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Avoidance of strobe lights by zooplankton

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Abstract

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Underwater strobe lights can influence the behavior and distribution of fishes and are increasingly used as a technique to divert fish away from water intake structures on dams. However, few studies examine how strobe lights may affect organisms other than targeted species. To gain insight on strobe lighting effects on nontarget invertebrates, we investigated whether underwater strobe lights influence zooplankton distributions and abundance in Lake Oahe, South Dakota. Zooplankton were collected using vertical tows at 3 discrete distances from an underwater strobe light to quantify the influence of light intensity on zooplankton density. Samples were collected from 3 different depth ranges (0–10 m, 10–20 m and 20–30 m) at <1 m, 15 m and ≥100 m distance intervals away from the strobe light. Copepods represented 67.2% and *Daphnia* spp. represented 23.3% of all zooplankton sampled from 17 August to 15 September 2004. Night time zooplankton densities significantly decreased in surface waters when strobe lights were activated. Copepods exhibited the greatest avoidance patterns, while *Daphnia* avoidance varied throughout sampling depths. These results indicate that zooplankton display negative phototaxic behavior to strobe lights and that researchers must be cognizant of potential effects to the ecosystem such as altering predator–prey interactions or affecting zooplankton distribution and growth.

Key words: behavior, deterrent, interactions, strobe lights, zooplankton

Strobe light technology is commonly used to modify fish behavior (Nemeth and Anderson 1992). Although responses of fishes to strobe lights can be variable (Popper and Carlson 1998, Bullen and Carlson 2003), strobe light technology has proven useful, particularly in salmonid diversion applications. While successful use of strobe lights often hinges on understanding abiotic and biotic factors that influence the effectiveness of underwater light as a fish deterrent technology (Popper and Carlson 1998, Bullen and Carlson 2003), we are unaware of any studies that examine the potential effects strobe lights pose to other biota that may be present.

Investigators who use underwater strobe lights are typically interested in deterring or repelling fish. For example, Johnson et al. (2001) successfully used strobe lights to vertically displace salmon smolts away from entering a culvert used to fill a navigation lock chamber. Maiolie et al. (2001) used strobe lights to deter kokanee salmon (*Oncorhynchus nerka*) away from water intake structures on the Dworshak Reservoir dam. Finally, Adams et al. (2001) used strobe lights to guide migratory salmonids away from turbines toward an alternative safe passage route.

Many zooplankton taxa are negatively phototaxic, as evidenced by diel vertical migration (DVM) behaviors. Although the ultimate factors responsible for DVM are not completely known, empirical data strongly suggest that predator avoidance plays a critical role (Zaret and Suffern 1976, Gliwicz 1986). Previous research has generally shown that zooplankton do not make DVM in the absence of predators (Dodson 1990). Light serves as the cue for triggering zooplankton migrations and also affects the amplitude if light levels are sufficiently high at night (Forward et al. 1984, Moore et al. 2000). For example, the light of a full moon affects the DVM of many species of zooplankton, displacing them to deeper waters where visually feeding predators cannot effectively feed (Gliwicz 1986, Moore et al. 2000).

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Because natural ambient light is the proximate stimulus for DVM, artificial light may have confounding affects on zooplankton distributions. Strobe lights have recently been evaluated as a possible solution for reducing entrainment of rainbow smelt (*Osmerus mordax*; Hamel et al. 2008). While strobe lights were successful at deterring rainbow smelt, our purpose in this study was to elucidate the effects strobe lights have on zooplankton distributions and local abundance and discuss the implications artificial light may have on the feeding ecology of primary and secondary consumers.

Methods

Strobe lights were deployed during summer 2004 on the lower portion of Lake Oahe, the largest of 4, main-stem reservoirs on the Missouri River in South Dakota. Water is released through the Lake Oahe dam by 7 intake structures, each containing 8 openings that are positioned toward the middle of the structure to facilitate deep-water releases. Throughout the study period, water depth was approximately 45 m at the intake structures, which corresponds to an approximate depth of 21 m for the intake openings. Each structure contains a 7.3 m dia steel-lined concrete tunnel that transports water to the powerhouse to power 1 of 7 Francis-type turbines (USACOE 1998).

With an average depth of 18.3 m, Lake Oahe supports a cool–coldwater fishery consisting mainly of walleye (*Sander vitreus*), Chinook salmon (*Oncorhynchus tshawytscha*) and smallmouth bass (*Micropterus dolomieu*). The reservoir surface area is 150,144 ha at full pool; 47,755 ha are classified as coldwater habitat, where water temperatures below the metalimnion are typically <15 C in August (Lott et al. 2002). Turbidity in the lower portion of Lake Oahe is relatively low and displayed an average Secchi disk reading of 5–6 m during this study.

A flashhead strobe light (Model AGL-FH 901, Flash Technology, Franklin, TN), consisting of 4 horizontal lights positioned at 90° intervals was used during zooplankton collections. The flashhead produced a flash rate of 450 flashes/min and had an approximate light intensity of 2634 lumens/flash. The light source was produced by xenon gas tubes, which emit broad spectrum white light (D. Jones, Flash Technology, Franklin, TN, pers. comm.). An anchored boat, equipped with a hydraulic winch, was used to lower the strobe light to a depth of 25 m. This depth corresponds to the thermocline and is the approximate proposed depth for installation of strobe lights near the Lake Oahe dam intake structures (Hamel et al. 2008).

Zooplankton were collected using stratified, vertical zooplankton tows on 5 dates from mid-August through mid-September 2004. Three diagonal transects were established at 120° angles perpendicular to the strobe light. The first of the 3 sites along each transect was located <1 m from the strobe light; the second site was located approximately 15 m away (at the outer peripheral region of the AGL-FH 901 strobe light; Hamel et al. 2008); and the third site was located at 100 m, beyond any observable light. Zooplankton were collected using a conical-shaped closing net (0.5 m dia), constructed of 150 μm mesh, at depths of 0–10 m (upper), 10–20 m (middle) and 20–30 m (lower) at the 3 distances along each transect. Therefore, there were 3 replicates for each depth zone (upper, middle and lower) at each site (<1 m, 15 m and >100 m) for a total of 27 samples. All sampling began after 45 min of darkness (i.e., after sunset) to ensure adequate time for zooplankton to migrate up the water column to the depth of the strobe light (25 m). Samples were immediately preserved in a 10% Lugols solution.

On 17 and 19 August 2004, zooplankton were sampled during 2 time periods (0 h and 5 h). Sampling was conducted in complete darkness (continuous control, without strobe light activation) to evaluate temporal changes in zooplankton abundance over a 5 h period. We used these data for comparisons with zooplankton densities during strobe light testing (below), which used a 5 h sampling interval to assess the influence of the strobe light. On 23 August, 31 August and 15 September 2004, strobe lights were deployed and zooplankton were collected during a control period (0 h, no light) followed by another collection after 5 h of strobe light exposure. Moon phases were recorded for each sampling date (Table 1).

In the laboratory, zooplankton were counted by diluting the sample to 50 mL and taking five 1-mL subsamples. Subsamples were placed in a counting wheel and enumerated under a dissecting microscope at 40× magnification (Wild Heerbrugg M3C). Organisms were identified to the lowest practical taxon, usually to genus. Copepods were separated into calanoid and cyclopoid copepods. Estimates of zooplankton density were expressed volumetrically as numbers per liter (n/L).

To detect temporal and spatial differences in densities of zooplankton, a repeated measures, mixed model analysis of

Table 1.-Moon phase, moon rise and set time (24-h clock) and illumination fraction for each sampling date.

Sampling Date	Moon phase	Moon rise	Moon set	Illumination fraction
17 Aug 2004	New moon	7:16	20:50	0.051
19 Aug 2004	Waxing crescent	9:34	21:28	0.178
23 Aug 2004	Waxing gibbous	14:34	23:18	0.592
31 Aug 2004	Full moon	20:23	7:42	0.939
15 Sep 2004	New moon	7:22	19:33	0.032

variance (ANOVA, autoregressive covariance structure) was used. Grouping factors included sample depth (0–10, 10–20 and 20–30 m), distance away from the strobe light (<1, 15 and 100 m) and time (0 and 5 h).

Results

Zooplankton composition

Eleven zooplankton genera were identified, including 8 Copepoda and 3 Cladoceran genera. Copepods represented 67.2% and *Daphnia* spp. represented 23.3% of all zooplankton sampled from 17 August to 15 September 2004. Thus, *Daphnia* spp. was used as the representative Cladoceran genera for statistical analysis. Copepods were combined into cyclopoid or calanoid groups for analysis.

Temporal changes in zooplankton abundance

There were no perceptible movement trends throughout the continuous control experiments. Zooplankton abundance typically remained constant throughout the sampling night or increased after the 5 h period. Data collected on 17 August showed that the time by depth interaction was significant only for cyclopoid copepods ($F = 9.04$; df = 2; $P < 0.01$). Cyclopoid copepod densities in the middle and lower samples were similar at 0 and 5 h; however, cyclopoid copepod densities decreased significantly ($t = 4.36$; $P < 0.01$; n= 9) in the upper stratum after 5 h. Mean density of daphnids and calanoid copepods in the upper, middle and lower depth strata were not significantly different after 5 h than mean densities detected at 0 h.

On 19 August 2004 the interaction between time and depth was significant for daphnids and calanoid and cyclopoid copepods ($F = 17.27, 4.09$, respectively; df = 2; $P < 0.05$). The mean density of daphnids increased significantly ($t = -9.02$; $P < 0.01$; n = 9) in the middle stratum after 5 h; however, mean densities were similar in the upper and lower strata after 0 and 5 h of complete darkness. Similarly, we observed a significant ($t = -3.10$; $P < 0.01$; n = 9) increase in calanoid densities in the middle strata, but samples in the upper and lower strata remained similar throughout the sampling period (0 to 5 h). The mean density of cyclopoid copepods increased significantly ($t = -2.42$; $P = 0.02$; n = 9) in the middle strata following 5 h of complete darkness, whereas densities in the upper and lower strata remained similar between 0 and 5 h of complete darkness.

Effects of strobe lights

The repeated measures ANOVA showed that distance away from the strobe light had no effect on zooplankton abundance (e.g., no main or interaction effects). We therefore removed this term from the model and used analysis of covariance to evaluate the effects of time and depth on zooplankton densities. Subsequent comparisons between times for each depth range were performed using t-tests. A Bonferonni correction was used to account for multiple comparisons ($\alpha = 0.016$).

Strobe light testing began on 23 August 2004. *Daphnia* spp. and cyclopoid copepods exhibited a significant interaction between time and depth ($F = 11.00, 4.91$, respectively; df = 2; $P < 0.05$). The mean density of daphnids in the upper strata (1.66 n/L ± 0.32; n= 9) significantly decreased (0.23 n/L ± 0.16; n = 9) following 5 h of strobe light illumination, ($t = 4.00$; $P < 0.01$; n = 9; Fig. 1). Daphnid density in the middle and lower samples were not significantly different from controls (i.e., 0 h). The mean density of calanoid copepods in the upper (1.75 n/L ± 0.28; n = 9), middle (1.13 n/L; ± 0.10; n = 9) and lower (0.67 n/L ± 0.18; n = 9) strata significantly decreased following 5 h of strobe light illumination ($P < 0.016$). The same pattern was observed for cyclopoid copepods; mean density in the upper (7.22 n/L ± 0.81; n = 9), middle (3.68 n/L ± 0.68; n = 9) and lower (3.34 n/L ± 0.89; n = 9) strata significantly decreased following 5 h of strobe light exposure ($P < 0.016$).

On 31 August 2004, there was a significant interaction between time and depth for *Daphnia* spp. and cyclopoid copepod densities ($F = 16.38, 47.04$, respectively; df = 2; $P < 0.05$). The density of daphnids in the upper sample (1.57 n/L ± 0.12; n = 9) decreased significantly (0.71 n/L ± 0.18; n = 9) after 5 h of strobe light illumination ($t = 4.36$; $P < 0.01$; n = 9). However, densities in the lower strata increased significantly ($t = -3.64$; $P < 0.01$; n = 9) after strobe lights were turned on (Fig. 1). Calanoid and cyclopoid copepods exhibited significant ($P < 0.016$) decreases in densities in all 3 strata following 5 h of strobe light exposure.

On 15 September 2004, daphnids, calanoid copepods and cyclopoid copepods exhibited a significant interaction between time and depth ($F = 19.33, 9.95$ and 0.56, respectively; df = 2; $P < 0.05$). *Daphnia* spp., calanoid and cyclopoid copepod densities significantly decreased at all depth intervals following 5 h of strobe light exposure ($P < 0.016$; Fig. 1).

Discussion

Following strobe light activation, calanoid and cyclopoid copepods exhibited a marked reduction in densities, particularly in the upper water column. Strobe lights consistently reduced densities of *Daphnia* spp. in the upper stratum, but results were inconsistent for the middle and lower strata. Similar to copepods, we observed a consistent pattern of reduced *Daphnia* abundance in the upper strata following

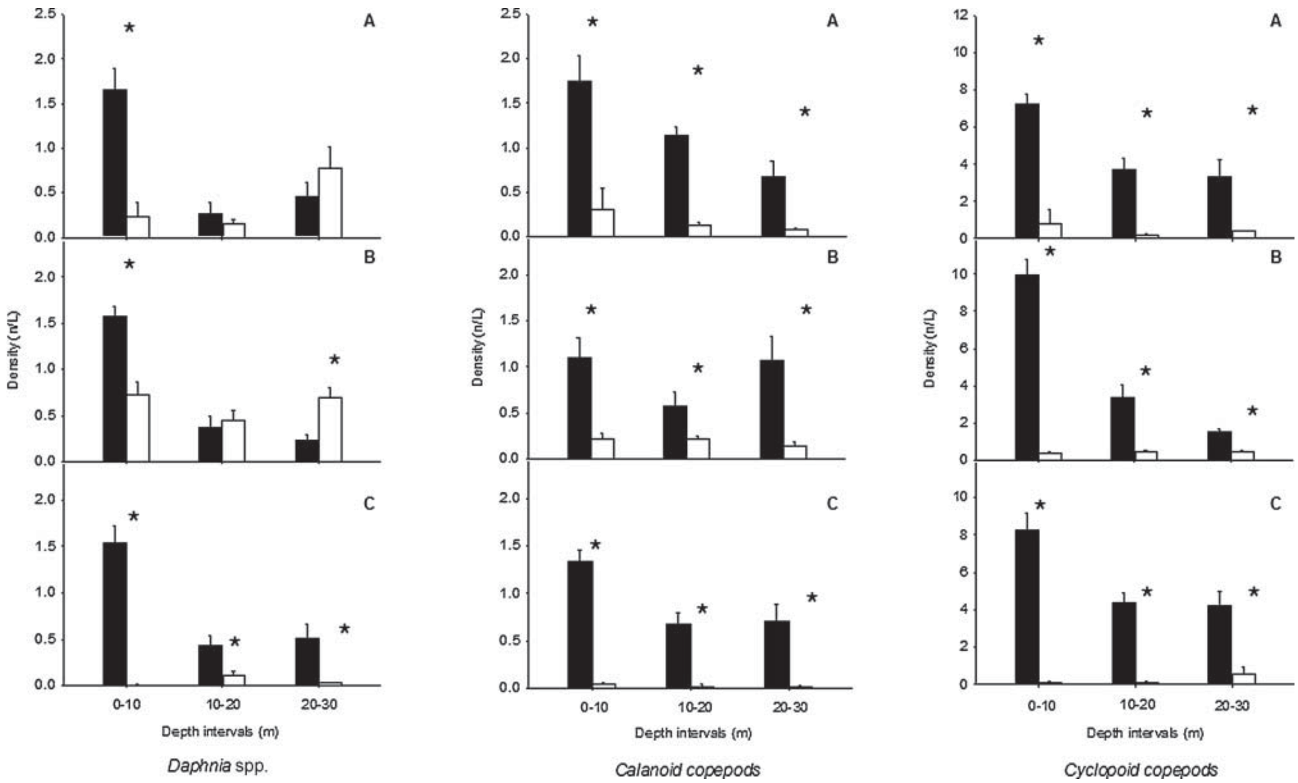

Figure 1.-Mean density (n/L; ± 1 SE) of *Daphnia spp*., calanoid copepods, and cyclopoid copepods before strobe light illumination (black bars) and following 5 h of strobe light illumination (white bars) for each of three depth intervals on A) August 23, 2004, B) August 31, 2004, or C) September 15, 2004. At each depth interval, data were pooled from three transects established at 120° angles perpendicular to the strobe light. Vertical lines indicate standard error and asterisks indicate a significant difference ($\alpha = 0.016$) in mean density at the specified sampling depth.

strobe light activation on all 3 sampling dates. Because distance from the strobe light did not have a significant effect in the original repeated measures model, zooplankton were likely reacting to the strobe lights by retreating vertically to deeper and presumably darker waters; however, it may be possible that zooplankton were deterred horizontally beyond the farthest sampling location (i.e., 100 m). In the absence of strobe light illumination (17 and 19 August), we found little evidence that zooplankton density decreased in the upper water column over the course of these 5 h sampling bouts.

Although our results identified negative phototaxic behaviors of zooplankton to strobe lights, several questions arise that may warrant further investigation. Past studies on the effects of strobe lights have shown that artificial light may attract some fish species (Popper and Carlson 1998). Although it is unclear why some fishes are attracted to strobe lights, it has been hypothesized that strobe lights could potentially concentrate prey and/or increase feeding efficiency for visual-feeding fish (Johnson et al. 2005). In Hamel et al. (2008), rainbow smelt were deterred 15 m away from the strobe light in tests conducted in 2004. However, hydroacoustic estimates taken at distances farther than 15 m showed similar rainbow smelt densities as control estimates and may have increased in abundance after sustained operation (Hamel et al. 2008). Because cyclopoid and calanoid copepods and daphnid densities were reduced near the strobe lights in this study, it is unlikely that the attraction of fish to strobe lights found in other studies is due to concentration of zooplankton. Strobe lights possibly illuminate peripheral areas outside of the effective fish deterrence range, however, allowing visual-feeding fish to more effectively feed. Displacement of zooplankton from strobe lights to illuminated peripheral areas has the potential to increase size-selective predation on the population size structure of zooplankton (Gardner 1981, Gliwicz et al. 2004). Gliwicz et al. (2004) reported that planktivorous fish reduce zooplankton size structure to a certain threshold before moving on to forage in other areas and/or switching prey. Longcore and Rich (2004) noted that artificial light may extend foraging times for planktivorous fishes into the night by improving their capture efficiency on zooplankton prey. Finally, Gliwicz (1986) stated that artificial light could play the same role as a full moon by attracting predators to intensely feed on zooplankton. Therefore, extended feeding opportunities of planktivorous fish provided by strobe lights may change the local zooplankton abundance and composition. In addition, increased predation efficiency due to illumination may attract additional fish to proximal areas of strobe lights, possibly increasing angling pressure. Because most strobe light systems are installed near dam intake structures, a concentration of fish in proximal areas may pose additional risks such as the entrainment or impingement of fishes through emergency spillways, trash racks or other man-made structures.

Our study did not address all potential limitations to the overall understanding of strobe light affects. We were unable to determine the range (i.e., horizontal and vertical distance away from strobe light) at which zooplankton distributions were affected. More sampling locations are needed to accurately determine directionality and magnitude of movements, a likely explanation for why distance away from strobe light was not a significant effect in the original repeated measures model. Light attenuation from the strobe light was unknown and may have helped with predicting deterrence distances. Finally, we were unable to conduct concurrent rainbow smelt sampling to determine if rainbow smelt in illuminated peripheral areas were feeding more efficiently.

Our results indicate that strobe lights may have inadvertent effects on nontarget organisms (i.e., zooplankton) as well as incidentally affecting the feeding ecology of primary and secondary consumers. Although the consequential effects will vary by system, implications such as those discussed here should be considered prior to installment.

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References

Adams NS, Johnson GE, Rondorf DW, Anglea SM, Wik T. 2001. Biological evaluation of the behavioral guidance structure at Lower Granite Dam on the Snake River, Washington in 1998. In: Coutant C, (editor). Behavioral technologies for fish guidance. Bethesda (MD): American Fisheries Society Symposium 26. p. 145–160.

Bullen CR, Carlson TJ. 2003. Non-physical fish barrier systems: their development and potential applications to marine ranching. Rev Fish Biol Fisher. 13:201–212.

Dodson S. 1990. Predicting diel vertical migration of zooplankton. Limnol Oceanogr. 35:1195–1200.

Forward RB, Cronin TW, Stearns DE. 1984. Control of diel vertical migration: photoresponses of a larval crustacean. Limnol Oceanogr. 29:146–154.

Gardner MB. 1981. Mechanisms of size selectivity by planktivorous fish: a test of hypotheses. Ecology. 62:571–578.

Gliwicz ZM. 1986. A lunar cycle in zooplankton. Ecology. 67:883–897.

Gliwicz ZM, Jawinski A, Pawlowicz M. 2004. Cladoceran densities, day-to-day variability in food selection by smelt, and the birth-rate-compensation hypothesis. Hydrobiologia. 526:171–186.

Hamel MJ, Brown ML, Chipps SR. 2008. Behavioral responses of rainbow smelt to *in situ* strobe lights. N Am J Fish Manage. 28:394–401.

Johnson PN, Goetz FQ, Ploskey GR. 2001. Evaluation of strobe lights for vertically displacing juvenile salmon near a filling culvert intake at the Hiram M. Chittenden Locks, Seattle, Washington. In: Coutant C, (editor). Behavioral technologies for fish guidance. Bethesda (MD): Am Fish Soc Symp 26. p. 13–25.

Johnson RL, McKinstry CA, Cook CB, Tano DK, Faber DM, Francis S, Simmons MA, Simmons CS, Brown RS, Thorsten SL, LeCaire R. 2005. Strobe light deterrent efficacy test and fish behavior determination at Grand Coulee Dam third power plant forebay. Richland (WA): Pacific Northwest National Laboratory: Report No. PNNL-15007,.

Longcore T, Rich C. 2004. Ecological light pollution. Front Ecol Environ. 2:191–198.

Lott J, Johnson B, Nelson-Stastny W. 2002. Annual fish population and angler use, harvest, and preference surveys on Lake Oahe, South Dakota. Pierre (SD): South Dakota Department of Game, Fish, and Parks: Annual Report 02–19.

Maiolie MA, Harryman B, Amment B. 2001. Response of free-ranging kokanee to strobe lights. In: C. Coutant (editor). Behavioral technologies for fish guidance. Bethesda (MD): Am Fish Soc Symp 26., p. 27–35.

Moore MV, Pierce SM, Walsh HM, Kvalvik SK, Lim JD. 2000. Urban light pollution alters the diel vertical migration of Daphnia. Verh Internat Verein Limnol. 27:1–4.

Nemeth RS, Anderson JJ. 1992. Response of juvenile coho and chinook salmon to strobe and mercury vapor lights. N Am J Fish Manage. 12:668–692.

Popper, A N. and T J. Carlson. 1998. Application of sound and other stimuli to control fish behavior. Trans Am Fish. Soc. 127:673–707.

[USACOE] US Army Corps of Engineers. 1998. Missouri River main stem system and operation. Missouri River Region Reservoir Control Center, Omaha, Nebraska.

Zaret TM, Suffern JS. 1976. Vertical migration in zooplankton as a predator avoidance mechanism. Limnol Oceanogr. 21:804–813.