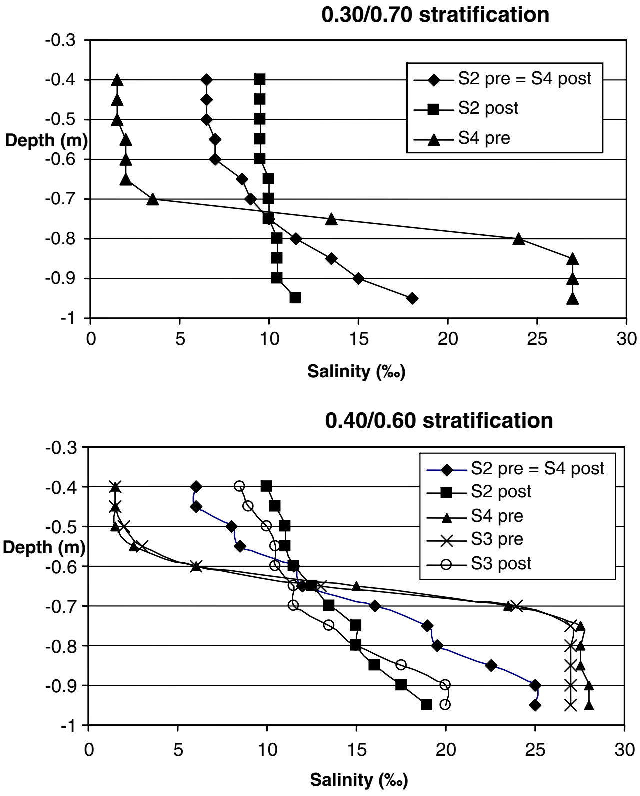

Fig. 4 Salinity profiles measured before (pre) and after (post) each sample as a function of depth below the surface for subjects $S_{2,3,4}$ for two (h1/h2) stratifications, characterized by lower/upper layer depths (m)

Discussion

Comparing stratified to homogeneous water, the two main results of this study are as follows: Firstly, the gain in kinetic energy produced by a single stroke of a subject lying on a carriage, rolling above a tank, is lower (experiment 1) and secondly, the swimming velocity as measured over a 5 m distance is lower (experiment 2).

The observation in experiment 1 that the cross-hand pressure difference was not reduced in the stratified conditions is somewhat paradoxical. It appears to conflict with the expectation that this pressure difference can relax rapidly, as, by displacing fluid against gravity, it is lost to the water. The paradox is resolved by realizing that as a result also the pressure drag is diminished. This allows the hand to continue to move relative to the water, refreshing the pressure difference, until a balance is attained in which the hand's underwater path length is extended and its speed is increased, comparing stratified to homogeneous conditions. A 10% increase in horizontal path length was indeed observed comparing stratified to homogeneous circumstances. As it is the pressure drag due to the pressure difference between palm and back of the hand which offers the hand grip, by means of which muscular power can propel the body, the reduction of pressure drag leads to less propulsive power. This explains both the reduction in the observed kinetic energy gain produced by a single stroke (experiment 1), as well as the increase in time needed to cover a preset distance (experiment 2). In line with the latter observation, the video footage of experiment 2 suggests that the swimmer's stroke pattern changed. Comparing swimming in homogeneous and stratified conditions, subjects 2 and 4 indeed reported an increase in number of strokes from six to eight (+33%) per trial. This indicates that with every stroke, less distance is covered in stratified water compared with homogeneous water, indicative of a reduction in propelling efficiency (Toussaint et al. 1991).

Looking more into the details of experiment 1, we observed that while in a homogeneous fluid acceleration of the carriage persisted when the hand decelerated (Fig. 2b, solid curve), likely due to lift forces, in the stratified case the kinetic energy of carriage and subject reduced and the carriage decelerated as well (Fig. 2b, dashed curve). The exact cause of this deceleration still remains enigmatic as the measured cross-hand pressure difference did not change sign. We offer the following explanation.

Recall that paddling employs the action of a lever to propel the carriage forward. The lever consists in applying a strong backward directed force which is to some extent balanced by form (pressure) drag acting on the hand. Depending on the degree of balance, the lever's pivot is closer or farther away from the hand. When the hand finds a fixed grip, for instance when there is a line to hold on to, the pivot sits in the hand; when the hand moves through air, the pivot sits in the shoulder. This lever produces a forward-directed reaction force, (actually a torque) propelling the carriage. In stratified fluids, in the vicinity of the interface, a deepening lee-wave is generated that sucks up dense fluid at the back of the hand, which moves at hand speed. The water appears 'sticky', reminiscent of the sailor's exclamation that 'we swept the whole sea along with us'. When the hand is retracted towards the body, during out-sweep, the dense water sticking to the hand is raised against gravity. The gravitational force on the added, dense mass has a component that acts into the swimming direction and hence appears to reverse the lever and retard the carriage. Moreover, it will also have an along-arm downward component which is of course supported by the frame on which the carriage runs. But when applied to a swimmer, obviously lacking such a supporting structure, this acts to pull a swimmer's body down. This provides a possible direct cause and effect relationship entailing dead-water, of relevance to fair-weather drowning. Future work needs to investigate the details of this admittedly speculative explanation.

While stratification in natural waters will be less than that constructed initially for subjects 3 and 4 (which would correspond to unrealistic temperature differences of 60° or more), the fact that all subjects experienced obstructive effects during swimming, even when the stratification became less sharp, indicates this may be relevant in nature too. The implication of this study, therefore, is that any open water swimmer who occasionally senses a temperature difference between surface and deeper layer might find some obstruction. Such temperature stratification arises in particular on sunny windless days in deep (>10 m, say), thermally inert lakes, due to insolation and lack of wind (mixing). In these circumstances, less work done by a swimmer will be used beneficially for moving forward. Instead, interfacial waves will be generated, that may collapse and mix, and may turn the water sticky. This will draw on the swimmer's energy supplies, causing fatigue and possibly even drowning. The current results should therefore be considered when composing guidelines for the prevention of drowning. Swimmers should be made aware of the potential dangers of dead-water.

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