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低水温による海水移行後サケ稚魚の運動性低下（短報）

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北海道立総合研究機構さけます・内水面水産試験場

Low water temperatures decrease the motility of chum salmon fry after seawater transfer (short paper)

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The effects of low water temperature on the motility of chum salmon *Oncorhynchus keta* fry after seawater transfer were examined in a rearing experiment. After freshwater rearing, chum salmon were reared in artificial seawater at 2 °C, 4 °C, and 8 °C for 3 days. After rearing in seawater, the motion distance (MD), nearest neighbor distance (NND), and separation angle (SA) were measured via video analysis. The MD was 15% lower at 4 °C and 50% lower at 2 °C than at 8 °C, which is the optimum water temperature range for chum salmon. NND was markedly greater in the 2 °C treatment. SA indicated the maintenance of the schooling structure and no significant differences among the three treatments were observed. These results suggest that the motility of chum salmon after seawater transfer is reduced at low water temperatures.

キーワード：nearest neighbor distance, *Oncorhynchus keta*, separation angle, video analysis

Temperature is an important environmental factor that affect animal physiology, behavior, and geographic distribution (Magnuson *et al.*, 1979). In fish, the water temperature also affects ontogeny, oxygen consumption, growth rate, and maturation (Watanabe, 2017). However, the optimal water temperature or temperature preference differs among fish species (Tsuchida, 2002), and the water temperature preference in salmonids is closely associated with feeding, metabolism, and growth (Brett, 1971；Webster and Dill,2006；Torao, 2022). Thus, water temperature may be a major environmental factor limiting salmon behavior.

Chum salmon (*Oncorhynchus keta*) is an anadromous fish, and their juveniles descend to estuaries in a relatively short time after their emergence from spawning redds in rivers (Kobayashi and Ishikawa, 1964；Mayama *et al.*, 1983), where it transitions to marine life. Early marine life is considered a major mortality period for salmon (*e.g.*, Parker, 1962；Healey, 1982；Bax, 1983；Fukuwaka and Suzuki, 2000；Willette *et al.*, 2001；Mueter *et al.*, 2002). Several studies have reported that the body size and growth rate are closely related to salmonid mortality during this period (Healey, 1982；Saito *et al.*, 2011；Tucker *et al.*, 2016；Honda *et al.*, 2017, 2020；Hasegawa *et al.*, 2021).

Several coastal field studies have indicated that the distribution and growth of chum salmon fry/juveniles during their early marine life are strongly influenced by sea surface temperature (SST) (*e.g.*, Mayama and Ishida, 2003；Nagata *et al.*, 2005, 2007). Along the Hokkaido coast, juvenile chum salmon are distributed in the SST range of 5 °C–13 °C, with good growth occurring between 8 and 13 °C (Irie, 1990；Kasugai *et al.*, 2012;Seki, 2013). Conversely, a low SST of <5 °C may limit the migration and depress the growth of salmon fry (Nagata *et al.*, 2005；Nagata *et al.*, 2008；Kasugai *et al.*, 2012). As juvenile chum salmon grow, their habitats expand from the coastal to nearshore waters. However, low water temperatures hinder habitat selection.

Low water temperatures generally reduce the metabolism, feeding rate, and growth of teleosts fish (Brett, 1979；Jobling, 1994). This phenomenon has also been observed in chum salmon fry (Torao, 2022). Low water temperatures during early

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ocean life are believed to limit the migration, distribution, and growth of juvenile chum salmon; however, their impact on individual behavior remains unclear.

Changes in behavioral activity and schooling behavior are expected if low ocean temperatures affect the behavior of salmon fry. The swimming and schooling behaviors of salmon fry can be quantified using video analysis (Torao *et al*., 2020, 2023). Therefore, this study used video analysis to examine whether salmon fry activity was affected by low water temperatures.

MATERIALS AND METHODS

Fish stock and rearing conditions Experiments were conducted in 2018 using a 2017-year class of chum salmon fry at the rearing facility of the Salmon and Freshwater Fisheries Research Institute (SFFRI) of the Hokkaido Research Organization. Fish were obtained from artificially inseminated eggs at the Chitose River Hatchery of the Nihon Kai Salmon Enhancement Program Association on October 30, 2017. Fertilized eggs were kept at the Chitose River Hatchery, transported to the SFFRI rearing facility on December 13, and incubated in a vertical incubation system until emergence. On March 1, 2018, 1000 fry were moved from the incubators and placed in a plastic rearing chamber (length × width × height: 3.26 × 0.33 × 0.33 m) supplied with a constant flow of fresh water. Water temperature during the rearing period averaged 8.2 °C (range, 7.4 °C–8.5 °C). The fry were fed a commercial diet (Alpha Crumble EX-Masu #1 and #2; Nosan Co., Ltd., Yokohama, Japan) six times a day at 3.5% of their body weight until seawater transfer. Three fish bowls each filled with 10 L of artificial seawater were placed in water temperature control tanks at 2 °C, 4 °C, and 8 °C. Aerated water was used as artificial seawater in the fish bowls. On April 11, ten freshwater-reared salmon fry were placed in each bowl. After 3 days of seawater rearing, the fry were used for behavioral measurements on April 14.

Video recording of chum salmon behavior Behavioral activity was measured using video recordings. A circular polyethylene tank (diameter, 48 cm; experimental tank) was used to record the behavior of the chum salmon fry. Artificial seawater, adjusted to the water temperature for seawater rearing, was added to the experimental tank. The water depth of the experimental tank was maintained at 3 cm to restrict fry behavior in two dimensions. The amount of water in the experimental tank was approximately 5.7 L. Video recordings were conducted in a low-temperature room. Iced gel packs were placed under the experimental tank to maintain the water temperature. Ten fry from three fish bowls at each seawater temperature were randomly transferred to the experimental tank and acclimated for 5 min. The fry behavior was then video-recorded for 5 min using a digital camera (PENTAX Optio WG-4 GPS, Ricoh Imaging Co., Ltd., Tokyo, Japan) set above the experimental tank. All fry used in these trials were anesthetized after each recording and fork length (FL; mm) and body weight (BW; g) were individually measured. Their condition factor (CF) was calculated as follows: $CF = (10^6 \times BW)/FL^3$.

Video Analysis Three parameters were used as behavioral activity indices: motion distance (MD), nearest neighbor distance (NND), and separation angle (SA). For MD measurements, the free Windows software "Undo-kun for Windows 2.0" (http://www.vector.co.jp/download/file/win95/edu/fh537268.html, March 31, 2020) was used to measure the distance and calculate the movement speed from the coordinates of the video images. The coordinates were recorded by clicking on the fish snout on the screen. The measurement interval was every 15 frames (approximately 0.25 s), and the distances between the obtained coordinates were calculated. Preliminary analysis revealed that the distance moved by the chum fry during the first 30 s of recording was representative of the entire recording time. Therefore, the distance measured during 30 s was converted to the distance moved per minute, and this value was defined as the MD. The MD was expressed as the value (cm) divided by the FL of the individual measured on the image (×FL).

NND is an indicator of schooling behavior; the shorter the NND, the stronger the schooling structure (Masuda, 2010). NND was measured following that of Torao (2023). That is, a still image was extracted every minute from the recorded video, and five still images were obtained per experimental temperature treatment. For each image, the distance between the nearest neighbors of each individual was measured using ImageJ (Schneider *et al*., 2012), and the average value was used as the NND for each temperature treatment. The NND was expressed as the value (mm) divided by the FL of the individual measured on the image (×FL).

SA is defined as the angle between the body axes of the focal and neighboring fish (Masuda *et al*., 2003) and indicates the parallel orientation of individuals constituting the school. SA was the average angle between the body axes of all individuals measured using ImageJ for the above still images.

Statistical Analysis One-way analysis of variance (ANOVA) was conducted on the FL, BW, and CF of chum salmon fry to test for body size differences after water temperature treatment. The Tukey–Kramer test was used to compare MD, NND, and SA across the three seawater temperature treatment intervals for multiple comparisons. The SA in each treatment was also compared to 90°, the value expected in a random distribution, using Student's t-test. All statistical analyses were performed using R statistical computing package v4.2.2(R Core Team, 2022).

RESULTS

No differences were observed in the body size of the chum salmon fry after the 3-day seawater rearing treatment (Table 1). The mean FL of fry in the 2 °C, 4 °C, and 8 °C treatments was 47.1, 48.6, and 47.1 mm, respectively, without significant differences (Tukey–Kramer test, $p > 0.05$). BW was slightly higher in the 4 °C group (0.73, 0.82, and 0.73 g, in the 2 °C, 4 °C, and 8 °C treatments, respectively), but without significant differences, and CF were similar (Tukey–Kramer test, $p > 0.05$). The body size of all groups was <1 g, which is considered an appropriate release size (Nogawa and Yagisawa, 2011); however, no mortality occurred during seawater rearing.

The mean MD was 56.4 FL at 2 °C, 93.9 FL at 4 °C, and 114.1 FL at 8° C; the lower the water temperature, the shorter the MD (Fig. 1A). The MD of the 2 °C treatment was 50% smaller than that of the 8 °C treatment, and that of the 4 °C treatment was 15% smaller. The 2 °C treatment was significantly different from the 4 °C and 8 °C treatments (Tukey–Kramer test, $p < 0.001$). No significant difference was observed between the MD of 4 °C and 8 °C treatments (Tukey–Kramer test, $p > 0.05$).

NND (×FL), an index of schooling structure, was 1.7, 1.2, and 1.3 in the 2 °C, 4 °C, and 8 °C treatments, respectively (Fig. 1B). The NND in the 2 °C treatment was significantly larger than that in the 4 °C treatment (Tukey–Kramer test, $p < 0.01$). No significant differences were observed between the 2 °C and 8 °C and the 4 °C and 8 °C treatments (Tukey–Kramer test, $p > 0.05$).

Table 1 Fork length (FL), body weight (BW), and condition factor (CF) of chum salmon fry in the experimental groups at different seawater temperatures. All characteristics were not significantly different between water temperature treatments (Tukey–Kramer test, $p > 0.05$).

Date of Experiment	Treatment temperature in seawater	Mean ± SD		
		fork length (mm)	body weight (g)	condition factor
Apr. 14, 2018	2°C	47.1 ± 3.91	0.73 ± 0.17	6.90 ± 0.59
	4°C	48.6 ± 2.55	0.82 ± 0.16	7.09 ± 0.48
	8°C	47.1 ± 3.17	0.73 ± 0.16	6.94 ± 0.42

The mean SA values were 52.2°, 47.1°, and 41.4° for the 2 °C, 4 °C, and 8 °C treatments, respectively (Fig. 1C). Multiple comparisons revealed no significant differences in SA among the three treatment groups (Tukey–Kramer test, $p > 0.05$). Conversely, SA in all water temperature treatments was significantly different from the expected 90° in the absence of parallel orientation (Student's t-test, $p < 0.001$).

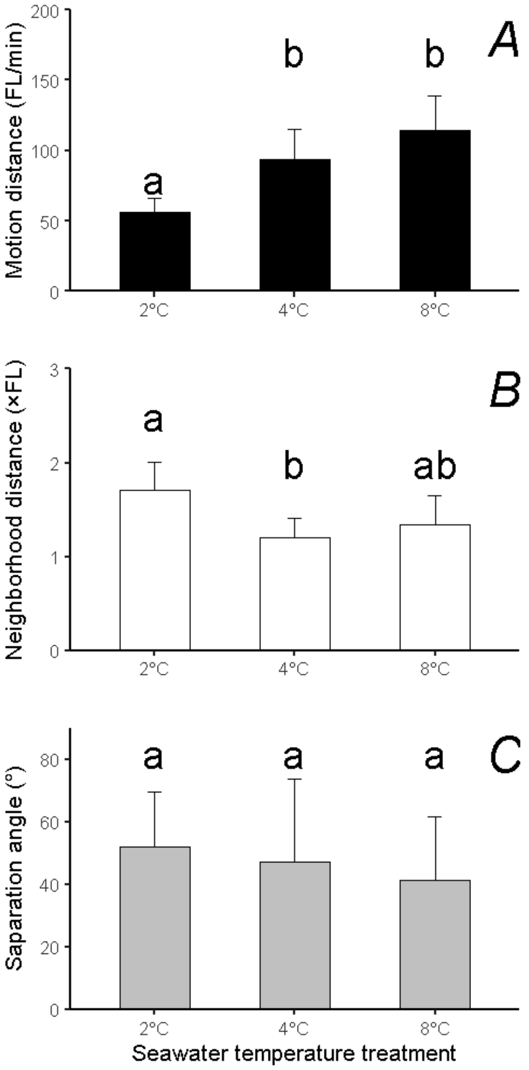

Fig. 1 (A) Motion distance (MD), (B) nearest neighborhood distance (NND), and (C) separation angle (SA) of chum salmon fry in different low-temperature seawater rearing treatments. Error bars indicate standard deviations ($n = 10$). Bars with different letters in the same panel are significantly different (Tukey–Kramer test, $p < 0.05$).

DISCUSSION

This study demonstrated that the motility of chum salmon fry after seawater transition was reduced in a low temperature environment. The effect of water temperature on burst swimming speed is generally small in fish but has a greater effect on sustained swimming speed (Brett, 1967 ; Wardle, 1980;Batty and Blaxter, 1992). The MD included in sustained swimming speed is likely to be sensitive to water temperature. SA, an indicator of the parallel orientation of individuals constituting the school, indicated that the school structure was maintained and no effect of water temperature was observed. Conversely, the large NND of 1.7 at 2 °C indicates that a very low water temperature may affect the retention of NND. NND was enlarged during fasting due to a decrease in inter-individuals following the behavior of chum salmon fry (Torao, 2023), and NND may be enlarged when fry conditions are poor. Even under low seawater temperatures, decreased behavioral activity may have reduced the subsequent behavior of individuals, resulting in the expansion of NND.

These changes in motility and school structure due to low water temperatures may increase the risk of predation in chum salmon fry. Swimming ability is one of the most important characteristics of fish survival (Plaut, 2001 ; Cano-Barbacil *et al*., 2020) that affects avoidance of predation, feeding, and migration to new habitats (Webb, 1994 ; Drucker, 1996 ; Plaut, 2001;Nelson *et al*., 2002). Water temperature is one of the main factors affecting swimming ability, and its effects and the optimum water temperature range vary among fish species (Beamish, 1978). Furthermore, low or high water temperatures outside the optimum water temperature range reduce swimming ability (Zeng *et al*., 2009). A low temperature of 2 °C could be considered outside the optimum water temperature range for motility of chum salmon fry. In addition, in many fish species, schooling is regarded as an anti-predator behavior, and the formation of schools is thought to have early detection of predators or dilution effects on predation risk (Masuda, 2010). Water temperature affects both the social behavior and energy expenditure of fish, with lower water temperatures leading to lower fish activity and more cohesive schools (Bartlini *et al*., 2015). Changes in school structure due to low water temperatures differed from those observed in chum salmon fry. Although there is still little evidence that low water temperature conditions increase predation on chum salmon fry in the field, reduced behavioral activity and changes in schooling behavior at low water temperatures may be detrimental to predator avoidance in terms of anti-predator behavior.

In hatchery programs, releasing chum salmon fry at 7 °C –11 °C SST is recommended to allow for their downstream migration period in the river after release (Nagata *et al*., 2007; Seki, 2013). However, salmon catches in Japan have continued to decline in recent years, despite continued hatchery releases (Miyakoshi *et al*., 2013). One possible reason for this is that climate change may have caused the SST to rise faster, shortening the optimal water temperature period for the growth of chum salmon in coastal and offshore areas (Saito and Miyakoshi, 2018 ; Kuroda *et al*., 2020). In response, hatchery release programs continue to search for the optimal release timing and size for chum salmon fry. Chum salmon need to grow to a FL of 7 cm (3 g body weight) and migrate offshore by the time water temperatures reach 13 °C, the upper limit of their distribution (Mayama, 1982). Low water temperatures immediately after sea entry may limit foraging behavior, resulting in slower growth rates in the coastal zone. In addition, when chum salmon fry enter the seawater at low temperatures, short-term fasting in freshwater suppresses their growth (Nakamura *et al*., 2019) and reduces swimming ability (Torao *et al*., 2021). Avoiding such growth and behavioral influences requires chum salmon fry to remain in good nutritional conditions until they enter the sea. Feeding fish oil-supplemented diets effectively in increases lipid accumulation in chum salmon fry (Murai *et al*., 1983) and has been conducted in some hatchery programs. The effects of feeding conditions and nutritional status on behavior at low water temperatures should be examined in the future. Water temperatures of <5 °C are not necessarily good for chum salmon fry. However, if the optimal water temperature period continues to decrease in the future, the release of salmon fry at lower water temperatures should be considered. The effects of low water temperature on the behavior of chum salmon fry should be clarified, and effective release methods should be considered.

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