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Context-dependent responses to turbulence for an anguilliform swimming fish, Pacific lamprey, during passage of an experimental vertical-slot weir

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ABSTRACT

Fish passage systems (fishways) have become the most common mitigation tool for improving the connectivity of migratory fish populations in ecosystems with barriers to movement. Because fishways often have high-velocity and high-turbulence environments, fish should seek low-energy movement paths during passage. We tested this hypothesis by analyzing the swimming paths of 90 adult Pacific lamprey (*Entosphenus tridentatus*) in response to hydraulic conditions when passing a vertical-slot weir in an experimental fishway. Varying hydraulic conditions were achieved by manipulating three variables: water velocity (1.2, 1.8, 2.4 m/s), vertical-slot length (0.33 m, 0.66 m, 1.00 m), and presence or absence of a turbulence-inducing structure. Turbulence parameters, such as turbulent kinetic energy (*TKE*), were quantified using an Acoustic Doppler Velocimeter (ADV). Pacific lamprey exhibited context-dependent behaviors in response to turbulence whereby lamprey were more likely to move towards areas of lower turbulence along their swimming paths, but only as the surrounding turbulence within the vertical-slot increased. In contrast, when the surrounding turbulence within the vertical-slot was low, Pacific lamprey became more likely to move towards areas of higher turbulence. The 'turbulence-avoidance' behaviors likely allowed passage of the hydraulic obstacle by reducing energy expenditure or physiological stress, while the 'turbulence-attraction' behaviors may have resulted from lamprey using turbulence as a mechanism for upstream orientation. Overall, our results provide new insight into how fish may use turbulence as an important sensory modality for perceiving the aquatic environment.

1. Introduction

Evaluating how fish respond to their hydraulic environment can be challenging because fish behavior is often as dynamic as the environment. The biological consequences of hydraulic parameters can often be a "double-edged" sword with both positive and negative consequences (Liao 2007; Lacey et al., 2012). Water velocity, for example, has been frequently cited as an important factor that affects swimming performance and limits upstream distribution because passing through high velocities requires intensive energy use or may exceed fish swimming speed (Haro et al., 2004; Rodriguez et al., 2006; Sanz-Ronda et al., 2015). Turbulence also negatively influences swimming performance because increased work is required to traverse chaotic flows (Hinch and Rand 1998; Enders et al., 2003; Hockley et al., 2013). Notably, both water velocity and turbulence can also positively influence fish behavior by creating attraction cues (i.e., rheotaxis; Bunt et al., 2012; Silva et al., 2012), increasing individual motivation (Castro-Santos 2004), and providing potential energy to assist in upstream propulsion in complex flows (Lindberg et al., 2015). This presents an interesting trade-off for both fish and fishway designers, where hydraulic conditions have to be balanced between potential physiological limitations and the necessary sensory cues for upstream orientation.

The migration corridors for many riverine fish species have been impounded and blocked through the construction of dams. The primary solution for maintaining connectivity of river corridors has been the development of fish passage systems, or fishways (Roscoe and Hinch 2010; Bunt et al., 2012; Noonan et al., 2012). Fishways typically create environments of high velocity and turbulence, which are necessary to compensate for the often large head differential that occurs at these dams. As a result, many of

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