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Divergence in physiological factors affecting swimming performance between anadromous and resident populations of brook charr *Salvelinus fontinalis*

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Abstract :

In this study, an anadromous strain (L) and a freshwater-resident (R) strain of brook charr *Salvelinus fontinalis* as well as their reciprocal hybrids, were reared in a common environment and submitted to swimming tests combined with salinity challenges. The critical swimming speeds (Ucrit) of the different crosses were measured in both fresh (FW) and salt water (SW) and the variations in several physiological traits (osmotic, energetic and metabolic capacities) that are predicted to influence swimming performance were documented. Anadromous and resident fish reached the same Ucrit in both FW and SW, with Ucrit being 14% lower in SW compared with FW. The strains, however, seemed to use different underlying strategies: the anadromous strain relied on its streamlined body shape and higher osmoregulatory capacity, while the resident strain had greater citrate synthase (FW) and lactate dehydrogenase (FW, SW) capacity and either greater initial stores or more efficient use of liver (FW, SW) and muscle (FW) glycogen during exercise. Compared with R♀L♂ hybrids, L♀R♂ hybrids had a 20% lower swimming speed, which was associated with a 24% smaller cardio-somatic index and higher physiological costs. Thus swimming performance depends on cross direction (i.e. which parental line was used as dam or sire). The study thus suggests that divergent physiological factors between anadromous and resident *S. fontinalis* may result in similar swimming capacities that are adapted to their respective lifestyles.

Keywords : hybrids, local adaptation, metabolism, swimming performance.

1. Introduction

During their life cycle, many fishes species undergo migrations between habitats that are essential for completing their life cycle (e.g. reproductive, nursery and feeding habitats). These movements occur on temporal and spatial scales ranging from daily to annual and from a few metres to thousands of kilometres (McDowall, 1997; Klemetsen *et al.*, 2003; Fraser & Bernatchez, 2005; Kitano *et al.*, 2012). The environmental

1 conditions encountered largely determine the physiological cost associated with these
2 migratory movements.

3 In salmonids, swimming ability and support capacities (*e.g.* oxygen transport,
4 cardiovascular performance and energy metabolism) fundamentally contribute to the
5 success of migratory movements (Eliason *et al.*, 2011; Eliason & Farrell, 2016). In
6 these species, migratory behaviour involves rapid transitions between fresh water and
7 sea water and osmoregulatory ability is a strong determinant in the success of such
8 movements (McDowall, 1997; Peake *et al.*, 1997; Claireaux & Audet, 2000; Boula
9 *et al.*, 2002; Wagner *et al.*, 2006). Links between swimming ability and capacity to
10 maintain body fluid osmolality have been amply documented in fishes (Brauner *et al.*,
11 1992, 1994; Nelson *et al.*, 1996; McKenzie *et al.*, 2001*a,b*). For instance, in Coho
12 salmon *Oncorhynchus kisutch* (Walbaum 1792) smolts and juvenile Adriatic sturgeon
13 *Acipenser naccarii* Bonaparte (1796), an acute increase in water salinity associated
14 with an increase of plasma ions and osmolality was found to be directly related to
15 a reduction in maximum sustainable swimming speed (Brauner *et al.*, 1992, 1994;
16 McKenzie *et al.*, 2001*a,b*). Conversely, the lack of significant effects of ambient
17 salinity on European seabass *Dicentrarchus labrax* (L. 1758) swimming and cardiac
18 performance was linked to an exceptional capacity of this species to maintain plasma
19 osmolality and tissue water content when exposed to an acute change in ambient
20 salinity (Chatelier *et al.*, 2005).

21 In salmonids, migratory behaviour has evolved as an obligate phase in the life cycle
22 of some species whereas it is facultative in others (McDowall, 1997; Klemetsen *et al.*,
23 2003; Fraser & Bernatchez, 2005; Thériault *et al.*, 2007; Arai & Goto, 2008). In brook
24 charr *Salvelinus fontinalis* (Mitchill 1814), the ancestral form of anadromy is now
25 facultative (Castric & Bernatchez, 2003; Curry *et al.*, 2010) and different migratory
26 patterns exist depending on the biotic and abiotic conditions in the native environment
27 of a population (Castric & Bernatchez, 2003). The anadromous *S. fontinalis* popula-
28 tion of the Laval River (L) (48° 44' N; 69° 05' W) on the north shore of the St Lawrence
29 Estuary migrates to fresh water for reproduction and overwintering and to salt water
30 in summer for feeding. These fish can thrive in habitats encompassing a wide range of
31 environmental conditions, from low to high salinity (1–34), temperature (5–18° C) and
32 water velocities (Boula *et al.*, 2002; Curry *et al.*, 2006). The Rupert population (R) is
33 a strictly freshwater resident *S. fontinalis* population originating from the Rupert River
34 (51° 05' N; 73° 41' W) near Lake Nemiscau (near James Bay in north-western Québec).
35 These fish always live in cold fresh water and migrate from the river to lakes for repro-
36 duction (MAPA-Pêcheries, 1992). In addition to living in two different environments
37 and having different lifestyles, previous genetic studies revealed a pronounced genetic
38 differentiation between these two populations (mean \pm s.e. $F_{st} = 0.427 \pm 0.020$; Martin
39 *et al.*, 1997), as well as important differences in gene expression when reared in a same
40 environment (Bougas *et al.*, 2010). It is not known, however, whether these differences
41 are accompanied by a divergence in their swimming capacity.

42 Previous studies on salmonids have revealed that different lifestyles among species
43 or populations may result in differences in their swimming ability (Taylor & McPhail,
44 1985; Hawkins & Quinn, 1996; Peake *et al.*, 1997). In Atlantic salmon *Salmo salar*
45 (L. 1758), anadromous individuals possess greater sustained swimming ability than
46 landlocked ones, possibly related to their different morphology (the anadromous form
47 has a more fusiform body shape than the landlocked one) and migratory histories
48 (Peake *et al.*, 1997). When swimming tests were conducted in common environments,

1 the differences between populations remained (Taylor & Foote, 1991), suggesting a
2 genetic basis for swimming performance and thus a potential for evolutionary adap-
3 tation. In three-spined stickleback *Gasterosteus aculeatus* L. 1758, comparisons of
4 swimming performance in freshwater resident and anadromous populations, both in
5 Europe (Tudorache *et al.*, 2007) and North America (Dalziel *et al.*, 2011), have shown
6 that anadromous fish had a greater swimming performance than the freshwater resi-
7 dents. In the North American populations, this difference is genetically based (Dalziel
8 *et al.*, 2011). Understanding the genetic and physiological bases of evolutionary change
9 in swimming capacity in *S. fontinalis* could provide further insight into the functional
10 bases of differential adaptation in swimming capacity of fishes (Odell *et al.*, 2003;
11 Collin & Fumagalli, 2011; Dalziel *et al.*, 2011).

12 Hybridization between different populations may also provide important informa-
13 tion on the genetic basis of swimming performance and the degree of divergence
14 between populations. For example, measuring traits in F1 hybrids could reveal the
15 relative importance of additive or non-additive genetic effects in the expression of
16 performance (Dalziel *et al.*, 2011). When populations are genetically closer, hybrids
17 tend to express additive genetic effects and show intermediate performance compared
18 with their parental lines. On the contrary, when populations are genetically divergent
19 and adapted to their own environments, hybrids may express non-additive genetic
20 effects due to complex genetic associations (Falconer & Mackay, 1996; Edmands,
21 1999; Cooke *et al.*, 2001; Cooke & Philipp, 2005; Stelkens *et al.*, 2009). Non-additive
22 genetic effects have been reported for various morphological and physiological traits
23 such as size, survival and other fitness-related traits in rainbow trout *Oncorhynchus*
24 *mykiss* (Walbaum 1792) (Tymchuk *et al.*, 2009), *O. kisutch* (Emlen, 1991) and *S. font-*
25 *inalis* (Granier *et al.*, 2011; Crespel *et al.*, 2012) and also in swimming performance
26 in largemouth bass *Micropterus salmoides* (Lacépède 1802) (Cooke *et al.*, 2001).
27 The occurrence of non-additive genetic effects controlling fitness-related traits thus
28 provide further evidence for evolutionary divergence among the populations studied.
29 The occurrence of non-additive genetic effects in swimming performance, however,
30 and its underlying physiological basis among populations with different migratory
31 lifestyles has rarely been investigated.

32 Whether anadromous fish are better swimmers than freshwater residents has been
33 tested, hypothesizing that this trait would be a major fitness component in migratory
34 fish. In addition to condition factor and energy reserve levels, a whole range of physio-
35 logical factors can affect fish swimming capacity, thus the measurement of these vari-
36 ables gives information on their relative contributions. Blood oxygen-carrying capacity
37 was inferred from blood haematocrit and haemoglobin concentration, leading to the
38 calculation of the mean cellular haemoglobin concentration. The capacities of experi-
39 mental populations to mobilize energy reserves to fuel working muscles were compared
40 by measuring blood glucose as well as liver and white muscle glycogen content. For
41 the same reason, white muscle and heart pyruvate and lactate concentrations were also
42 assessed. The activities of white muscle lactate dehydrogenase (LDH) and citrate syn-
43 thase (CS) were measured because these enzymes are important regulators of aerobic
44 and anaerobic metabolism responding to substrate:product ratios. These measurements
45 provided insight into the relative contribution of aerobic *v.* anaerobic pathways to meet
46 the energy needs associated with swimming. Since the capacity to maintain plasma
47 osmotic and ionic characteristics is a key factor affecting fish swimming capacity, gill
48 $\text{Na}^+ - \text{K}^+ - \text{ATPase}$ activity was also assessed.

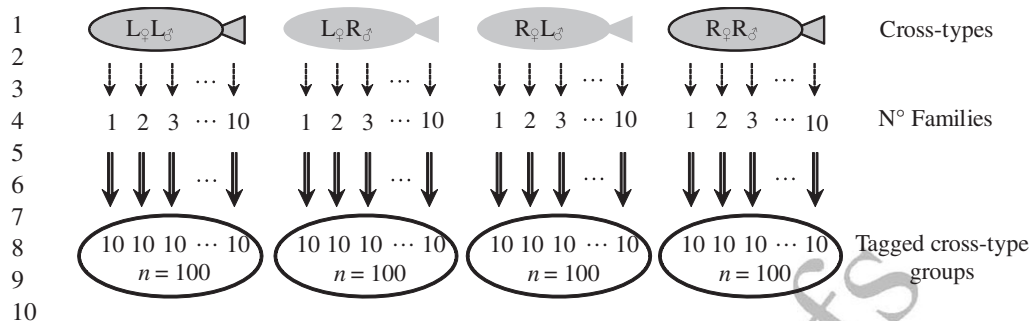



FIG. 1. Schematic diagram of the cross-types used to test swimming performance in purebred crosses of *Salvelinus fontinalis* (L, Laval anadromous strain; R, Rupert freshwater-resident strain) and of their reciprocal hybrids. The first letter of the cross-type indicates the dam and the second letter the sire.  rious families within cross-types ($n = 10$); \downarrow , the number of fish sampled from the different families ($n = 100$).

The occurrence of non-additive effects in the hybrids was investigated to obtain additional insight into the genetic divergence between anadromous and resident strains. For this, two alternative hypotheses were tested. First, non-additive effects are present in hybrids, indicating a divergence for swimming performance between the two populations of origin and creating complex genetic associations during adaptation. Alternatively, the hybrids do not express non-additive effects, indicating that swimming performance is supported by compatible genes in the two populations of origin.

MATERIALS AND METHODS

EXPERIMENTAL ANIMALS

Experiments were conducted using two strains of wild *S. fontinalis* (Laval and Rupert) and the corresponding hybrid crosses. Breeders were third generation fish produced in captivity at the Station aquicole (ISMER-UQAR, Rimouski, QC, Canada) and at the Laboratoire de Recherche en Sciences Aquatiques (LARSA, Université Laval, Québec, QC, Canada). Four cross-types were produced during winter 2005: ♀ Laval \times ♂ Laval ($L_{\text{♀}}L_{\text{♂}}$), ♀ Rupert \times ♂ Rupert ($R_{\text{♀}}R_{\text{♂}}$), ♀ Laval \times ♂ Rupert ($L_{\text{♀}}R_{\text{♂}}$) and ♀ Rupert \times ♂ Laval ($R_{\text{♀}}L_{\text{♂}}$) (Fig. 1). For each cross-type, 10 full-sib families were obtained through single-pair mating. All families were reared under similar conditions in recirculating fresh water (FW) at LARSA from egg incubation (January) to exogenous feeding (at the end of the summer). Water temperature was maintained at 6° C during egg incubation and at 8° C after hatching. Photoperiod followed the natural seasonal cycle (46° 45' N) and fish were fed according to commercial charts.

In September, fish were transferred to the Station aquicole ISMER-UQAR, where they were reared under natural temperature and photoperiod (48° 30' N) conditions in running dechlorinated FW. They were fed daily (food ration of 1% fish wet mass) with commercial dry pellets. In March, 10 fish from each family (100 fish per cross-type) were tagged using fingerling tags (Floy Tag Inc.; www.floytag.com) (Fig. 1).

THE FLUME

The swimming tests were performed using a circular flume (with a linear swimming section) designed to provide non-turbulent water flow (Redjah *et al.*, 2010). Briefly, a variable-speed motor propelled the water at a constant velocity. Plastic honeycomb structures

TABLE I. Summary of experimental design: experimental groups of purebred and hybrid *Salvelinus fontinalis* used to test the repeatability of the swimming tests and perform the critical swimming speed (U_{crit}) test in salt water (SW) and the control groups with different fish used to perform the critical swimming speed (U_{crit}) test in fresh water (FW)

	$L_{\sigma}L_{\delta}$		$L_{\sigma}R_{\delta}$		$R_{\sigma}L_{\delta}$		$R_{\sigma}R_{\delta}$	
	Repeats	Fish	Repeats	Fish	Repeats	Fish	Repeats	Fish
Experimental group								
Repeatability test 1 (FW)	2	15	2	15	2	15	2	15
Repeatability test 2 (FW)	2	15	2	15	2	15	2	15
Repeatability test 3 (FW)	2	15	2	15	2	15	2	15
U_{crit} (SW)	2	15	2	15	2	15	2	15
Control group								
U_{crit} (FW)	1	10	1	10	1	10	1	10

L, Laval anadromous strain; R, Rupert freshwater-resident strain. The first letter of the cross-type indicates the dam and the second letter the sire.

and deflectors were inserted in the circulation loop upstream from the swimming chamber (23 cm × 37 cm × 22.3 cm) to promote rectilinear flow and a uniform velocity profile. An acoustic Doppler velocimeter (type 16 MHz MicroADV, Sontek; www.sontek.com) was used to calibrate water velocity to voltage output from the motor controller. The flume was supplied with fully aerated and thermoregulated (6.8°C, range ± 0.3°C) water at a flow rate of 10 l min⁻¹.

VALIDATION TEST AND CRITICAL SWIMMING SPEED PROTOCOL

To validate the swimming challenge procedure, two subgroups of 15 tagged fish per cross-type were submitted to three consecutive swim tests in FW with a 4 h recovery period between tests 1 and 2 and a 16 h recovery period between tests 2 and 3, which is in line with the capacity of salmonids to fully recover from exhaustion (45–90 min; Jain *et al.*, 1998; Lee *et al.*, 2003; Tierney & Farrell, 2004). Cross-types were tested separately, with subgroups of fish swimming together in each trial (Table I). The repeatability of individual performances was confirmed (Table II; $P > 0.05$) as was the fish swimming performance ranking ($P > 0.05$).

Following transfer into the swimming chamber, fish were left undisturbed for 30 min at a water speed of 5.5 cm s⁻¹ (*i.e.* 0.5 standard length s⁻¹; L_S s⁻¹). Following this acclimation period, fish were submitted to a stepwise increase of water velocity from 5.5 to 11.0 to 16.5 cm s⁻¹ at

TABLE II. Repeatability of mean ± s.e. critical swimming speed (U_{crit}) in the purebred strains of *Salvelinus fontinalis* and their reciprocal hybrids

	$L_{\sigma}L_{\delta}$ 30	$L_{\sigma}R_{\delta}$ 30	$R_{\sigma}L_{\delta}$ 30	$R_{\sigma}R_{\delta}$ 30
U_{crit} 1 (L_S , s ⁻¹)	2.85 ± 0.21	2.83 ± 0.20	3.08 ± 0.13	2.24 ± 0.11
U_{crit} 2 (L_S , s ⁻¹)	2.59 ± 0.18	2.65 ± 0.17	3.00 ± 0.17	1.90 ± 0.11
U_{crit} 3 (L_S , s ⁻¹)	2.22 ± 0.15	2.47 ± 0.10	3.13 ± 0.18	2.44 ± 0.11

The repeatability tests were done in fresh water. U_{crit} among trials were not statistically different.

L, Laval anadromous strain; R, Rupert freshwater-resident strain (The first letter of the cross-type indicates the dam and the second letter the sire.); n , the number of individuals per swim test; L_S , standard length.

TABLE III. Mean \pm S.E. standard length (L_S), body mass (M_B), condition factor (K) and cardio-somatic index (I_C) of two purebred strains of *Salvelinus fontinalis* and their reciprocal hybrids used for swimming challenges and biochemical samples

	$L_{\sigma}L_{\sigma}$ 38	$L_{\sigma}R_{\sigma}$ 40	$R_{\sigma}L_{\sigma}$ 40	$R_{\sigma}R_{\sigma}$ 38
L_S (cm)	11.08 \pm 0.16 ^a	13.29 \pm 0.34 ^c	12.00 \pm 0.24 ^b	11.94 \pm 0.21 ^b
M_B (g)	11.11 \pm 0.61 ^a	21.98 \pm 1.98 ^c	13.63 \pm 0.91 ^a	17.30 \pm 0.95 ^b
K (g cm ⁻³)	0.79 \pm 0.02 ^a	0.86 \pm 0.02 ^b	0.76 \pm 0.03 ^a	0.98 \pm 0.02 ^c
I_C (%)	0.15 \pm 0.01 ^{ab}	0.14 \pm 0.01 ^a	0.18 \pm 0.01 ^b	0.16 \pm 0.01 ^{ab}

Different superscript lower case letters indicate significant differences among cross-types ($P < 0.05$).

L, Laval anadromous strain; R, Rupert freshwater-resident strain (the first letter of the cross-type indicates the dam and the second letter the sire.); n = the number of individuals.

5 min intervals and then to 22.0, 27.5, 33.0, 38.5, 44.0, 49.5 and in some cases, 55.0 cm s⁻¹ at 15 min intervals. Fish were considered to be fatigued when they were unable to remove themselves from the screen situated downstream from the swimming chamber. At that time, fish were removed from the swim chamber, identified (tag reading) and placed in their original rearing tank. The corresponding water velocity and time were recorded. The critical swimming speed (U_{crit} , L_S s⁻¹) was calculated according to Brett (1964)

$$U_{crit} = [U + (TT_i^{-1}) U_i] L_S^{-1} \quad (1)$$

where U is the highest velocity maintained for the whole interval (cm s⁻¹), T is the time elapsed at fatigue velocity (s), T_i is the prescribed interval time between each speed increment (300 or 900 s) and U_i is the velocity increment (5.5 cm s⁻¹). No correction for blocking effect was applied since the total cross-sectional area of the fish did not exceed 5% of the swimming chamber (Bell & Terhune, 1970).

EVALUATION OF SWIMMING CAPACITY

Following the assessment of measurement repeatability, the fish used for the validation tests were directly transferred into salt water (SW; salinity 20, 6.8° C, range \pm 0.3° C). Salinity was adjusted by mixing St Lawrence estuarine water (salinity 31–32) with dechlorinated FW before it entered rearing tanks. After a 48 h acclimation period, fish subgroups were submitted to the U_{crit} test as described above (Table I). As one fish reached exhaustion, it was rapidly removed from the flume and anaesthetized in 0.12 g l⁻¹ MS-222 until opercular movements ceased (c. 1.5–2 min) for blood and tissue samplings. Control fish were submitted to the same U_{crit} procedure described above in FW, but only one group of 10 fish per cross-type swam together for these trials (Table I). Fish were not fed for 48 h before their transfer to the swimming chamber. To avoid circadian bias in hormonal measurements, SW and FW U_{crit} tests began at 1400 h and were completed by 1630 h.

BLOOD AND TISSUE SAMPLING

Following measurement of L_S (to the nearest 0.1 cm) and body mass (M_B , to the nearest 0.1 g) (Table III), blood was drawn by caudal puncture using ammonium-heparinized syringes. A small quantity of blood was kept for haematocrit and haemoglobin measurements and the remainder was centrifuged at 7200g for 3 min. Plasma aliquots were frozen in liquid nitrogen and stored at -80° C for further analyses. Gill filaments, liver, heart and three pieces of epaxial muscle (one for each biochemical analysis) were excised and liver and heart (M_H) wet mass were recorded. The

1 cardio-somatic index (I_C) was calculated as $I_C = 100 M_H M_B^{-1}$. Tissue samples were immedi-
2 ately frozen on dry ice and then stored at -80°C prior to analysis. An additional piece of epaxial
3 dorsal muscle was excised, weighed and dried for 72 h at 70°C for calculation of water con-
4 tent. Because body shape can affect swimming performance, condition factor (K) was estimated
5 according to the equation $K = 100 M_B L_S^{-3}$.

6 Plasma osmolality was measured with an Advanced Micro-osmometer (model 3MO,
7 Advanced Instruments Inc.; www.aicompanies.com), blood haemoglobin concentration was
8 determined by Drabkin's method (Drabkin & Austin, 1935), plasma glucose was measured
9 by enzymatic determination (Alexander & Griffiths, 1993) and cortisol levels were measured
10 using a cortisol ^{125}I RIA kit (MP Biomedicals; www.mpbio.com). Mean cellular haemoglobin
11 concentration (MCHC) was calculated using haematocrit data. Gill $\text{Na}^+ - \text{K}^+ - \text{ATPase}$ capacity
12 was measured using the micro-method described in Seigler *et al.* (1996).

13 Muscle and liver glycogen contents were determined according to the amyloglucosidase
14 digestion method (Carr & Neff, 1984) followed by glucose concentration determination.
15 Heart lactate, heart pyruvate, white muscle lactate and white muscle pyruvate concentrations
16 were measured using enzymatic assays (Henry, 1968). Muscle samples were weighed and
17 homogenized in 10 volumes of cold 100 mM imidazole-HCl buffer (pH 7.4) and LDH and CS
18 capacity were measured according to Le François & Blier (2003). The Michaelis constant (K_m)
19 was evaluated using different substrate concentrations, *i.e.* from 0.01 to 0.5 mM oxaloacetate
20 for CS and from 0.25 to 1 mM pyruvate for LDH and calculated using a non-linear regression
21 procedure (GraphPad Prism 5, GraphPad Software Inc.; www.graphpad.com).

22 STATISTICAL ANALYSES

23 It was assumed that fish were observed independently and that the number of d.f. in the statis-
24 tical analysis should be the number of fish. This was supported by the repeatability of individual
25 performances (consecutive swim trials on the same groups of fish; Table II, $P > 0.05$) as well as
26 fish swimming performance ranking ($P > 0.05$).

27 Spearman rank order correlation and ANOVA with repeated measures were used to determine
28 the repeatability of fish swimming performance rank. Normality and homogeneity of variances
29 were verified by Kolmogorov–Smirnov and Brown–Forsythe tests, respectively. Muscle pyru-
30 vate concentration data were not normally distributed, so data were ranked and statistical pro-
31 cedures were applied on ranks (Quinn & Keough, 2002). Cortisol data were \log_{10} transformed
32 and lactate:pyruvate ratio data were square-root transformed to avoid heteroscedasticity. The
33 different variables were analysed using two-way ANCOVA with salinity and cross-type as fixed
34 effects and body mass as the covariable. If no covariance effect was found, a two-way ANOVA
35 was run. The presence of non-additive effects was determined by the presence of significant
36 differences between the mean trait values of hybrids compared with the mean traits of both
37 parental strains (Bryden *et al.*, 2004). When significant factor effects were found, *a posteriori*
38 Tukey comparison of means tests ($\alpha = 0.05$) were used (Sokal & Rohlf, 1981). For those vari-
39 ables for which transformations failed to give homogeneity of variances, the Games and Howell
40 test was used (Sokal & Rohlf, 1981). The least significant difference (LSD) test was used for
41 muscle pyruvate concentration. All statistical analyses were performed with Statistica software
42 (Statsoft 6; www.statsoft.com).

43 RESULTS

44 The different cross-types used in this study were significantly different in terms of
45 length and body mass even though they were raised under similar conditions and were
46 the same age (Table III). K was 20% lower in anadromous *S. fontinalis* ($L_\varphi L_\delta$) than
47 in resident fish ($R_\varphi R_\delta$) (Table III). K of $R_\varphi L_\delta$ hybrids was similar to the paternal line
48 ($L_\varphi L_\delta$), while that of $L_\varphi R_\delta$ hybrids was intermediate compared with parental lines. The
49 cardio-somatic indexes (I_C) of the two purebred strains were similar and intermediate
50 to those of the hybrids, with $R_\varphi L_\delta$ having a higher I_C than $L_\varphi R_\delta$ hybrids (Table III).

1 SWIMMING CHALLENGES

2 Critical swimming speed varied according to both cross-type and salinity with no
3 significant interaction between the two factors and body mass did not influence U_{crit}
4 (Table IV). While U_{crit} values were similar in pure crosses of the anadromous and resi-
5 dent strains, swimming performance was 18% lower in $L_{\varphi}R_{\delta}$ compared with the recip-
6 rocal $R_{\varphi}L_{\delta}$. Also, swimming performance was significantly higher in FW (mean \pm s.e.
7 $3.50 \pm 0.13 L_S s^{-1}$) compared with SW ($3.00 \pm 0.07 L_S s^{-1}$) (Fig. 2).

9 STRESS AND OSMOTIC RESPONSE

11 Cortisol concentration was similar among all groups that underwent the swim chal-
12 lenge both in FW and SW (Table IV), with an overall mean \pm s.e. of $6.25 \pm 0.60 \mu g dl^{-1}$.
13 Even though significant treatment effects were found (Table IV), multiple comparison
14 tests did not indicate differences in plasma glucose between the different cross-types
15 and salinity groups. The overall mean \pm s.e. plasma glucose was $0.90 \pm 0.04 mg ml^{-1}$.

16 Muscle water content varied according to cross-type and salinity with no significant
17 interaction between the two (Table IV) and it was negatively correlated to body mass.
18 The $L_{\varphi}L_{\delta}$ fish had significantly higher muscle water content (*c.* 1.7%) compared with
19 fish from the other cross-types (Table IV). Overall, muscle water content was close to
20 2% lower in fish challenged in SW than in fish challenged in FW. A significant inter-
21 action between cross-type and salinity was observed for plasma osmolality as was a
22 significant negative body mass covariance effect (Table IV). In FW, plasma osmolality
23 was 4.9% higher in the $L_{\varphi}R_{\delta}$ cross-type than in the $L_{\varphi}L_{\delta}$ fish [Fig. 3(a)]. Swimming to
24 exhaustion in SW was associated with an increase in plasma osmolality in all groups
25 of fish, but plasma osmolality was 6% higher in resident fish than in the two hybrid
26 cross-types [Table IV and Fig. 3(a)]. $Na^{+}-K^{+}-ATPase$ capacity was similar among
27 cross-types that swam in FW (significant interaction between factors with no signifi-
28 cant covariance effect; Table IV), but activity was almost three times higher in $R_{\varphi}R_{\delta}$
29 individuals than in the other three cross-types in SW challenges [Fig. 3(b)].

30 Blood haematocrit varied according to cross-type (Table IV) and was positively cor-
31 related to body mass. Blood haematocrit was 12% lower in $L_{\varphi}L_{\delta}$ fish (the smallest
32 cross-type) than in the other cross-types [Fig. 4(a)]. Blood haemoglobin varied accord-
33 ing to both cross-type and salinity (significant interaction between factors) and a sig-
34 nificant positive body mass covariance effect was noted (Table IV). In SW, blood
35 haemoglobin concentration was highest in $L_{\varphi}R_{\delta}$ hybrids while no difference could
36 be seen among cross-types in fish that swam in FW [Fig. 4(b)]. The resulting MCHC
37 differed among cross-types but not salinities: there was no significant covariate effect
38 for body mass (Table IV). MCHC was 16% lower in $R_{\varphi}L_{\delta}$ than in $L_{\varphi}R_{\delta}$ hybrids and
39 MCHC levels in hybrids were similar to their respective maternal line [Fig. 4(c)].

41 ENERGY RESERVES

43 A significant interaction between cross-type and salinity was observed for muscle
44 glycogen content with no M_B covariance effect (Table IV). After fish were challenged
45 in FW, muscle glycogen content was 64.4% lower in anadromous and $R_{\varphi}L_{\delta}$ hybrids
46 than in $R_{\varphi}R_{\delta}$ fish [Fig. 5(a)]. The muscle glycogen content in the other hybrid was
47 intermediate to those of the parental lines. Following exhaustion in SW, muscle glyco-
48 gen content was similar among cross-types (Fig. 5). Within each cross-type, muscle

TABLE IV. Summary of ANOVA results for the different variables measured in *Salvelinus fontinalis*: critical swimming speed (U_{crit}), stress and osmotic response [cortisol, glucose, muscle water, osmolarity, gill $Na^+ - K^+ - ATPase$, haematocrit, haemoglobin, mean cellular haemoglobin concentration (MCHC)], energy reserves (muscle glycogen, liver glycogen), metabolic response [citrate synthase, CS; lactate dehydrogenase, LDH; muscle lactate; muscle pyruvate; muscle lactate:pyruvate ratio (muscle ratio L:P), heart lactate, heart pyruvate, heart lactate:pyruvate ratio (heart ratio L:P)]

	Cross-type effect			Salinity effect			Cross-type x salinity			Body mass covariable			
	F	d.f.	P	F	d.f.	P	F	d.f.	P	F	d.f.	P	r ²
U_{crit}	2.86	3:148	<0.05	11.85	1:148	<0.01	0.54	3:148	>0.05				
Cortisol	1.14	3:96	>0.05	0.05	1:96	>0.05	0.11	3:96	>0.05				
Glucose	5.62	3:81	<0.01	1.13	1:81	>0.05	2.9	3:81	<0.05				
Muscle water	2.12	3:146	>0.05	33.9	1:146	<0.01	1.77	3:146	>0.05	4.86	1:146	<0.05	-0.17
Osmolarity	5.1	3:119	<0.01	96.35	1:119	<0.01	5.69	3:119	<0.01	12.31	1:119	<0.01	-0.26
Gill $Na^+ - K^+ - ATPase$	9.78	3:144	<0.01	0.91	1:144	>0.05	3.76	3:144	<0.01				
Haematocrit	4.6	3:135	<0.01	3.51	1:135	>0.05	2.08	3:135	>0.05	14	1:135	<0.01	0.36
Haemoglobin	0.81	3:141	>0.05	2.51	1:141	>0.05	3.42	3:141	<0.05	8.15	1:141	<0.01	0.29
MCHC	5.11	3:132	<0.01	6.04	1:132	<0.05	2.03	3:132	>0.05				
Muscle glycogen	5.47	3:117	<0.01	5.23	1:117	<0.05	4.13	3:117	<0.01				
Liver glycogen	14.27	3:140	<0.01	9.94	1:140	<0.01	5.57	3:140	<0.01	4.05	1:140	<0.05	0.31
CS	11.11	3:133	<0.01	10.14	1:133	<0.01	4.79	3:133	<0.01				
LDH	16.44	3:147	<0.01	5.59	1:147	<0.05	0.36	3:147	>0.05	118.76	1:147	<0.01	0.67
Muscle lactate	14.5	3:145	<0.01	0.13	1:145	>0.05	3.85	3:145	<0.01	46.02	1:145	<0.01	0.61
Muscle pyruvate	0.51	3:145	>0.05	2.52	1:145	>0.05	3.77	3:145	<0.01	20.97	1:145	<0.01	-0.44
Muscle ratio L:P	2.25	3:145	>0.05	4.88	1:145	<0.05	2.62	3:145	<0.05	33.1	1:145	<0.01	0.56
Heart lactate	0.23	3:135	>0.05	2.04	1:135	>0.05	13.33	3:135	<0.01	4.9	1:135	<0.05	-0.24
Heart pyruvate	6.07	3:135	<0.01	40.33	1:135	<0.01	0.94	3:135	>0.05	43.28	1:135	<0.01	-0.38
Heart ratio L:P	6.06	3:145	<0.01	55.49	1:145	<0.01	8.26	3:145	<0.01	59.38	1:145	<0.01	0.32

The variables for which body mass (covariable) had a significant effect are indicated in bold. When body mass had no significant effect, two-way ANOVAs were performed.

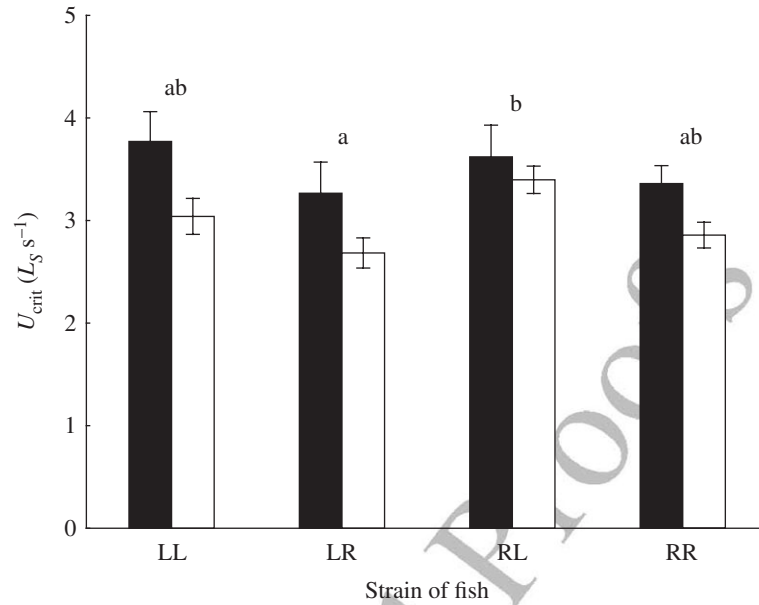


FIG. 2. Mean \pm S.E. critical swimming speeds (U_{crit}) of the two purebred strains (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their reciprocal hybrids in fresh (■) and salt water (□). The first letter of the cross-type indicates the dam and the second letter the sire. Different lower case letters indicate significantly different means among cross-types ($P < 0.05$). No significant interaction between cross-type and salinity was found. L_S , Standard length.

glycogen content was similar whether swimming challenges were performed in FW or SW. A significant interaction between cross-type and salinity was also observed for liver glycogen content along with a significant positive body mass covariance effect (Table IV). Exhaustion in SW or FW only had a distinct effect in $L_{\varphi}R_{\delta}$ hybrids, for which liver glycogen was 60% lower after the SW challenge compared with the concentration in fish exercised in FW [Fig. 5(b)]. In FW-exhausted fish, liver glycogen was *c.* 60% lower in Laval fish than in the three other cross-types, while liver glycogen concentration in SW was 56% lower in $L_{\varphi}L_{\delta}$ and $L_{\varphi}R_{\delta}$ than in the two other cross-types.

METABOLIC RESPONSE

There was a significant interaction between cross-type and salinity for white-muscle CS capacity (Table IV). In FW, CS capacity was 27% higher in the Rupert fish ($R_{\varphi}R_{\delta}$) than in the other cross-types, while no cross-type difference was observed in SW-exhausted fish [Fig. 6(a)]. No salinity effect was present within cross-types. CS K_m was also similar between fish challenged in FW (0.012 mM l^{-1}) and SW (0.011 mM l^{-1}). White muscle LDH capacity varied with both cross-type and salinity (but without significant interaction) and a significant positive M_B covariance effect was present (Table IV). The LDH capacity was 48% lower in $L_{\varphi}L_{\delta}$ fish than in the three other cross-types [Fig. 6(b)] and LDH K_m was similar for fish swim-challenged in FW (0.79 mM l^{-1}) and SW (1.00 mM l^{-1}).

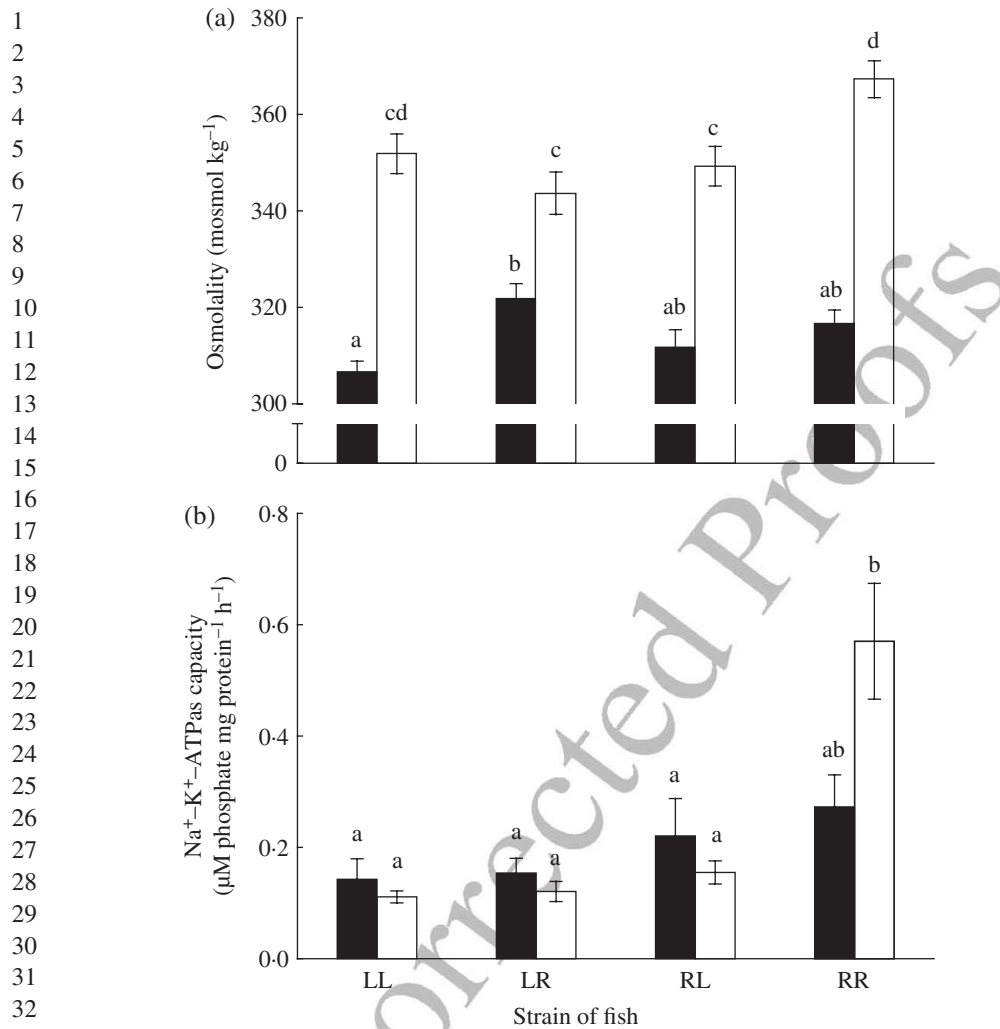


FIG. 3. Mean \pm S.E. (a) plasma osmolality and (b) gill $\text{Na}^+ - \text{K}^+ - \text{ATPase}$ specific activity in two purebred strains (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their reciprocal hybrids in fresh (■) and salt water (□). The first letter of the cross-type indicates the dam and the second letter the sire. Different letters indicate significantly different means ($P < 0.05$).

Muscle lactate concentration was different among cross-types and salinity trials (Table IV) and there was a positive correlation with body mass (Table IV). The $L_{\varphi}L_{\sigma}$ fish had 66% less muscle lactate compared with the $R_{\varphi}R_{\sigma}$ and $L_{\varphi}R_{\sigma}$ cross-types while the concentration in $R_{\varphi}L_{\sigma}$ hybrids was intermediate [Fig. 7(a)]. Within each cross-type, no difference was present between swimming trials in FW or SW. A significant interaction between cross-type and salinity was observed for muscle pyruvate content along with a significant negative correlation with M_B (Table IV). After the FW challenge, muscle pyruvate content in $L_{\varphi}R_{\sigma}$ hybrids was 3.7 times lower than in the $R_{\varphi}R_{\sigma}$ cross-type [Fig. 7(b)], but there was no difference among cross-types

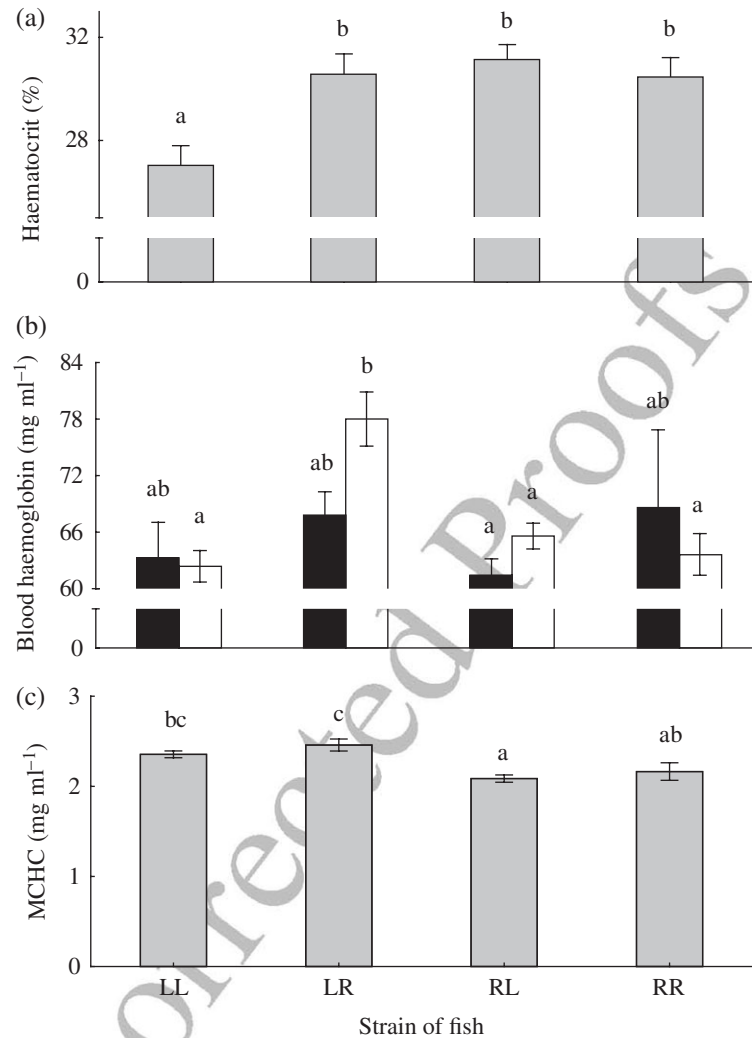


FIG. 4. Mean \pm S.E. (a) haematocrit, (b) blood haemoglobin and (c) mean cellular haemoglobin concentration (MCHC) in two purebred strains (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their reciprocal hybrids in fresh (■), salt water (□), or combined fresh and saltwater data (◻). The first letter of the cross-type indicates the dam and the second letter the sire. Different lower case letters indicate significantly different means ($P < 0.05$).

following exhaustion in SW. Within cross-types, only $L_{\sigma}R_{\delta}$ hybrids exhibited a significant difference in muscle lactate between FW and SW challenges: the muscle lactate:pyruvate ratio was 2.7 times higher in FW compared with SW [Fig. 7(c)] and a significant negative M_B covariance effect was observed (Table IV).

There was a significant interaction between cross-type and salinity on heart lactate content with a concomitant negative M_B covariance effect (Table IV). After challenge in FW, the heart lactate concentration of $R_{\sigma}L_{\delta}$ hybrids was 37% lower than in purebred crosses [Fig. 7(d)] while it was highest in this cross-type following SW swimming

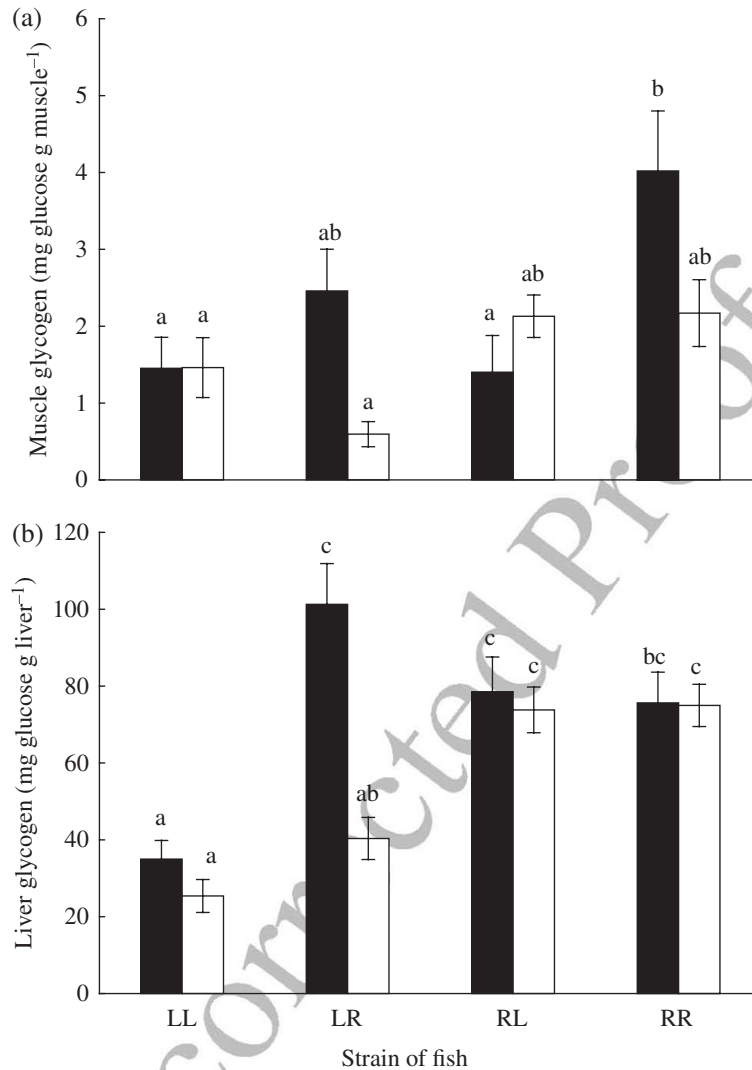
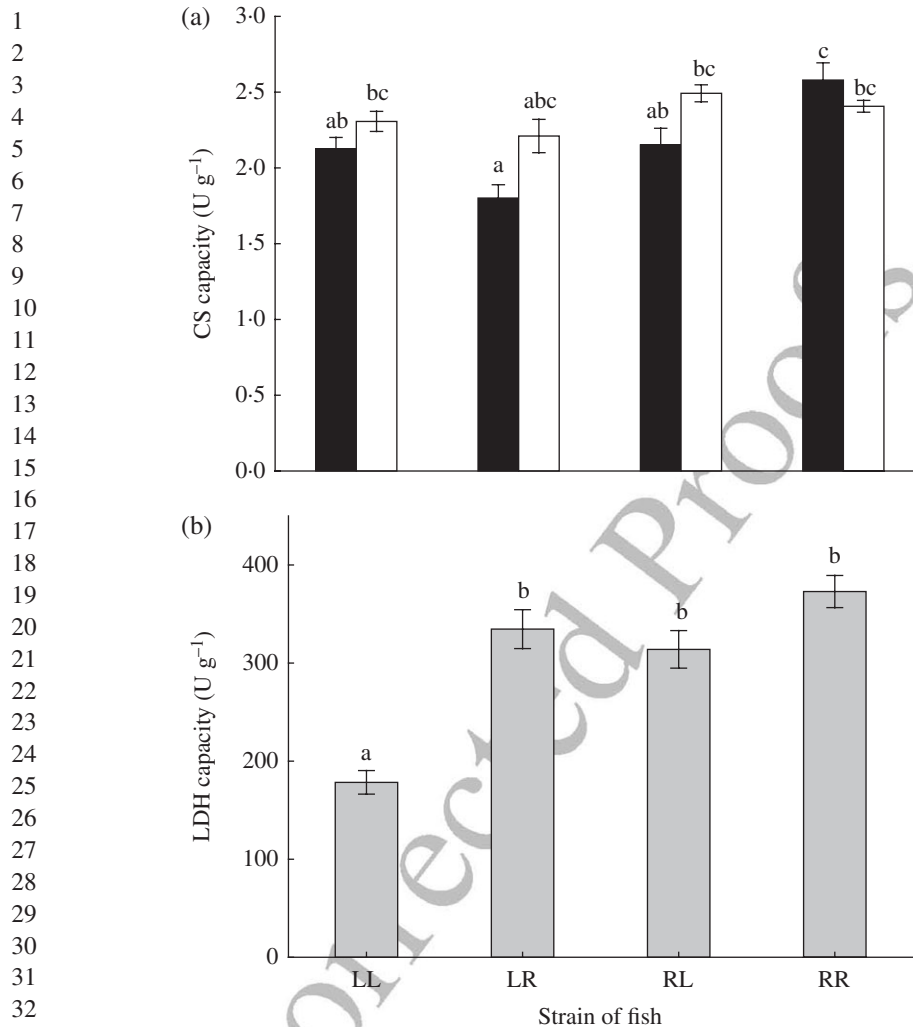


FIG. 5. Mean \pm s.e. (a) muscle and (b) liver glycogen concentration in two purebred strains (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their reciprocal hybrids in fresh (■), salt water (□). The first letter of the cross-type indicates the dam and the second letter the sire. Different lower case letters indicate significantly different means ($P < 0.05$).

exhaustion. Thus heart lactate concentration differed between the two environments only in the $R_{\phi}L_{\delta}$ cross-type (1.9 times higher in FW than in SW). Heart pyruvate concentration also varied according to cross-type and salinity (but without interaction), with a significant negative M_B covariance effect (Table IV): it was 69% higher in $L_{\phi}L_{\delta}$ fish than in $R_{\phi}L_{\delta}$ hybrids. Globally, heart pyruvate concentration was 34.6% lower after the SW swimming challenge than after the FW challenge [Fig. 7(e)]. This resulted in the highest heart lactate:pyruvate ratio for $R_{\phi}L_{\delta}$ hybrids challenged in SW (twice as high as the overall mean ratios of all other challenged fish) [Fig. 7(f)].



34 FIG. 6. Mean \pm S.E. (a) citrate synthase (CS) and (b) lactate dehydrogenase (LDH) capacity in two purebred strains
35 (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their recip-
36 rocal hybrids in fresh (■), salt water (□), or combined fresh and saltwater data (◻). The first letter of the
37 cross-type indicates the dam and the second letter the sire. Different lower case letters indicate significantly
38 different means ($P < 0.05$).
39

40 DISCUSSION

41 The main objective of this study was to test for the occurrence of functional diver-
42 gence in the factors affecting swimming performance (estimated by U_{crit}) between pure
43 strains and reciprocal hybrids issued from two wild populations of *S. fontinalis* having
44 different migratory lifestyles (anadromous Laval strain v. freshwater resident Rupert
45 strain). Pure cross types had similar swimming performance in FW and swimming per-
46 formance was reduced by 14% following abrupt transfer to SW in both anadromous and
47 resident fish. The pure cross types, however, reached similar swimming speeds using
48

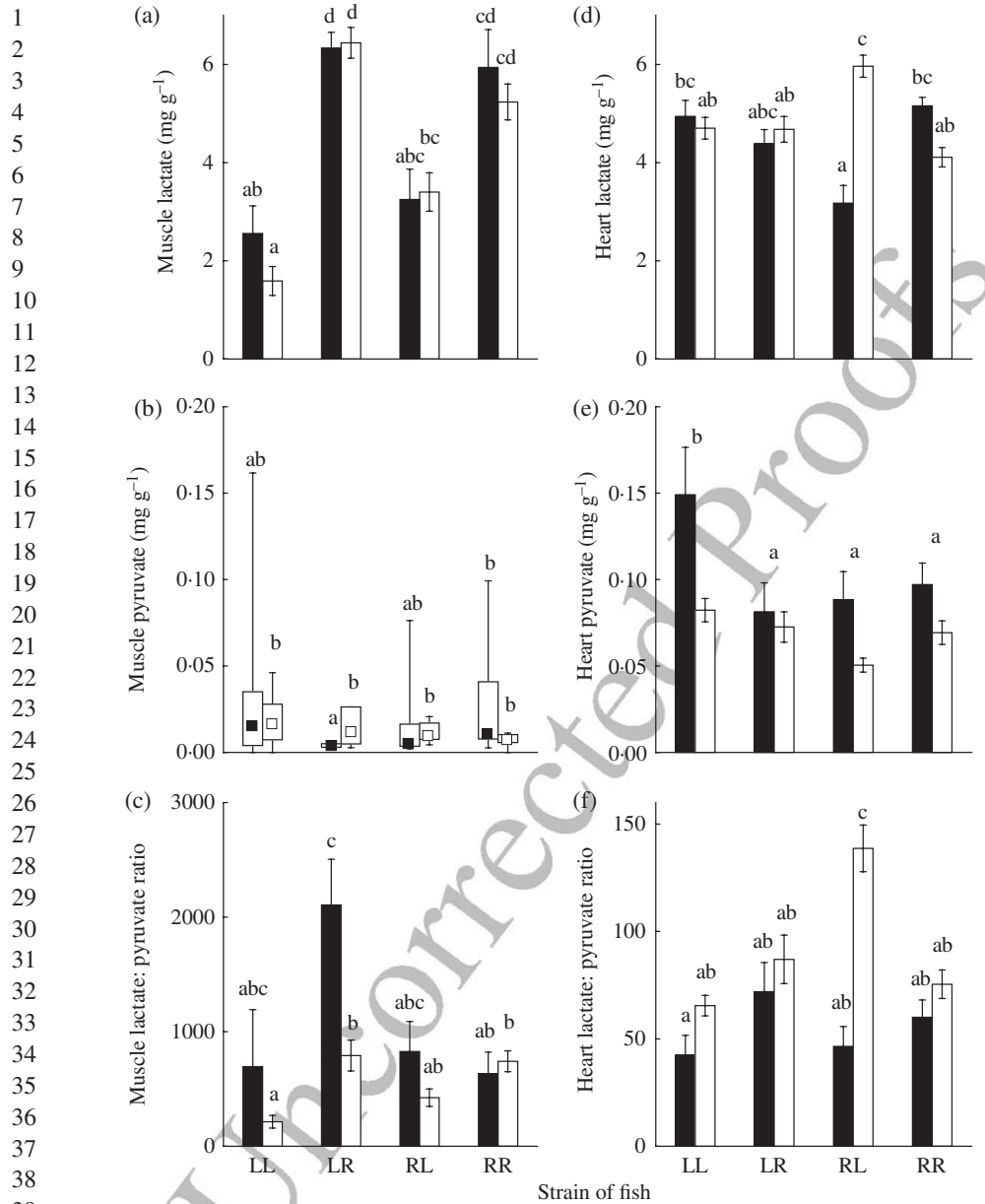


FIG. 7. Mean \pm S.E. (a) muscle lactate, (b) box plot of muscle pyruvate (■, fresh and □ saltwater medians within box of middle two quartiles and whiskers for range) and mean \pm S.E. (c) muscle lactate:pyruvate ratio, (d) heart lactate, (e) heart pyruvate and (f) heart lactate:pyruvate ratio in two purebred strains (L, Laval anadromous strain; R, Rupert freshwater-resident strain) of *Salvelinus fontinalis* and their reciprocal hybrids in fresh (■), salt water (□). The first letter of the cross-type indicates the dam and the second letter the sire. Different lower case letters indicate significantly different means ($P < 0.05$). Muscle pyruvate concentration data were not normally distributed and statistical analyses were carried out on ranks, but to facilitate comparison with other studies, data are presented using median and range. The muscle lactate:pyruvate ratio data were square-root transformed prior to statistical analysis, but to facilitate comparisons with other studies, arithmetic data are presented.

1 different physiological strategies, suggesting different genetically-based physiological
2 solutions to the same functional challenge. While no evidence was found for extreme
3 non-additive genetic effects (*i.e.* heterosis or outbreeding depression) in hybrids, sig-
4 nificant differences between the two reciprocal hybrids ($L_{\phi}R_{\delta}$ v. $R_{\phi}L_{\delta}$) were noted,
5 with lower performance in $L_{\phi}R_{\delta}$.

7 PURE STRAINS

8
9 Fishes swimming performance is controlled by a number of physiological, morpho-
10 logical and behavioural traits, all of which interact and involve potential trade-offs
11 (Walker, 2010; Dalziel *et al.*, 2011; Marras *et al.*, 2013). Considering the principle
12 of many-to-one mapping, many different combinations of traits can generate equiv-
13 alent performance and multiple underlying factors can affect a single quantitative trait
14 (Wainwright *et al.*, 2005; Walker, 2010; Dalziel *et al.*, 2011).

15 Condition-factor data are consistent with previous studies, which showed that
16 anadromous fishes are more streamlined than resident fishes (Taylor & Foote, 1991;
17 Eliassen *et al.*, 1998; Howland *et al.*, 2001; Morinville & Rasmussen, 2008; Dalziel
18 *et al.*, 2011). On that basis, the similar swimming performance of resident and
19 anadromous fish may seem counterintuitive as the most streamlined body shape of the
20 anadromous strain should be energetically advantageous. Swimming is energetically
21 demanding and requires high aerobic metabolic capacity (Gamperl *et al.*, 2002; Tудо-
22 rache *et al.*, 2008; Dalziel *et al.*, 2011; Eliason & Farrell, 2016). Resident fish must
23 then compensate for the advantage that body shape conferred to anadromous fish.

24 Here, the results suggest that anaerobic swimming contributed more to their over-
25 all swimming performance. In both FW and SW, maximal swimming was associated
26 with a muscle lactate concentration and an LDH capacity that was twice as high in
27 resident compared with anadromous fish, suggesting a larger contribution of anaerobic
28 component in the former. Despite a 20% higher white-muscle CS capacity in resident
29 fish exercised in FW, no clear between-strain difference or pattern emerged regarding
30 aerobic performance. It should be noted that CS activity was low in both resident and
31 anadromous fish.

32 Higher glycogen storage and more efficient mobilization and utilization have been
33 suggested to improve swimming performance (Fu *et al.*, 2011; Yang *et al.*, 2015).
34 During anaerobic swimming, fish white muscles rely on three endogenous fuel
35 sources, *i.e.* adenosine triphosphate (ATP), phosphocreatine and glycogen. In the very
36 first stages of white-muscle mobilization, ATP and phosphocreatine stores are rapidly
37 exhausted (Dobson & Hochachka, 1987) and it is glycogenolysis that then provides
38 most of the ATP anaerobically, depleting muscle glycogen (Wood, 1991; Milligan,
39 1996). The Rupert fish (FW resident) may not only have reached a swimming per-
40 formance similar to that of anadromous fish due to their greater anaerobic capacities,
41 but also because of higher energy reserves. The glycogen levels in epaxial muscle
42 and liver following FW exercise were more than twice as high in resident than in
43 anadromous fish. The exception was the epaxial muscle of resident fish tested in SW,
44 which may indicate greater energetic demand following this trial. Thus, the resident
45 population compensated for its lower natural swimming ability (compared with the
46 anadromous population) by having a higher metabolic capacity.

47 For species moving between FW and SW, a large osmoregulatory capacity is an addi-
48 tional and critically important determinant for maintaining swimming performance

1 (Brauner *et al.*, 1992; Nelson *et al.*, 1996; McKenzie *et al.*, 2001b; Chatelier *et al.*,
2 2005). Regardless of FW rearing conditions, cross-type differences in the stress
3 response to SW transfer were expected and a lower SW swimming performance
4 in resident fish. Following the SW challenge, resident fish had plasma osmolality
5 similar to anadromous fish combined with a gill $\text{Na}^+ - \text{K}^+ - \text{ATPase}$ activity that was
6 4.4 times higher. No differences in other stress indicators, however, were observed
7 whether fish were exercised in FW or in SW. One may ask why experimental animals
8 were reared in FW. In captivity, rearing 0+ and 1+ year-old animals for prolonged
9 periods in SW greatly increased events of opportunistic myxobacteria infections,
10 suggesting impaired homeostasis, which is why young stages are routinely maintained
11 in FW (C. Audet, unpubl. data). Otherwise, 2+ years and older anadromous Laval
12 fish (including breeders) are reared at a salinity of 20 between the beginning of June
13 and late September, mimicking the migration pattern of this wild anadromous fish
14 population (Curry *et al.*, 2010).

15 Previous studies comparing the performance of anadromous and resident populations
16 in different fish species showed that anadromous fishes possessed significantly greater
17 swimming capacities than those from resident populations [*O. kysutch* (Taylor & Foote,
18 1991); *S. fontinalis*, *Salmo trutta* L. 1758, *Salmo salar* L. 1758 (Peake *et al.*, 1997);
19 *G. aculeatus* (Dalziel *et al.*, 2011; Kitano *et al.*, 2012)]. It has been hypothesized that
20 their exposure to fast-water habitats, which are more energetically costly, allowed the
21 anadromous fishes to evolve more efficient swimming abilities than resident popula-
22 tions [*O. kysutch* (Taylor & Foote, 1991); *S. fontinalis*, *S. trutta*, *S. salar* (Peake *et al.*,
23 1997); *S. fontinalis* (Morinville & Rasmussen, 2003, 2008)]. In the present study, even
24 though the swimming performance was similar between anadromous and freshwater
25 resident fish, the results indicate a higher contribution of non-aerobic pathways in res-
26 ident fish which suggests that they may be less adapted to sustained swimming.

27 28 RECIPROCAL HYBRIDS

29 Swimming performance and its underlying traits were different between the recip-
30 eral hybrids. Compared with $\text{R}_\text{♀}\text{L}_\text{♂}$ hybrids, $\text{L}_\text{♀}\text{R}_\text{♂}$ hybrids had a 20% lower swimming
31 speed, which was associated with a 24% smaller cardio-somatic index, a 21% higher
32 MCHC and a 19% higher haemoglobin concentration when swimming in SW as well as
33 a larger metabolic (1.9 times higher muscle lactate accumulation) and energetic (44%
34 less liver glycogen in SW) response. $\text{L}_\text{♀}\text{R}_\text{♂}$ hybrids thus expended greater effort and
35 still had a lower performance than the reciprocal hybrid. Therefore, this performance
36 depends on cross direction (parental line used as dam or sire). Such cross-direction
37 phenomena have also been reported in *M. salmoides* (Cooke *et al.*, 2001) and Chi-
38 nook salmon *Oncorhynchus tshawytscha* (Walbaum 1792) (Falica & Higgs, 2012), but
39 hybrids can often be similar in their swimming performance (Hawkins & Quinn, 1996;
40 Dalziel *et al.*, 2011). The reciprocal effect may be explained by various factors such
41 as maternal or paternal effects, or genetic linkage between sex genes and performance
42 genes. Swimming performance may be influenced by maternal effects, which are often
43 involved in cross direction. These effects, however, generally occur during early life
44 development (due to egg size or yolk quality) with a decrease over time and thus should
45 probably be negligible in the present study since fish were tested at age 1+ year (Taylor
46 & Foote, 1991; Heath *et al.*, 1999; Perry *et al.*, 2004, 2005). Paternal effect could have a
47 strong influence on swimming performance; this was the explanation given for the cross
48

1 direction observed in *M. salmoides* and *O. tshawytscha*. The underlying genetic mech-
2 anisms of these sire effects still need to be more thoroughly investigated (Cooke *et al.*,
3 2001; Evans *et al.*, 2004; Falica & Higgs, 2012), but could hypothetically be under
4 genetic control. In the present study, no evidence of paternal effect was found. The
5 genetic linkage between sex genes and genes associated with performance traits can
6 result in sex-specific gene expression under the control of the sex-determining region
7 (Ellegren & Parsch, 2007; Derome *et al.*, 2008), which might then influence the pre-
8 dominance of a specific parental line as dam or sire in the expression of performance.
9 Testing this hypothesis will require further investigation. In addition, other possible
10 effects related to the genetic architecture (*e.g.* pleiotropy or other genetic linkage) of
11 swimming performance merit further investigation.

12 13 GENETIC AND EVOLUTIONARY CONSIDERATIONS

14 Because the experiment was conducted in a common-garden environment, differ-
15 ences in condition factor and physiological support features must have a genetic basis
16 specific to each population. The different underlying traits affecting swimming per-
17 formance thus have the potential to evolve under natural selection as does swimming
18 performance itself, for which heritability has recently been estimated in *D. labrax* (Van-
19 deputte *et al.*, 2016). Similar results have been observed between different populations
20 of Atlantic cod *Gadus morhua* L. 1758 originating from different salinity environments
21 (salt and brackish water) and tested in both environments (Nelson *et al.*, 1996). In the
22 Nelson *et al.* (1996) study, swimming performance (U_{crit}) did not differ between popu-
23 lations even though there were inter-population differences in key support performance
24 traits such as metabolic rate and aerobic and anaerobic capacities. These populations
25 had been separated for <3000 years and the authors considered that this was too short
26 for genetic changes to have occurred under normal natural selection; they rather sug-
27 gested that these inter-population differences mostly resulted from acclimation. More
28 recent studies have suggested that genetic adaptation could occur very quickly, *e.g.*
29 within a small number of generations (Reznick *et al.*, 1997; Pearse *et al.*, 2009; Ellner
30 *et al.*, 2011; Westley *et al.*, 2013). Since the separation of the *S. fontinalis* populations
31 used in this study occurred around 10 000 years ago (Castric & Bernatchez, 2003), it
32 seems that such a time frame would have been sufficient for the different populations to
33 evolve distinct genetically based physiological adaptations to cope with their respective
34 environments.

35 Differences between the two populations could be the results of local adaptation to
36 different migratory lifestyles. Since swimming performance integrates the actions of
37 a large number of organs and supporting functions, the investigation of the variability
38 in swimming capacity within and among populations can be considered as a relevant
39 means to reveal elements of local adaptation (Cooke *et al.*, 2001; Odell *et al.*, 2003;
40 Pon *et al.*, 2007). Although this needs to be more rigorously investigated, ecological
41 differences in the populations' migratory conditions (*i.e.* differences in fluctuations
42 of temperature, velocity and salinity experienced by the anadromous and the resident
43 populations in their respective environments) could have influenced the physiological
44 processes involved in swimming performance. Since the resident population probably
45 faces strong currents during spring, swimming ability probably remained a key deter-
46 minant of fitness for freshwater residency. It should be noted, however, that the crosses
47 in this study were only between the Rupert and the Laval strains. It is possible that
48

1 crosses involving different anadromous and resident *S. fontinalis* populations could
2 lead to results different from what was found here. Thus the possibility exists that the
3 differences observed between the Rupert and Laval strains might not be linked to their
4 migratory behaviour but to other forces shaping local adaptation. The Rupert and Laval
5 fish used for this study were F3 fish and domestication effects may already be present
6 (Sauvage *et al.*, 2010). Other studies undertaken on the same families, however, have
7 shown that they are still very different in terms of reproductive period, stress response
8 (Crespel *et al.*, 2011), growth, gene \times environment interactions on growth (Crespel
9 *et al.*, 2013a) and storage and use of energy reserves (Crespel *et al.*, 2013b). Could
10 short-term domestication have eliminated differences in swimming capacity but main-
11 tained differences in other traits? It is a possibility that cannot be completely rejected.


12 One of the objectives was to test the occurrence of non-additive effects in the
13 hybrids. No evidence of heterosis or outbreeding depression was observed. When
14 populations are very divergent and adapted to their respective environments, this
15 may provide evidence that their genome has evolved towards local genetic complex
16 associations. Hybridization between divergent populations alter these associations and
17 hybrids may thus express extreme non-additive genetic effects that can be positive
18 (when hybrids outperform parental lines due to synergy between the genomes: het-
19 erosis) or negative (when hybrids underperform parental lines due to incompatibilities
20 between the genomes: outbreeding depression) (Edmands, 1999; Cooke *et al.*, 2001;
21 Stelkens *et al.*, 2009). Outbreeding depression has been observed in *M. salmoides*
22 for the swimming performance of hybrids between two locally adapted populations,
23 revealing a breakdown of co-adapted gene complexes (Cooke *et al.*, 2001; Cooke &
24 Philipp, 2005, 2006). In the present study, which used two populations with different
25 migratory lifestyles known to have very divergent genetic bases from both neutral
26 (Martin *et al.*, 1997) and functional (Bougas *et al.*, 2010) standpoints, the occurrence
27 of extreme non-additive genetic effects, and most specifically, outbreeding depression,
28 would be expected (Bieri & Kawecki, 2003; Cooke & Philipp, 2005). This was not the
29 case, however. The absence of pronounced non-additive effects for swimming and the
30 underlying performance between the two populations that was found thus suggest that
31 the extent of the genetic differences that have accumulated between these populations
32 since their separation has not been sufficient to cause genomic incompatibilities
33 between the parental genomes (Bieri & Kawecki, 2003; Rosenfield *et al.*, 2004).

34
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