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Effect of Turbidity on the Swimming Performance of the Golden Shiner, *Notemigonus crysoleucas*

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Of the many environmental factors that could affect swimming performance and critical swimming speed (U_{crit}), turbidity has received relatively little attention. The purpose of this study was to examine the effects of turbidity on Golden Shiner (*Notemigonus crysoleucas*) swimming performance through the analysis of critical swimming speed. It was found that turbidity had an effect on critical swimming speeds; critical swimming speeds increased significantly with rising turbidity values. At the highest turbidity levels reported in this paper, Golden Shiner experienced a 56.5% increase in critical swimming speed over controls swimming in clear water. We likewise observed an increase in swimming efficiency and cost of transport with increasing turbidity. We suggest that a hydrodynamic effect may be the most likely explanation for the increase in performance and swimming efficiency observed in this study.

PROLONGED and acute changes in turbidity regimes have been shown to affect a wide variety of fish conditions and life strategies, including alterations in reproduction (Henley et al., 2000; Engstrom and Candolin, 2007), growth rate effects (Sigler et al., 1984), and changes in feeding behavior (Robertis et al., 2003; Carter et al., 2010). The exact definition of turbidity is variable depending on the application of the study, but in this context it is defined as the amount of sediment suspended in the water column, as opposed to other causes of turbidity, such as algal blooms (Wilson et al., 2010). Despite the work that has been done examining turbidity as an influential environmental factor, few studies address turbidity effects in the context of swimming performance, particularly in regard to critical swimming speed (U_{crit}). A single paper by Gradall and Swenson (1982) reported that Creek Chubs (*Semotilus atromaculatus*) and Brook Trout (*Salvelinus fontinalis*) were more active in moderately turbid water. However, the majority of the small number of studies that have examined the effects of turbidity on swimming have tested the alterations to predator-prey interactions. To our knowledge, there have been no studies published concerning turbidity effects on critical swimming speed.

Critical swimming speed, introduced by Brett (1964), is the maximum speed a fish can achieve for a predetermined time period and is the most widely used method for determining aerobic swimming capabilities (Beamish, 1978; Parsons and Sylvester, 1992; Hammer, 1995).

As a whole-body indicator, swimming performance is a useful diagnostic tool because it allows for the linkage of lower-level biological and mechanical effects with behavior and fitness (Wilson et al., 2007). As with any laboratory measurement, ecological relevancy is of concern. However, as reported by Brauner et al. (1994), even though limitations exist due to the inability to account for all the variables necessary for survival in a natural setting, critical swimming speed provides a quantifiable and comparable index of the physical status of the fish. Currently, critical swimming speed is considered to be the best measurement of swimming performance, both in its indication of the physical condition of the fish and its ability to predict ecological consequences (Adams and Parsons, 1998; Plaut, 2001).

The objective of this study was to determine the effect of suspended particulates on the swimming performance of Golden Shiner, *Notemigonus crysoleucas*, using critical swimming speed as a whole-body indicator of fish performance.

MATERIALS AND METHODS

Pond-raised *Notemigonus crysoleucas* were obtained commercially and maintained in a large aquarium in clear water at either 22 or 28°C. Light was ambient, and photoperiod was set at a 12:12 light-dark cycle. Fish were fed a generic flake food in the evening, but not 24 hours before testing. Only fish that appeared healthy and ranged in size from 4.5 to 6.5 cm TL were used for testing.

Swimming performance was tested using a Blazka et al. (1960)-style swim tunnel (Fig. 1), as described in Boyd and Parsons (1998). Water velocity in the tunnel was determined using a Marsh-McBirney electronic flow meter (model #201D30). Groups of eight fish at a time were tested at turbidity levels of 0, 10, 20, and 30 Nephelometric Turbidity Units (NTU) and at 22 and 28°C ($n = 32$/treatment, 128 total). Prior to testing, all fish were allowed a two-hour acclimation period in the tunnel during which the flow in the tunnel was maintained at 5 cm/sec. At the start of testing, the velocity was increased to 10 cm/sec for 15 minutes. If the fish swam the entire 15 minutes, the speed was increased in increments of 10 cm/s per 15 minutes until exhaustion. Exhaustion was defined as the point where a fish could no longer maintain swimming position and was pushed against the back grill of the working section of the tunnel. Individual fish were not retested in order to prevent any training effect. This process was repeated for each temperature and turbidity treatment. We used the above procedure to determine critical swimming speeds (U_{crit}) using the following equation:

$$U_{crit} = u_1 + (t_1/t_2)xu_2$$

where u_1 is the highest speed maintained for the prescribed time period, u_2 is the speed increment, t_1 is the length of time the fish swam at the fatigue speed, and t_2 is the prescribed period of swimming.

Acclimation temperature was set at 22 or 28°C and was controlled through the placement of aquarium heaters (Second Nature: Acura 1000) within the tunnel and in the

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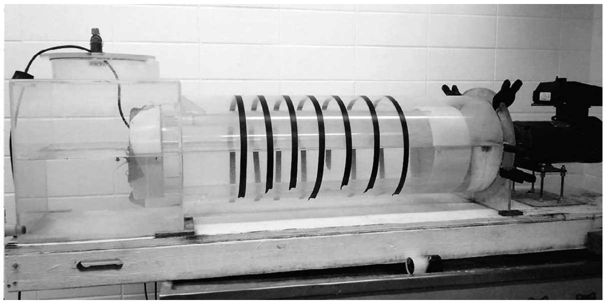

Fig. 1. Blazka et al. (1960) swim tunnel—half full. To the right of the picture is the motor that provides the current. To the left is the cap on the end of the swim tunnel with the flow meter attached.

holding tank. The heater in the swim tunnel was removed prior to testing to reduce water flow interference, but the temperature was checked with a thermometer (Fisher Scientific) after each trial to make certain temperature did not change during testing.

Turbidity was increased by mixing collected clay sediment (with an average particle size of 40.35 μm) with water in the swim tunnel to obtain 10, 20, and 30 NTU. Clear water was used as the base level of turbidity (0 NTU). Turbidity was measured with a Hach Turbidometer (model #2100A). Swimming performance at each level of turbidity was measured at 22°C. After completion of all swimming trials, temperature was increased to 28°C and performance at each turbidity level was tested again.

To address the possibility that reduced light levels caused by increased turbidity may result in altered swimming performance, separate tests were conducted. For these tests, fish performance was measured in clear water at an illumination of 0.32 lm/m^2, thus mimicking the reduced visibility in the higher turbidity trials. Reduced illumination was accomplished by using indirect lighting provided by a single fluorescent lamp in a darkened room. Otherwise the performance testing procedure was the same as that of the other group trials.

To estimate Golden Shiner swimming efficiency, we used the metabolic rate relationship reported by Beecham et al. (2009):

$$MR = 0.8x + 0131$$

where MR equals metabolic rate in mg O_2 $g^{-1}h^{-1}$ and x = swimming speed in cm s^{-1} to estimate oxygen consumption at each critical swimming speed. We used an oxycalorific coefficient of 3.25 cal mg O_2^{-1} to convert those oxygen consumption values to caloric consumption and to calculate total cost of transport in cal $g^{-1}km^{-1}$.

Data analysis.—Fifteen-minute critical swimming speeds were calculated as in Plaut (2001). Data were analyzed with paired t-tests and Kruskal-Wallis tests, where appropriate, using Microsoft Office Excel ver. 2010 (Microsoft Corp., Redmond, WA; http://office.microsoft.com/en-us/excel) and JMP ver. 7.0 (SAS Institute, Inc., Cary, NC; http://www.jmp.com). A *P*-value of <0.05 was required for all significance testing.

RESULTS

Swimming performance testing revealed that critical swimming speeds increased significantly (K-W, $F_{1,3} = 89.58$, $P \ll 0.01$) with increasing turbidity values (Fig. 2). Average critical swimming speeds increased from 51.03 cm/s at 0 NTU to 79.84 cm/s at 30 NTU. There was no significant (K-W, $F_{1,2} = 0.21$, $P > 0.05$) effect of temperature on critical swimming speed at any turbidity level, with a difference in mean U_{crit} between the two temperatures of 1.01 cm/s. No difference in critical swimming speed ($t(4) = -0.02$, $P > 0.05$) was detected between treatments for tests done in clear water with full illumination and in reduced illumination, with a difference in mean U_{crit} between the two light conditions of 0.08 cm/s.

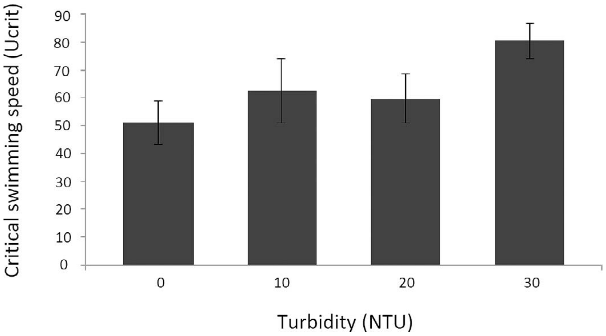

Fig. 2. Golden Shiner critical swimming speeds versus turbidity (NTU). Sample sizes for each treatment group are 0 NTU = 60, 10 NTU = 61, 20 NTU = 60, and 30 NTU = 58.

Oxygen consumption was estimated to be between about 0.18 and 0.2 mg O_2 $g^{-1}h^{-1}$ and caloric consumption was about 0.56 to 0.63 cal $g^{-1}h^{-1}$. Using these values cost of transport was estimated to be about 0.21 to 0.3 cal $g^{-1}km^{-1}$ (Fig. 3).

DISCUSSION

Despite the numerous studies that can be found testifying to the influence of temperature on critical swimming speed, it was not shown to have an effect in this study. This is not entirely surprising as the levels chosen were not extreme or widely varied. The temperature differences were intended to add a potential factor of interest to the testing process, and in the absence of a significant effect, turbidity remains the focus of the study.

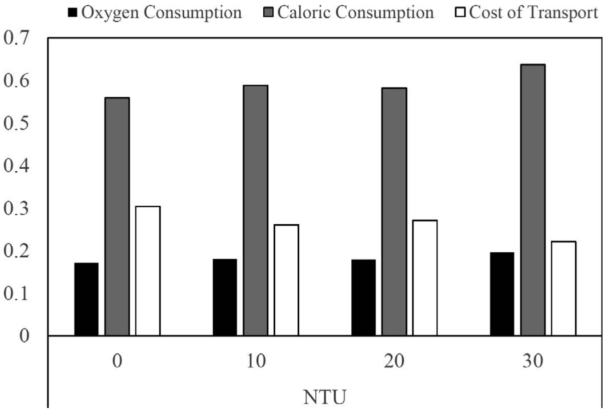

Fig. 3. The effect of turbidity (NTU) on Golden Shiner oxygen consumption (mg O_2 $g^{-1}h^{-1}$), caloric consumption (cal $g^{-1}h^{-1}$), and cost of transport (cal $g^{-1}km^{-1}$).

While not as extensively covered as temperature, turbidity has been shown to strongly influence fish condition and swimming behavior (Wilson et al., 2010). Specific studies on prolonged effects have touched on turbidity's effect on spawning habits, particularly for substrate spawners (Henley et al., 2000), courtship behavior (Engstrom and Candolin, 2007; Candolin et al., 2008), and the intensity of sexual selection (Seehausen et al., 1997; Jarvenpaa and Lindstrom, 2004). Turbidity also has been shown to reduce growth in Steelhead Trout (*Salmo gairdneri*) and Coho Salmon (*Oncorhynchus kisutch*; Sigler et al., 1984), and prolonged exposure to suspended sediment has been shown to increase mortality in numerous species (Newcombe, 1994; Newcombe and Jensen, 1996).

The majority of studies testing the acute effects of turbidity have considered its role in altering predator-prey interactions and general feeding behavior. Because turbidity has the potential to alter visual and olfactory cues (Domenici et al., 2007), it can alter the advantages held by either the predator or the prey, depending on the effects on their respective detection abilities. Changes in turbidity have been shown to alter prey choice (Carter et al., 2010), alter prey capture success (Robertis et al., 2003), reduce foraging success in Rainbow Trout (Wolter and Arlinghaus, 2003), and alter prey search behavior in Cod (*Gadus morhua*; Domenici et al., 2007).

Due to the volume of studies detailing the largely negative influence of turbidity on fish physiology and behavior, the results of this study—that turbidity may enhance critical swimming speeds—were unexpected. It is possible that the reduction in visibility caused by increasing turbidity may have had a calming effect similar to that reported by Boyd and Parsons (1998); however, the results of the test to determine the effect of a low illumination of 0.32 lm/m^2 on critical swimming speed revealed no significant effect.

We suggest that a hydrodynamic effect may be the most likely explanation for the increase in performance observed in this study. Fish must overcome drag force in order to move forward in the water. The total drag a fish experiences while swimming is composed of both form and frictional drag. Frictional drag refers to the transfer of momentum from the surface of the fish to the water that is in contact with that surface, and is exacerbated by turbulent flow. There is evidence to suggest that suspended solid particulates have a dampening effect on turbulent fluctuations, causing a decrease in transverse momentum transport (Patterson et al., 1969). In a study measuring the drag reduction potential of various particulate suspensions, it was found that nearly all concentrations of solids in water reduced drag by some measure, and a suspension of clay decreased drag up to 57% (Zandi, 1967). We propose that the phenomenon observed in this study may be caused by suspended particulates dampening turbulent fluctuations in the boundary layer around the fish, encouraging laminar flow, reducing frictional drag, and increasing critical swimming speed.

The apparent increase in critical swimming speed at the tested turbidity levels would result in an increase in swimming efficiency. Beecham et al. (2009) reported that the speed at which similarly sized Golden Shiner swim most efficiently was about 40 cm/s where cost of transport was minimized (cost of transport $= 0.36$ cal g^{-1}km^{-1}). However, our work suggests that a Golden Shiner can increase swimming efficiency by a significant percentage by taking advantage of turbid water conditions. In this study, the lowest cost of transport (0.221 cal g^{-1}km^{-1}) was observed when swimming at approximately 80 cm/s (the critical swimming speed) and 30 NTU turbidity (Fig. 3). Based on these estimates, a shiner swimming in turbid waters would enjoy a 38.6% caloric savings. It is worth noting that the critical swimming speed is the maximum aerobic speed and may not necessarily be the speed at which minimum cost of transport is observed. In fact, it would be reasonable to predict that even greater swimming efficiency would be observed at 30 NTU and a speed below the critical swimming speed.

The results presented in this paper suggest that fishes and other mobile aquatic organisms moving through slightly turbid waters may experience an increase in swimming ability and efficiency. This effect is likely to disappear at higher turbidities because of the documented deleterious effects of turbidity on gill function (Bruton, 1985) as well as increases in total immunoreactive corticosteroid (IRC) levels (Sutherland et al., 2008). However, at the highest turbidity levels reported in this paper, Golden Shiner experienced a 56.5% increase in critical swimming speed over controls swimming in clear water. It is worth noting that the increase in critical swimming speed reported here is very similar to the reduction in drag (57%) caused by a clay suspension in pipe flow reported by Zandi (1967).

The turbidity-mediated increase in swimming performance and efficiency observed for the Golden Shiner may be unique to this species. Its small size, its shape, or perhaps other as yet undescribed species-specific characteristics might make it uniquely adapted to turbid waters. It is worth noting that in the one study found on increased turbidity on pure swimming capacity, this pattern was observed (Gradall and Swenson, 1982). The cyprinid species, Creek Chub, preferred highly turbid water (56.6 formazin turbidity units-FTU) over moderately turbid water (5.8 FTU), but the salmonid species, Brook Trout, did not show a preference. But in moderately turbid waters, both species were more active, and used overhead cover less, than in clear water.

If the effect observed is indeed a hydrodynamic one that can be applied across other species, the results suggest some interesting biological ramifications. For instance, it may be advantageous for migrating fishes to choose to swim in the turbid waters that can sometimes be found close to the sediment-water interface. The energy savings associated with this effect would mean that a migrating fish may be at a selective advantage when swimming in waters that have moderate levels of turbidity. Similarly, smaller fishes may stay in more turbid environments (river and lake bottoms and edges) not only for shelter, but for the energy savings from slightly increased turbidity levels on feeding and evasive maneuvers. An interesting question going forward would be to determine if the effect of turbidity on critical swimming speed is proportional to the size of the fish, or if this is only a phenomenon experienced by smaller fishes similar to Golden Shiner. If the latter is true, there may be implications for escape behavior by prey/forage fishes, where a more turbid route is preferable. Because the drag-reducing capabilities of suspended particles has rarely been discussed in the context of biological systems, the potential for expanding on these results warrants further study.

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