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Behavioural response of juvenile Chinook salmon *Oncorhynchus tshawytscha* during a sudden temperature increase and implications for survival

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ABSTRACT

- Juvenile Chinook salmon *Oncorhynchus tshawytscha* survival and behaviour were evaluated during a temperature increase from 8.8 to 23.2 °C.
- Relatively little mortality (12%) occurred, which was unexpected.
- The percent of fish with an active swimming behaviour increased from 26% to 93% and opercular beat rates increased from 76 to 159 beats per minute.
- Although sublethal in the laboratory, thermal stress was likely incurred by juvenile salmon in this study and the associated behavioural changes may increase predation potential in the wild.

1. Introduction

Water temperature is a critical factor contributing to the behaviour and survival of fishes. Poikilothermic fishes are directly dependent on water temperature to regulate internal body temperature and to control physiological processes necessary for survival (Moyle and Cech, 2000; Logue et al., 1995). Water temperatures that are near the edge of a species' thermal tolerance zone can cause thermal stress, which may result in direct mortality (Clapp et al., 1997) or sublethal effects that increase the probability of predation (Sylvester, 1972; Coutant, 1973; Yocom and Edsall, 1974; Deacutis, 1978; Fuiman, 1991; Mesa et al., 2002; Logue et al., 1995).

Thermal stress on fishes occurs naturally; however, anthropogenic modifications to aquatic systems throughout the world likely increase thermal stress on fish. Electric power plants (e.g., nuclear or fossil-fuel) use water for cooling during power generation and release heated water back into water bodies, creating a thermal environment that can lead to increased predation potential on fish (Sylvester, 1972; Coutant, 1973; Yocom and Edsall, 1974). Hydroelectric dams create unique riverine thermal environments, which can affect fish by degrading cold water refugia in reservoirs (Sauter et al., 2001) and increasing temperatures in the river reach immediately downstream of the dam (Hamblin and McAdam, 2003).

Snake River fall Chinook salmon *Oncorhynchus tshawytscha*, a threatened sub-species under the United States Endangered Species Act (NMFS, 1992), experience environmental conditions that have been altered dramatically by hydroelectric dams in the past 50 years. Hydroelectric development in the Snake River basin has affected the life history of Snake River fall Chinook salmon (Dauble and Geist, 2000; Venditti et al., 2000; Dauble et al., 2003), but also has provided an opportunity to manage summer water temperatures in the warm and arid lower Snake River Basin when juvenile Chinook salmon are emigrating. Cool water releases by Dworshak Dam on the North Fork of the Clearwater River (a tributary of the Snake River) during summer have the intended effect of lowering Snake River water temperatures to improve juvenile salmon survival as they emigrate through this section of river on their way to the ocean (Tiffan et al., 2003). Because of this practice, the Clearwater River can be up to 15 °C cooler than the Snake River at the confluence area during late summer (Cook et al., 2006; USGS, 2009). The temperature difference between the cooler Clearwater River and the warmer Snake River at the confluence zone may negatively affect juvenile salmon survival if the fish are unable to acclimate to this large temperature difference.

To better understand how juvenile fall Chinook salmon might be affected as they migrate from the relatively cold Clearwater River into the much warmer Snake River, thermal challenges were performed to simulate fish migration through the confluence during late summer when the temperature difference can be as much as 15 °C. It was presumed that some emigrating salmon migrate through the temperature transition zone in as little as 1 h based on unpublished migration data from tagged juvenile salmon in this area. The overall goal of this study was to determine the effects of this relatively rapid water temperature increase on the survival and behaviour of juvenile salmon. It was

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hypothesized that the temperature increase would result in high mortality based on previous research of juvenile Chinook salmon temperature tolerance (Brett, 1952; Mesa et al., 2002). Specific objectives were to: (1) quantify survival during observation periods up to 5 days following the temperature increase and (2) evaluate fish behaviour before and after the temperature increase. The 1 h change in temperature and subsequent days of exposure to the high temperature chosen was considered a worst-case scenario that juvenile salmon might encounter in the wild.

2. Materials and methods

Juvenile fall Chinook salmons were captured in the Hells Canyon Reach of the Snake River at Pine Bar (366 km upstream of the confluence with the Columbia River) and Russell Bar (354 km upstream of the Columbia River) using 0.32 cm mesh beach seines. The captured fish were transported to the Pacific Northwest National Laboratory (PNNL) in Richland, Washington in spring 2008. Oxygen was supplied during transit. Test fish were held in an 830 l outdoor circular holding tank supplied with 56 l min^{-1} of chilled well water (10 °C) for two months prior to the thermal challenges. Fish were fed to satiation twice per day with pellet Bio Diet Grower food (Bio-Oregon, Inc., Longview, WA, USA). Handling of fish was permitted and approved by the Institutional Animal Care and Use Committee of the Pacific Northwest National Laboratory under protocol 2008–2012.

All fish were transferred to a partitioned 720 l living stream trough (Frigid Units, Inc., Toledo, OH, USA) inside the Aquatic Research Laboratory at PNNL and acclimated to chilled well water (8.8 °C) for at least two weeks prior to the thermal challenges. Three 37 l glass aquaria (50.8 cm × 30.5 cm × 25.4 cm) were used as test chambers. Water was delivered to each test chamber from an elevated head tank (113 l) at approximately 7.2 l min^{-1}; test chamber volume was replaced approximately once every 4 min. Water level in the test chamber was maintained with a screened overflow. Temperature within each head tank was controlled by a computer program written in CRBasic and implemented via LoggerNet (Campbell Scientific Inc, Logan, UT, USA) that operated two solenoid valves (Irritrol Utra Flow 700 1; Irritrol Systems, Riverside, CA, USA) and controlled delivery of chilled well water (8 °C) or heated well water (24 °C) as needed to maintain target temperatures. Individual thermometers logged temperature in each aquarium during the experiment. Actual temperatures were normally ± 0.2 °C of target temperatures. Measurements of the well water chemical composition (e.g., alkalinity, chloride, iron, etc.) were taken throughout the experiment and all were within the limits set by the Washington Department of Fish and Wildlife for fish hatchery aquaculture. Dissolved oxygen of the well water was 9.48 mg l^{-1} at 17.7 °C throughout the experiment.

The evening before each of two trials, fish from the trough were anesthetized with 0.05 g l^{-1} tricaine methanesulfonate (MS-222), weighed (nearest 1 mg) and measured (L_F; nearest 1 mm), and transferred to test chambers that were the same temperature as the trough (8.8 °C). Sixty fish (10 in each test chamber for two trials) were used. Chinook salmon fork length varied from 60 to 96 mm, and weight varied from 2.2 to 10.1 g (there were no statistical differences in fish length or mass between test chambers (mean fork length =81 mm, ANOVA, d.f.=5, 54, P=0.98; mean weight=5.3 g, ANOVA, d.f.=5, 54, P=0.99). Fish were held overnight in the test chambers (approximately 18 h of acclimation) and the thermal challenge was initiated the following morning at about 1000 h. The computer program automatically raised the water temperature in each test chamber to 23.2 °C over an 84 min period (mean of about 0.17 °C min^{-1}). Water temperature was maintained at 23.2 °C for a period of 5 days after the temperature increase. The experiment was conducted twice (in three tanks each time), for a total of six replicate tanks with 10 fish in each tank.

Behavioural data and opercular beat rates (beats per min) were obtained from video recordings using high-resolution cameras (Ikegami Model ICD-4224, Ikegama Electronics, Maywood, NJ, USA) connected to digital 8 mm recorders (Sony Model GV-D800, Sony Electronics, New York, NY, USA). High-resolution video was recorded for a 3 h period starting 1 h before the temperature increase and for two 10 min intervals (i.e., morning and afternoon) each day following the temperature increase. A separate continuous digital video recording system (OpenEye Model HDDRX, OpenEye Electronics, Liberty Lake, WA, USA) was used to document behaviour and any mortality between the high-resolution recordings.

Fish behaviour and opercular beat rates were quantified during tape reviews on a high-resolution monitor. Observation periods used to quantify opercular beats occurred 1 h before the temperature increase (0 min), during the increase (100 min), 36 min after the increase (180 min), 3 days after the increase, and 5 days after the increase. The opercular beat rates of up to 5 fish in each aquarium were quantified by tallying opercular beats during the 60 s observation period. Fish opercular movements not observable for the entire 60 s were extrapolated from the length of observation (e.g., 30 opercular beats in 30 s equaled 60 opercular beats per min). The same observation periods (i.e., 0 min, 100 min, 180 min, 3 days after, and 5 days after) were used for behavioural analyses. Fish behaviours categorized concurrently during the 60 s observation periods included swimming behaviour (i.e., active, darting, and stationary; defined below), vertical position within the tank (i.e., bottom, middle, top, or combination), horizontal position within the tank (i.e., left, middle, right, or combination), and fish posture (i.e., equilibrium or non-equilibrium). Vertical and horizontal positions of fish within the tank were quantified to evaluate the spatial scale of swimming behaviours because the swimming behaviour metric alone did not incorporate spatial location. An "active" swimming behaviour was defined as a fish moving a distance more than one body length in a 5 s period and "stationary" fish moved less than one body length in a 5 s period. Fish with a "darting" swimming behaviour met the "active" swimming behaviour criterion but were differentiated by an agitated, downward-angled swimming (i.e., snout toward the tank bottom). An "equilibrium" posture was defined as fish with body parallel to the bottom of the tank, and a "non-equilibrium" posture was classified when the snout of a fish pointed up or down.

All statistical analyses were performed using JMP statistical software (version 7, SAS Institute, Inc., Cary, NC, USA) with a significance level of alpha=0.05. Observations on individual fish were grouped by tank because individual fish were unable to be differentiated and thus, the experimental unit was each aquarium. Opercular beat rate and equilibrium posture comparisons were made using a one-way analysis of variance (ANOVA) with an experiment-wise alpha level of 0.05. A two-way ANOVA was used to test the significance of main effects and interaction effects of swimming behaviour and fish location with an experiment-wise alpha level of 0.05. Pairwise differences were determined using the Tukey–Kramer honestly significant difference test for any significant ANOVA. Repeated measures analyses were not possible because fish were not individually identifiable and because a subset of fish in each aquarium was observed. Statistical assumptions (i.e., homogeneity of variances and normality) were verified before each test.

3. Results

No juvenile Chinook salmon mortalities occurred before, during, or within 4 h after the temperature increase from 8.8 to