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Swimming ability and behavior of Mrigal carp *Cirrhinus mrigala* and application to fishway design

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ABSTRACT: To mitigate the impact of river fragmentation on fish resulting from dams, specifically the fragmentation of Indian rivers, the design and construction of high-efficiency fishways is important. Information on fish swimming ability and behavior is necessary to develop design criteria for the target species, *Cirrhinus mrigala*, a cyprinid native to India, Pakistan and Bangladesh. Swimming ability and behavior data for the genus are limited. To augment existing information, the swimming ability and behavior of juvenile *C. mrigala* were investigated by determining their induced flow velocity (U_{ind}), critical swimming speed (U_{crit}), and burst speed (U_{burst}) in a swimming respirometer. To facilitate application to fishway design, swimming assessment data were converted to a cumulative response; for U_{ind}, it is the cumulative percentage of fish swimming against the current at a given velocity, and for U_{crit} and U_{burst}, it is the percentage of fish able to maintain a given velocity for the specified time interval without fatigue. Results include 2 primary findings. (1) The cumulative response velocity (%) of fish induced to swim, or reach fatigue, increased with flow velocity. The cumulative velocity is useful for developing fishway design criteria. (2) The mean values of U_{ind}, U_{crit}, and U_{burst} were 0.427 ± 0.013, 2.768 ± 0.146 and 3.493 ± 0.121 body lengths s^{-1} (±SE). The values of U_{crit} and U_{burst} indicate that the swimming ability of *C. mrigala* is relatively low for a cyprinid.

KEY WORDS: Flow velocity · Induction · Fatigue · Swimming performance

INTRODUCTION

Fish swimming ability and behavior are important for feeding, predator avoidance, seeking refuge and migration (Domenici & Kapoor 2010). Based on experimental tests of velocity and time to exhaustion, swimming modes are classified as sustained, prolonged and burst (Brett 1964). Information on swimming ability and behavior is important for setting design criteria for fishways (Katopodis & Williams 2012) and predicting the selectivity and efficiency of capture in trawl nets (Winger et al. 1999). When discussing trends in fishway science, engineering and practice, Silva et al. (2018) acknowledged the importance of integrating all relevant scientific knowledge (i.e. fish biology and ecohydraulic analysis), as well as the need for adaptive management. The importance of considering fish biology (particularly swimming ability and behavior) in fishway design has been recognized internationally for over a century, but little data is available for species other than salmon (Katopodis 2005, Williams et al. 2012). While abundant data on swimming ability and behavior of fishes has been gathered in developed countries, information is more limited in developing countries, including China and India.

Mrigal carp *Cirrhinus mrigala* is a species of Cyprinidae found in India, Pakistan and Bangladesh and is

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one of the major Indian carp in terms of abundance and commercial value (Ahmed & Khan 2004). It has been introduced into other parts of India and adjacent countries, including China in 1982. It is a bottom feeder, subsisting primarily on decaying vegetation. It attains a length of 99 cm and weight of 12.7 kg (Talwar & Jhingran 1991). Research related to aquaculture, toxicology and biochemistry has been carried out (Palaniappan & Karthikeyan 2009, Nigam et al. 2017, Kumar et al. 2018), but information on behavior, including movement, is limited.

To mitigate the impact of river fragmentation resulting from the construction of dams, specifically on Indian rivers (Grumbine & Pandit 2013, Grill et al. 2015), high-efficiency fishways have been constructed. Das & Hassan (2008) and Ravichandran & Semwal (2016) concluded that the absence of data on fish swimming ability and behavior has resulted in unsuccessful fishways in India.

This study provides data on the swimming ability and behavior of juvenile *C. mrigala* to help improve fishway design. Swimming was assessed by measuring induced flow velocity (U_{ind}; the lowest water velocity that induces continuous swimming against the current), critical swimming speed (U_{crit}; the maximum swimming speed that can be maintained for a 15 min time interval) and burst speed (U_{burst}; the maximum swimming speed that can be maintained for a 1 min time interval). These swim test parameters were used to develop flow velocity criteria (minimum flow velocity, attractive flow velocity and maximum flow velocity) for a fishway design that is optimal for *C. mrigala*.

MATERIALS AND METHODS

Fish and equipment

Approximately 100 juvenile *Cirrhinus mrigala* were obtained from an aquaculture operation in Lushan City (29° 42′ N, 116° 26′ E), China. The fish were maintained for 1 wk in holding tanks with dechlorinated, fully aerated tap water at ambient temperature and photoperiod. Healthy fish were randomly selected for testing (mean ± SE body length: 0.147 ± 0.001 m; mass: 52.3 ± 0.7 g). Fish were fasted for 24 h before testing.

Fish were tested in a swimming respirometer (Cai et al. 2014b) with a volume of 95 l and a 28 l rectangular swim chamber (70 × 20 × 20 cm). The respirometer was submerged in a 250 l (143 × 63 × 28 cm) tank. Normal respirometer operating assumptions were made: swimming speed (U) of the fish equals water flow velocity, as measured with a propeller flow velocity meter (LGY-II). The dissolved oxygen and temperature in the respirometer were monitored with a multi-parameter probe (YSI DO200A). Water temperature varied from 15.9 to 18.7°C and dissolved oxygen was >7.0 mg l^{-1}, maintained by aeration.

Experimental design

Stepped velocity tests were carried out to measure (1) induced flow velocity (U_{ind}), the speed at which a fish is not able to hold station without actively swimming, and (2) critical swimming speed (U_{crit}) and burst speed (U_{burst}), to indicate prolonged and burst swimming capability (Brett 1964).

In the U_{ind} and U_{crit} test (10 fish), (1) each fish was tested individually. Fish body length (BL) was measured and the test fish was allowed to adapt to experimental conditions at 0.04 m s^{-1} for 1 h. At the initial flow velocity of (0.04 m s^{-1}), the fish was nearly motionless along the flow direction. The water velocity was increased by approximately 0.01 m s^{-1} at 5 s intervals and, when the fish was no longer able to hold station and began actively swimming, the flow velocity was reported as U_{ind} (Cai et al. 2018). (2) The flow velocity was then increased to 1.0 BL s^{-1} and increased by 1.0 BL s^{-1} at 15 min intervals (Brett 1964). When the fish ceased swimming, the flow velocity was decreased and the swim chamber was rapped with a plastic stick to encourage the fish to continue swimming. If the fish resumed swimming, the velocity was reset to the velocity at which the fish ceased swimming. A fish was regarded as exhausted when it did not resume swimming and rested against the wire grid for 10 s. When the fish was exhausted, the test was over and body mass was measured.

For the U_{ind} and U_{burst} test (10 fish), step (1) was same as above; when swimming was induced, the flow velocity was adjusted to 1.0 BL s^{-1}. The velocity was increased by 1.0 BL s^{-1} at 1 min intervals (Wang et al. 2017) and when the fish was exhausted, the test was over and body mass was measured.

Among the fish selected for testing, 20% (4 fish, 2 fish in each test) failed to swim continuously when challenged. When a fish did not perform, the test was interrupted and another fish was selected for testing.

Data analysis

U_{crit} (and U_{burst}) were calculated according to Eq. (1) (Brett 1964):

$$U_{crit} = U_p + (t_f / t_i) \times U_t \quad (1)$$

where U_p (BL s^{-1}) is the highest velocity at which fish swam for the full time interval, U_t (BL s^{-1}) is the speed step, t_f (min) is the time to fatigue during the last velocity step and t_i (min) is the time step.

The dimensionless fish speed (U^*), calculated using Eq. (2), compresses the variation of fish speed with body length, and is useful for comparing swimming performance among fish species of different size (Katopodis & Gervais 2016):

$$U^* = U / \sqrt{g \times \mathrm{BL}} \quad (2)$$

where U (m s^{-1}) is the absolute fish speed (U_{ind}, U_{crit} or U_{burst}) and g is gravitational acceleration, 9.81 m s^{-2}.

The cumulative response velocities (%) were used to set design criteria for fishway velocities. For U_{ind}, this was the cumulative percentage of fish, at a given velocity, that sensed the current direction and swam against it. With U_{crit} and U_{burst}, it was the cumulative percentage of fish that maintained a given swimming velocity for the specified time interval. The percentage (y) induced for U_{ind} or exhausted for U_{crit} and U_{burst} was fit to the flow velocity (x) (i.e. fish swimming speed) using Origin 9.0 (OriginLab), giving Eq. (3):

$$y = a e^{-e^{-bx+c}} \quad (3)$$

where a, b and c are fitting parameters and e is the natural logarithm base. The velocity (x) at which y = 50% (the 50% response rate, a fitted value) is designated as U_{50}.

The mean, median and 50th percentile values and their differences were calculated and compared: $D_{mm} = (U_{mean} - U_{median}) / U_{mean}$ and $D_{m50} = (U_{mean} - U_{50}) / U_{mean}$.

RESULTS

The percentages of induction and fatigue, in relative (U; BL s^{-1}), absolute (U; m s^{-1}) and dimensionless (U^*) units of velocity all increased with flow velocity (Fig. 1). Fig. 1 also displays the 95% confidence intervals and 50% response velocity (U_{50}) for U_{ind}, U_{crit} and U_{burst}.

The mean, median and 50% response velocities U_{ind} (n = 20), U_{crit} (n = 10) and U_{burst} (n = 10) expressed in relative (BL s^{-1}), absolute (m s^{-1}) and dimensionless units are given in Table 1, which also includes D_{mm} and D_{m50}. The cumulative response velocity of U_{ind}, U_{crit} and U_{burst} in absolute units will be used in the discussion of fishway design, as it is most useful for hydraulic engineers.

DISCUSSION

Effect of flow velocity on induction and fatigue

Measures of fish swimming ability and behavior (U_{ind}, U_{crit}, and U_{burst}) are expressed as means (±SE) and the cumulative responses for induced swimming and fatigue versus flow velocity are provided to show the distribution in ability and behavior among test fish. The data could have been set to a linear function, but cumulative response is not linear if the behavior of test organisms is normally distributed (dose-response data from toxicity testing, for example). As expected, fitting cumulative response with flow velocity gave a higher R^2 value when fit using an exponential equation (Fig. 1) than when fit using a linear equation, in accord with Brett (1967). Fig. 1 was designed for convenient application by engineers when setting flow criteria for different sections of a fishway for maximal passage.

For example, the minimum fishway velocity for *Cirrhinus mrigala* could be set at the 80% response velocity for U_{ind} (0.070 m s^{-1}), rather than at the 50% response velocity (0.062 m s^{-1}) so that a larger fraction of fish avoid disorientation. The maximum flow could be set at the 20% response for U_{burst} (0.401 m s^{-1}), rather than the 50% response flow velocity (0.488 m s^{-1}) so that a larger fraction of fish are able to pass. However, it should be noted that fish swimming ability (especially U_{burst}) measured in a flume or a chamber may be slightly lower than in natural waters. Tudorache et al. (2007) found that swim chambers can restrict burst–coast swimming in *Cyprinus carpio*.

Setting the fishway entrance velocity is not as straightforward. Pavlov (1989) recommended that entrance velocity be set at 0.6–0.8 U_{crit}. However, a flow velocity in the range 0.2–0.3 U_{crit} resulted in the best attraction efficiency for the carp *Percocypris pingi* (L. Cai et al. unpubl. data). This shows clearly that Pavlov's (1989) recommendation is not appropriate for all species. Hence, to recommend the entrance velocity for *C. mrigala* with confidence, investigation of tropism behavior is necessary.

Swimming ability of *C. mrigala* compared to other species

Swimming ability data for the *Cirrhinus* genus are limited. *Spinibarbus sinensis*, *Onychostoma sima* and *C. mrigala* are in the Barbinae subfamily of Cyprinidae. For *S. sinensis* and *O. sima* (BL 0.06~0.07 m),

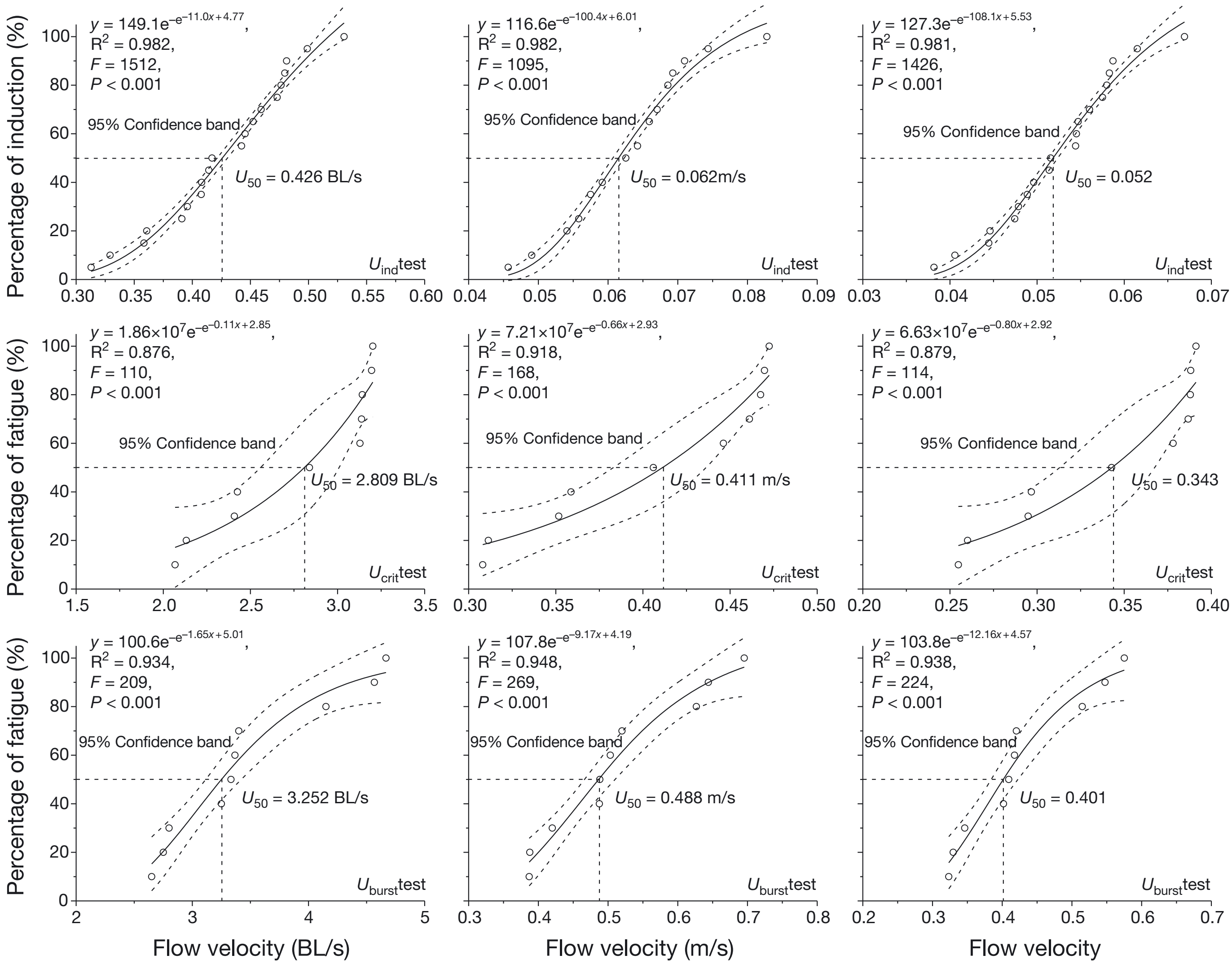

Fig. 1. Percentage of juvenile *Cirrhinus mrigala* induced to swim and reaching fatigue as flow velocity increased

Table 1. Mean (±SE), median and fitted values of swimming ability in *Cirrhinus mrigala* (body length [BL] 0.147 ± 0.001 m) at 15.9–18.7°C (n: number of fish). U_{ind}: induced flow velocity; U_{crit}: critical swimming speed; U_{burst}: burst speed; $U^* = U/\sqrt{g \times BL}$; U is U_{ind}, U_{crit} and U_{burst} (m s^{-1}), g: acceleration due to gravity (9.81 m s^{-2}). $D_{mm} = (U_{mean}-U_{median})/U_{mean}$ and $D_{m50} = (U_{mean}-U_{50})/U_{mean}$, U_{mean} and U_{median} are the mean and median value of U_{ind}, U_{crit} and U_{burst}, and U_{50} is the fitted value in Fig. 1

	U_{ind} (BL s^{-1}) n = 20	U_{ind} (m s^{-1}) n = 20	U_{ind}* n = 20	U_{crit} (BL s^{-1}) n = 10	U_{crit} (m s^{-1}) n = 10	U_{crit}* n = 10	U_{burst} (BL s^{-1}) n = 10	U_{burst} (m s^{-1}) n = 10	U_{burst}* n = 10
Mean	0.427 ± 0.013	0.063 ± 0.002	0.052 ± 0.002	2.768 ± 0.146	0.405 ± 0.021	0.338 ± 0.018	3.493 ± 0.121	0.516 ± 0.034	0.429 ± 0.028
Median & D_{mm}	0.430 & −0.7%	0.063 & 0%	0.053 & −1.9%	2.984 & −7.8%	0.426 & −5.2%	0.360 & −6.5%	3.350 & 4.1%	0.496 & 3.9%	0.496 & −15.6%
Fit (U_{50}) & D_{m50}	0.426 & 0.2%	0.062 & 1.6%	0.052 & 0%	2.809 & −1.5%	0.411 & −1.5%	0.343 & −1.5%	3.252 & 6.9%	0.488 & 5.4%	0.401 & −7.0%

U_{crit} was 0.45–0.6 m s^{-1} (7–9 BL s^{-1}) (Yan et al. 2012, 2013, Fu et al. 2013), faster than the U_{crit} measured for *C. mrigala* (BL 0.147 m) in this study (0.405 ± 0.021 m s^{-1}, 2.768 ± 0.146 BL s^{-1}). The swimming ability of *C. mrigala* (1 of 4 major Indian carps) is also lower than other Cyprinidae species, including the 4 major Chinese carps, *Mylopharyngodon piceus*, *Ctenopharynodon idellus*, *Hypophthalmichthys molitrix* and *Aristichthys nobilis* (BL 0.06–0.11 m, U_{crit} 0.43–1.09 m s^{-1}; Yan et al. 2013, Cai et al. 2014a).

Furthermore, the swimming ability of *C. mrigala* is lower than most Cypriniforme species according to the review of Katopodis & Gervais (2016). During the tests of swimming ability, it was observed that *C. mrigala* swam by tail oscillation and trunk undulation, which could result in lower swimming ability (Blake 2004). In short, the swimming ability of *C. mrigala* is relatively low, based on comparison with the species referenced above. Differences in swimming ability have been attributed to differences in morphology and physiology resulting from adaptation to habitat flow regimes (Kieffer 2000, Yan et al. 2013, Crespel et al. 2017). A novel fishway design may be required to accommodate *C. mrigala* as well as species with higher swimming abilities.

We found that U_{crit} of *C. mrigala* was lower than other carps of similar length (*C. carpio*, *Carassius auratus*, *S. sinensis*, *O. sima*, *Parabramis pekinensis* and *Ctenopharyngodon idellus*; Yan et al. 2012), the ratio of $U_{\text{burst}}/U_{\text{crit}}$ for *C. mrigala* (~1.2) at ~17°C is lower than the ratio for these 6 carps (1.8–2.5) at 15–25°C (Yan et al. 2012) and other 9 Schizothoracinae (also carps, 1.2–1.8) at 5–20°C (Hou et al. 2018), indicating that *C. mrigala* has more of an ability for sustained swimming than short bursts. We also found that U_{burst} of *C. mrigala* was lower than other similar-sized carp, such as *Luciobarbus bocagei* and *Pesudochondrostoma duriense* (Sanz-Ronda et al. 2015). Thus, a fishway for *C. mrigala* should have a low flow velocity over a longer distance rather than a high flow velocity over a shorter distance.

Reporting data on fish swimming ability and behavior

In Table 1, the deviations of mean value from median value (D_{mm}) and fitted value (D_{m50}) for U_{ind}, U_{crit} and U_{burst} were positive and negative, and ranged from 0 to ~15%. The D_{mm} and D_{m50} for U_{ind} were significantly lower than with U_{crit} and U_{burst}. This is attributed to small sample size (n = 20 for U_{ind}, n = 10 for both U_{crit} and U_{burst}) and asymmetrically distributed values. The results of this analysis indicate that reporting several measures of central tendency (e.g. mean, median and fitted values) has merit. Researchers can more effectively examine results on swimming ability and behavior reported by other researchers, particularly when experiments are carried out on a limited number of fish (n < 20). Improved reporting of experimental results will allow flow criteria to be set more precisely, improving fishway efficiency.

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