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RESEARCH ARTICLE

Evaluating a light-louver system for behavioural guidance of age-0 white sturgeon

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Abstract

Water diversions for hydropower and other applications are some of the most disruptive alterations affecting fish populations in lotic systems. Although many different strategies have been developed to reduce lethal encounters with such infrastructure, few studies have evaluated different forms of behavioural guidance concurrently. Here, we combine an LED-based light guidance device (LGD) equipped with adjustable wavelength and strobing output with a reverse-configured louver rack to assess the effectiveness of this two-part behavioural guidance system on downstream movement through a bypass by age-0 white sturgeon (*Acipenser transmontanus*). Several combinations of LGD and louver settings were tested under both simulated day and night (low light) conditions in a laboratory setting. In the absence of the LGD, louver slat spacings of 10 or 20 cm were most effective at achieving downstream bypasses with greater success rates (~ two-fold greater) under night conditions than under day conditions. Incorporating the LGD operating at the most attractive setting (green light strobing at 20 Hz) with the louver spacings of 10 or 20 cm achieved the highest rates of bypass usage (100% and 97%, respectively) under both day and night conditions while the control treatment (no LGD or louver) resulted in the lowest bypass rate (46%) among fish that moved downstream. Collectively, these results demonstrate that complementary cues can enhance the behavioural guidance of fishes and highlight the importance of continuing to explore the use of multiple strategies to mitigate entrainment for high priority fish species.

KEYWORDS

behavioural guidance, hydropower, light guidance device, migratory fishes, white sturgeon

1 | INTRODUCTION

The growing demand for water in hydropower production and other diversions (e.g., irrigation, drinking water, and industrial cooling) generates considerable problems for the conservation of aquatic systems (Vörösmarty et al., 2010) and freshwater communities (Dudgeon et al., 2006). Notably, the demand for water diversions increases the risk to fishes of entrainment through these structures and/or impingement on their debris racks (Barnthouse, 2013; Pracheil, Derolph, Schramm, & Bevelhimer, 2016), either of which can result in injury or mortality to affected organisms. Migratory species may be particularly susceptible as their movements may result in increased frequencies of encounters with these structures (Schilt, 2006; Poletto et al., 2014). Physical barriers such as small spaced louver arrays (Amaral, 2003; EPRI, 2001) and bar racks (Rosson, Kemp, & Calles, 2010) or screens (Gale, Zale, & Clancy, 2008) can potentially be used to prevent entry of aquatic organisms to intake pipes and turbines. However, smaller fishes may still be able to pass through many of these structures (Coutant & Whitney, 2000), and larger fishes may become impinged upon them (Swanson, Young, & Cech, 1998). Nonphysical barriers, by contrast, aim to exploit the sensory physiology of aquatic biota to repel them from potentially dangerous areas (negative taxis) or serve as an attractant (positive taxis) towards more desirable paths such as bypass channels (Noatch & Suski, 2012).

Behavioural guidance strategies have recently gained attention for their potential to decrease mortality rates associated with water

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diversion infrastructure (Coutant, 1999, 2001). Artificial lighting consisting of mercury vapour bulbs producing white light was one of the earliest behavioural guidance strategies (Nemeth & Anderson, 1992; Patrick, Christie, Sager, Hocutt, & Stauffer, 1985; Rodgers & Patrick, 1985), but with varying success. Strobing white lights have been used to deter Chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*), and sockeye salmon (*Oncorhynchus nerka*), as well as steelhead (*Oncorhynchus mykiss*), from entering a navigation lock (Johnson et al., 2005), and similar results were obtained for delta smelt (*Hypomesus transpacificus*; Hamel, Brown, & Chipps, 2008). Conversely, the effects of strobe lights in behavioural guidance were equivocal in sea lamprey (*Petromyzon marinus*; Stamplecoskie et al., 2012) and muskellunge (*Esox masquinongy*; Stewart, Wolter, & Wahl, 2014). One limitation of earlier light apparatus is that they were typically monochromatic (e.g., white mercury vapour), constraining their effects on fishes varying in diel activity patterns and sensitivities to different colours. White lights have been used, unsuccessfully, to guide white sturgeon in the past and had limited effectiveness at reducing rates of impingement on physical barriers (Poletto et al., 2014). Several different light devices (Brown, 2000; Mueller, Neitzel, & Amidan, 2001; Nemeth & Anderson, 1992; Richards, Chipps, & Brown, 2007) have also been tested, although light intensity, colours, and strobing rates have been evaluated independently (Mueller et al., 2001; Richards et al., 2007; Sullivan et al., 2016). In the context of diel patterning, larger groups of kokanee (*O. nerka*) and rainbow trout (*O. mykiss*) have been observed around white lights at night compared to during the day (Simmons et al., 2004), suggesting that single-colour lights may not be effective at achieving desirable behavioural outcomes throughout the full photoperiod.

Bubble screens (Sager, Hocutt, & Stauffer, 2000; Stewart et al., 2014), electrical fields (Clarkson, 2004; Noatch & Suski, 2012), and acoustics (Flammang, Weber, & Thul, 2014; Goetz, Dawson, Shaw, & Dillon, 2001; Popper & Carlson, 1998;) have all subsequently been incorporated into behavioural guidance strategies. Similarly, fish guidance efforts have tended to focus on the effectiveness of physical or nonphysical barriers in isolation (EPRI, 2001; Noatch & Suski, 2012), while generally neglecting to explore any complementary effects arising from integrated multisensory approaches (sensu Ferrari et al., 2008; Elvidge, Macnaughton, & Brown, 2013). Louver arrays have been used as a behavioural guidance device since at least the 1950s (Bates and Vinsonhaler, 1957). Louvers have been evaluated for their potential to help guide many species, including American eels (*Anguilla rostrata*; Amaral, 2003), Atlantic salmon (*Salmo salar*; Scruton et al., 2008), rainbow trout (Shepherd et al., 2007), and shortnose (*Acipenser brevirostrum*) and pallid sturgeon (*Scaphirhynchus albus;* Kynard & Horgan, 2001). Louver systems function by altering the hydrodynamics of the water (Scruton et al., 2008) in order to create turbulence that deters fish from passing through, which can also lead to reduced flow and power generation. A reversed louver array likely improves diversion of fish because the slat angle is reversed relative to the flow. This may allow flow to an intake to remain relatively unaltered while still creating turbulence and hydrodynamic conditions intended to deter fishes. Typical louver configurations place the slats at acute angles to the direction of flow (Kynard & Horgan, 2001), ranging from 7.2° (Shepherd et al., 2007) to 45° (Amaral, 2003; Kynard & Horgan, 2001).

White sturgeon (*Acipenser transmontanus*) are endemic to the Pacific coast in British Columbia, Washington, Oregon, and California. Some populations of this semianadromous species are listed as endangered under the Species at Risk Act in Canada (Fisheries and Oceans Canada, 2014), and overall the species is assessed as Least Concern on the IUCN Red List (Duke, Down, Ptolemy, Hammond, & Spence, 2004). Inhabiting rivers, bays, and estuaries along the coast, white sturgeon are the longest living freshwater fish in North America (Birstein, 1993) and have historically experienced pressures from fisheries harvesting (Semakula & Larkin, 1968) that have been exacerbated by the development of hydropower facilities that impede their migrations (Fisheries & Oceans Canada, 2014). Barriers to migration contribute to juvenile mortality when they encounter turbines (Beamesderfer and Farr, 1997), and alterations to river flow regimes reduce the amount and quality of habitat available to sturgeon populations (Fisheries & Oceans Canada, 2014). White sturgeon possess several characteristics suggesting that they may be an ideal candidate for behavioural guidance strategies: They are sensitive to light, especially the green and red spectra, during their juvenile stages (539 and 605 nm, respectively: Sillman, Spanfelner, & Loew, 1990, 2007); they are subject to impingement on screens over water intake structures; they exhibit diel patterning of behaviour (Poletto et al., 2014); and other species of sturgeon have been experimentally guided by louver arrays (Kynard & Horgan, 2001).

Using age-0 white sturgeon in a simulated stream channel under both simulated day (light) and night (dark) conditions, we examined the effectiveness of a combination of a reversed louver array and an LED-based light guidance device (LGD) at eliciting bypass usage during downstream movements. The LGD, unlike other light sources that have been used in guidance strategies, can produce any wavelength of light in the 400–670-nm spectrum at adjustable intensity and constant output or strobing at frequencies up to 40 Hz. On the basis of earlier studies (Amaral, 2003; Kynard & Horgan, 2001), we predict that the presence of the louver will have a positive effect on bypass usage and that including the LGD as an attractant towards the bypass will increase bypass rates. Individually, we predict that the louver will provide more effective guidance under day conditions than under night conditions as both conditions will provide sturgeon with hydraulic cues but the louver will only be visible under day conditions. We predict the opposite pattern for the LGD, with light stimuli having greater effects on fish movement patterns under night conditions. These results may serve not only to inform conservation efforts for white sturgeon and other species of concern around areas where there is risk of entrainment but also contribute to the design of integrated behavioural guidance strategies in the field that exploit the sensory perceptions of target species.

2 | METHODS

2.1 | Test fish

We obtained age-0 hatchery-reared white sturgeon of Fraser River, BC, stock from the International Centre for Sturgeon Studies (ICSS) at Vancouver Island University in Nanaimo, BC, Canada. The ICSS maintains their sturgeon indoors in dechlorinated, biofiltered, and UV-treated municipal water at a temperature of 14 °C and a photoperiod determined by external light sensors. Age-0 sturgeon are held in

2,000-L green cattle drum tanks with an average density of 500 fish per tank. Test fish were transported individually in 10-L buckets between their holding tanks and the trial arenas and placed in net pens in the holding tanks following trials to prevent reuse. All experimental work was conducted within the ICSS building between October 2015 and January 2016.

2.2 | Experimental apparatus

A dark green, fibreglass raceway tank (3 m length × 1 m width × 0.75 m depth) was supplied with water diverted from the ICSS aquaculture system and filled to a depth of 0.2 m (total volume = 600 L). Using a semiclosed recirculating flow system described that added water to the system at a rate of 1 L/min, we produced a constant flow rate of 0.24 m/s and prevented temperature changes greater than 1 °C. The raceway was outfitted with a reversed louver array (Figure 1) with the outer frame constructed out of 2.5 cm × 2.5 cm square aluminium bars in a rectangular shape measuring 122 cm × 36 cm (length × height). The louver frame was placed 1 m from the head of the raceway angled 70° to the side wall. Holes were drilled along the length of the frame at 5 cm intervals to allow slats to be inserted at different spacings. The louver slats consisted of grey PVC sheets measuring 25 cm × 30 cm × 0.6 cm (length × height × width) attached to the outer frame at top and bottom with galvanized screws. The slats were angled 45° to the louver frame in a "reversed" position such that they were 65° to the side of the tank. A guide bar was attached to the bottom of the slats on the headwater side, which closed the gap below the slats and prevented sturgeon from passing underneath the louver. A manual adjustment bar was fastened to the tops of the slats so their positions could be adjusted simultaneously. At the downstream end of the tank, we left a 20-cm gap between the louver frame and the tank wall to simulate a bypass. The effectiveness of different louver parameters was evaluated by manipulating the spacing of the slats and the presence or absence of the guide bar. Sturgeon were exposed to slat spacings of 5, 10, or 20 cm with the guide bar in place. Two additional configurations consisted of the louver frame and guide bar in place with no slats, and the louver frame without the guide bar or slats. Finally, we conducted movement trials with no louver infrastructure in place (control). This approach resulted in six different louver settings (5 treatments and 1 control).

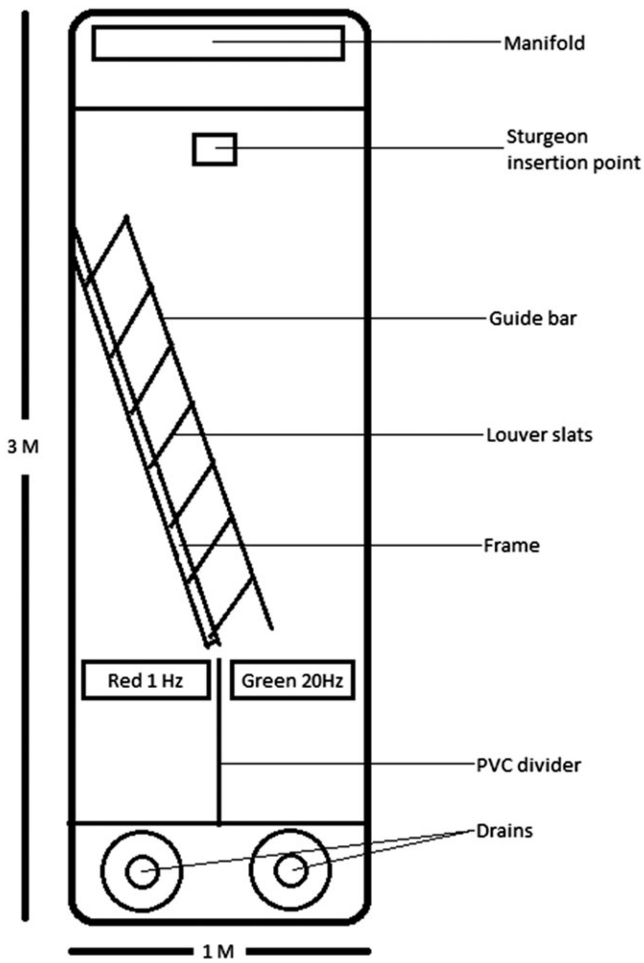

FIGURE 1 Schematic diagram of the raceway used to test the effectiveness of the integrated light-louver array on downstream passage of juvenile white sturgeon (*Acipenser transmontanus*). Louver slats could be removed entirely or spaced at 5, 10, or 20 cm

In addition, we incorporated an LED-based LGD developed by ATET-Tech, Inc. (Thornhill, ON). This device can produce any colour in the 400–670-nm spectrum at constant intensity or strobing between 1–40 Hz. The LGD was used with one of two output settings: green light (540 nm; cf. peak absorbance of 539: Sillman et al., 1990) strobing at 20 Hz, which had an attractive effect on this population of age-0 white sturgeon, and red light (605 nm) strobing at 1 Hz, which had a repellent effect (Ford et al., in review). The green setting involved placing the LGD downstream of the bypass to guide fish towards the passage, whereas the red setting was presented by placing the LGD behind the louver to deter the sturgeon from passing between the slats or through the louver frame. Movement trials were first conducted under day (light) conditions and later under night (dark) conditions. Over the course of the experiment, fish growth was sufficient to prevent them from being able to pass through the 5-cm slat spacing during night trials (day: 170.5 mm ± 1.16 mm; night: 196.7 mm ± 0.41 mm, mean total length ± SE), resulting in 35 different treatment combinations.

Each movement trial consisted of an individual sturgeon being released into the centre of the arena at the upstream end. Using Hero 2 digital cameras (GoPro, Inc., San Mateo, CA) mounted above the arena, we recorded their movements over 1 min postrelease for subsequent analysis based on whether or not (a) each fish moved downstream; (b) each fish moved through the bypass channel; (c) each fish moved through the louver array; and (d) the time (in seconds) to move downstream through the bypass or through the louver array area, if applicable. Each sturgeon was exposed to one treatment and no fish were tested more than once. We analysed the first three measures as general linear models with binomial distributions and time to passage as a linear model against louver spacing, LGD setting, and light condition (day/night) as fixed effects. Due to the size difference between fish tested under day and night conditions, we included individual body size (total length, mm) as a linear covariate in the analyses. The binary response variables were then converted to odds (where odds of 1 imply a 50% chance of either outcome) and odds ratios to highlight the effects of the LGD-louver settings on sturgeon behaviour in comparison to control trials. All analyses and figures were generated using R version 3.2.4 (R Core Team, 2016) and the "gplots" (Warnes et al., 2016) package.

3 | RESULTS

3.1 | Light intensity

Ambient light intensity and LGD output were measured using a Dr. Meter® LX1330B digital light meter (HISGADGET, Union City, CA) with a range of 0–200,000 lux. Under dark and light conditions, ambient light intensity at the midpoint of the water column in the trial arena was 3 and 169 lux, respectively. Intensities of the different colours of light are illustrated in Figure 2; sturgeon were placed into the arena 200 cm away from the LGD.

3.2 | Louver parameters

Of the fish used (n = 1349, ~4 months old, total length 182.7 mm ± 27 mm, mean ± SD), 60.6% (n = 818) of these moved downstream regardless of treatment (Table 1). LGD-control trials allowed us to test the effect of louver configuration on use of the downstream bypass and passage through the louver itself independent of the light stimulus. Overall, slat spacing (Wald's χ^2 = 19.5, df = 5, p = .0015) and background light condition (χ^2 = 85.1, df = 1, p < .0001) both significantly influenced whether or not a fish moved downstream in the trial arena (Figure 3a). Similarly, slat spacing (Wald's χ^2 = 37.4, df = 5, p < .0001) and background light condition (χ^2 = 24.5, df = 1, p < .0001) both had significant effects on bypass usage in the LGD-control trials, with a greater effect under night conditions (Figure 3b).

Within the subset of fish that did move downstream, only the interaction term between louver spacing and light condition was statistically significant in terms of latency (time) to use the bypass ($F_{4,457}$ = 3.75, p = .0052; Figure 3c). Slat spacing (χ^2 = 42.6, df = 7, p < .0001), light condition (χ^2 = 13.9, df = 1, p < .0001), and their interaction term (χ^2 = 13.9, df = 4, p = .0078) all significantly influenced the actual proportion of sturgeon using the bypass (Figure 2d; Table 1, all rows where "LGD parameter" is "Control"). All fish that moved downstream but did not use the bypass instead passed through the louver itself or through its footprint area in the case of louver-control treatments. Fish size (total length) did not have a significant effect on any of these responses.

Under day conditions only, louver spacing did not have a significant effect on the overall proportion of sturgeon moving downstream through the bypass (χ^2 = 10.5, df = 5, p = .061, Figure 3b). In the subset of fish that moved downstream, however, the presence of the louver significantly increased bypass usage (χ^2 = 12.6, df = 5, p = .027) whenever slats were present (Figure 3d). Under night conditions, both the overall rate (χ^2 = 43.3, df = 4, p < .0001) and the actual rate of bypass usage (χ^2 = 30.7, df = 4, p < .0001) were significantly influenced by the presence of louver slats (Figure 3b,d). Overall, louver spacings of 10 or 20 cm were the most effective at eliciting bypass usage under both day and night conditions, with no significant difference found between them in post hoc testing.

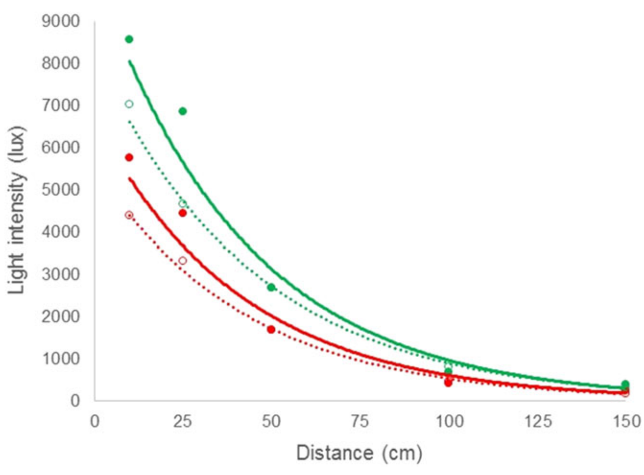

FIGURE 2 Light intensity (lux) of the colours used at distance intervals (10, 25, 50, 100, and 150 cm) under dark (open circles, dotted lines) and light (closed circles, solid lines) conditions [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Integrated LGD-louver system

Overall downstream movement was significantly influenced by LGD setting (χ^2 = 32.9, df = 2, p < .0001), louver spacing (χ^2 = 16.3, df = 5, p = .0061), light condition (χ^2 = 90.4, df = 1, p < .0001), and the two-way interactions between LGD and louver spacing (χ^2 = 18.6, df = 10, p = .045), LGD settings and light condition (χ^2 = 20.1, df = 2, p < .0001), and louver spacing and light conditions (χ^2 = 9.9, df = 8, p = .042; Table 1). LGD setting (χ^2 = 85.6, df = 2, p < .0001), louver spacing (χ^2 = 18.9, df = 5, p = .0019), and background light condition (χ^2 = 25.1, df = 1, p < .0001) had significant effects on the overall proportion of age-0 white sturgeon using the bypass (Figure 4a). In addition, there were significant two-way interactions between LGD and louver settings (χ^2 = 31.7, df = 10, p = .00045), louver settings and background light conditions (χ^2 = 10.3, df = 4, p = .036) and in the three-way interaction between LGD setting, louver spacing and background light condition (χ^2 = 25.8, df = 8, p = .0011) on the overall proportion of fish using the bypass. Sample sizes, proportions, and mean latencies of bypass usage for each treatment combination are listed in Table 1.

Of the fish that moved downstream, bypass usage was influenced by LGD and louver settings, light condition, and body size, with significant interaction terms between all fixed-effects factors (all p < .05; Figure 4a,b). In general, smaller sturgeon were more likely to use the bypass while fish that passed through the louver tended to be larger (mean total length 184.9 vs. 193.7 mm, respectively) although the mean difference was <10 mm. Latency to bypass was influenced by LGD setting ($F_{2,764}$ = 4.98, p = .0071), body size ($F_{1,764}$ = 21.62, p < .0001, Pearson's r = −0.19), and the interaction between louver spacing and light condition ($F_{4,764}$ = 3.42, p = .0088; Figure 4c,d).

Under day conditions, LGD setting (χ^2 = 9.1, df = 2, p = .01) and body size (χ^2 = 4.3, df = 1, p = 0.038) had significant effects on bypass usage (Figure 3a), and latency was influenced only by body size ($F_{1,288}$ = 17.75, p < .0001, r = −0.25; Figure 4c). Although larger sturgeon took longer to use the bypass, fish passing through the louver itself were larger on average than fish using the bypass (183 vs. 171 mm, respectively). Under night conditions, bypass usage was only influenced by LGD setting (χ^2 = 58.1, df = 2, p < .0001; Figure 4b)

TABLE 1 Sample sizes, summary results and odds of downstream movement patterns demonstrated by age-0 white sturgeon (*Acipenser transmontanus*) exposed to different LGD and louver array parameters

Parameters:				Proportions:		Latency to bypass (s)	Odds of bypass use[b]
Light condition	LGD	Louver	N	Moving downstream	Using the bypass[a]		
Light	Control	Control	115	0.29	0.86	16.9	0.34
		Frame	25	0.59	0.68	21.3	0.67
		Guide bar	25	0.41	0.52	27.7	0.27
		20 cm	25	0.43	0.91	32.9	0.63
		10 cm	25	0.37	1	24.7	0.60
		5 cm	20	0.3	1	25.4	0.43
	Red 1 Hz	Control	115	0.2	0.6	30.6	0.14
		Frame	24	0.5	0.67	36.1	0.5
		Guide bar	25	0.6	0.8	25.2	0.92
		20 cm	25	0.2	0.8	31.5	0.19
		10 cm	25	0.28	0.86	46.9	0.32
		5 cm	20	0.1	1	39.0	0.11
	Green 20 Hz	Control	115	0.64	0.94	34.6	**1.5**
		Frame	25	0.68	0.88	23.1	**1.5**
		Guide bar	25	0.8	0.95	17.5	**3.17**
		20 cm	25	0.84	0.95	39.1	**4.00**
		10 cm	25	0.64	1	27.4	**1.78**
		5 cm	20	0.8	1	21.4	**4.00**
Dark	Control	Control	115	0.83	0.32	25.7	0.36
		Frame	25	0.85	0.53	23.8	0.83
		Guide bar	25	0.81	0.61	21.2	0.97
		20 cm	25	0.91	0.84	19.9	**3.17**
		10 cm	25	0.69	1	20.7	**2.26**
	Red 1 Hz	Control	115	0.8	0.8	27.7	**1.78**
		Frame	25	0.6	0.27	26.6	0.19
		Guide bar	25	0.76	0.42	18.6	0.47
		20 cm	25	0.64	0.44	33.2	0.39
		10 cm	25	0.68	0.71	25.9	0.92
	Green 20 Hz	Control	115	0.8	1	30.9	**4.00**
		Frame	25	0.72	0.94	30	**2.13**
		Guide bar	25	0.88	0.82	20.7	**2.57**
		20 cm	25	0.72	1	24.8	**2.57**
		10 cm	25	0.76	1	25.2	**3.17**

Note. LGD = light guidance device.

[a]Proportion of individuals using the bypass are calculated as proportions of fish that moved downstream in each treatment combination.

[b]All odds of bypass usage >1 (i.e., greater than 50% chance) are listed in bold.

whereas latency was influenced by LGD setting ($F_{2,273}$ = 3.9, p = 0.021) and louver spacing ($F_{5,273}$ = 6.34, p < .0001; Figure 4d).

Independent of louver spacing, green light (540 nm) strobing at 20 Hz resulted in greater bypass usage overall under both day and night conditions, whereas red light (605 nm) strobing at 1 Hz tended to elicit fewer bypasses than either the green light or control treatments, particularly under night conditions (Figure 3a,b). In combination with the louver, green light strobing at 20 Hz and louver spacings of 10 or 20 cm resulted in the greatest odds of bypass usage (Table 1, last column).

4 | DISCUSSION

Our results demonstrate that an integrated light-louver system can be effective at behaviourally guiding age-0 white sturgeon towards a bypass while simultaneously decreasing the latencies of bypass approach and entry. These findings support the hypothesis that green light strobing at 20 Hz can serve as an attractant to age-0 white sturgeon. Conversely, when all trials are examined together, treatments involving red light strobing at 1 Hz had lower proportions of fish moving downstream, raising the possibility that red light was an effective repellent and inhibited downstream movement altogether as moving downstream in the trial arena required an individual to enter an area illuminated by red light. Background light conditions significantly influenced behavioural responses to the paired stimuli, with sturgeon demonstrating the greatest rate of bypass usage when the LGD was used to attract them to the bypass with green light under day (light) conditions, independent of louver parameters. Our experiment demonstrated relatively high levels of diversion with a louver system, although not all louver parameters were equal, as the 5- and 10-cm spacings had 100% diversion rates compared to 90% diversion with the 20-cm spacing. By contrast, the use of either red or green light under simulated night (dark) conditions did not increase the effectiveness of the louver when slat spacings were 10 or 20 cm. Overall, rates of bypass usage were highest when the louver spacing was 10 cm, with significantly more fish using the bypass during the night trials compared to the day trials.

The use of strobing lights on age-0 white sturgeon affected the rate of bypass usage and latency to bypass. Bypass rates increased for the higher strobing frequency and latency to bypass increased with the lower strobe frequency setting. Because strobe rate and wavelength were linked by setting, it is possible that strobe rate influenced bypass rate even though it was not tested independently. Previously,

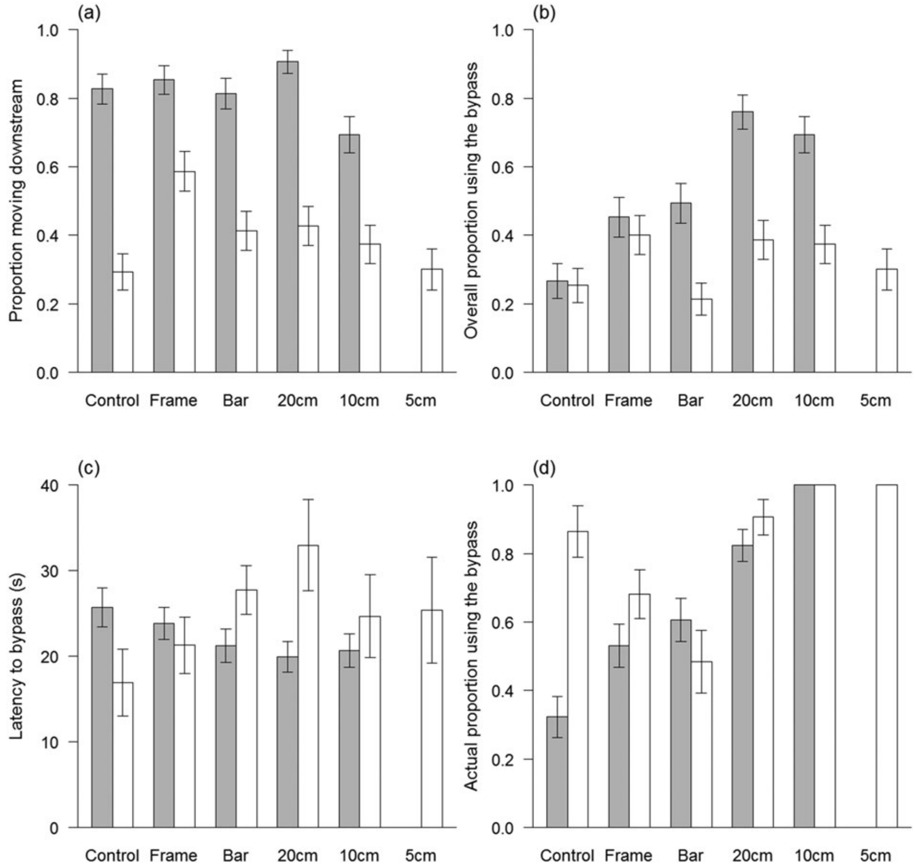

FIGURE 3 Overall proportions (±SE) of juvenile white sturgeon (*Acipenser transmontanus*) that (a) travelled downstream, and (b) used the bypass. For the sturgeon that moved downstream, (c) mean (±SE) latency to use the bypass and (d) the actual proportion that used the bypass with different louver configurations under both light (open bars) and dark (grey bars) conditions in the absence of illumination from the light guidance device

we found significant differences in attraction to the LGD in dichotomous choice tests (Ford et al., unpublished data), suggesting that both colour and strobe rate may affect the adoption of positive or negative taxis for behavioural guidance outcomes.

Colour vision is a known trait of fishes (Levine & MacNichol, 1982), and different species have demonstrated variable responses to different colours of light (Marchesan, Spoto, Verginella, & Ferrero, 2005). In our study, green light (540 nm) was a significant factor in increasing bypass usage, with a greater effect observed during the day than at night, and red light (605 nm) had a repellent effect. Spectral sensitivities (539 and 605 nm: Sillman et al., 1990) interacting with colour preferences or aversions may be the cause of attraction to green light in age-0 white sturgeon, providing a putative explanation for why the “attraction” setting of the LGD was associated with higher rates of bypass. However, ontogenetic shifts in spectral sensitivity towards red and blue wavelengths (Sillman et al., 1990) suggest that as white sturgeon mature, their reactions to green and red light may shift and therefore age-specific behavioural guidance strategies may be required.

The notable difference in the louver system we tested compared to earlier designs was that the slats were angled 65° to the flow direction, allowing more water passage. This did not change the success rate of diverting fish, as during both day and night conditions, there were no fish passing through the louver for the two smallest spacings (5 and 10 cm) and few (10%) passing through the 20-cm spacing. The added benefit to this integrated light-louver system is that the combination of stimuli allows for guidance depending on varying responses to the individual stimuli.

Because white sturgeon do not react the same diurnally to different stimuli (Poletto et al., 2014), it is important to make sure that they can be guided at all times. During the day, the green light was a more effective guidance tool than the louver as it elicited greater rates of downstream movement. Together, the two devices create the possibility for a 24-hr guidance strategy. It is conceivable that different individuals respond differently to behavioural guidance technologies and different times (e.g., day vs. night) such that the use of combined approaches may lead to greater effectiveness. Most behavioural guidance systems use only one technique to guide fish, or if they do use multiple, they are typically multiple nonphysical barriers (Noatch & Suski, 2012). The combination of using both a physical and nonphysical barrier increased the effectiveness in guidance for age-0 white sturgeon, providing a better chance of being protected during different photoperiods. The louver was most effective in simulated night conditions. This effectiveness could have been because the fish avoided the complex currents created by the louver when they could not rely on vision. Our findings suggest that age-0 white sturgeon downstream movement is greater at simulated night conditions, and similar results have been observed in other sturgeon species (shortnose and pallid, Kynard & Horgan, 2001; green and white sturgeon, Poletto et al., 2014); this may be a consequence of the higher activity levels and

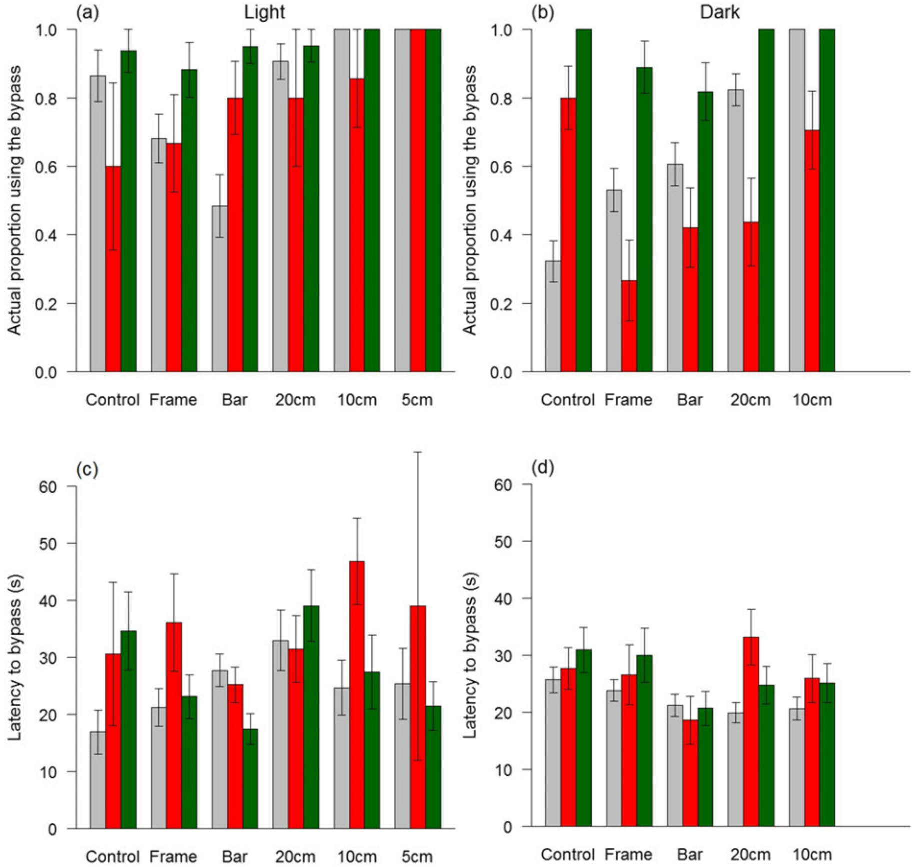

FIGURE 4 Proportion (±SE) of juvenile white sturgeon (*Acipenser transmontanus*) that moved downstream and that used (a, b) the bypass and (c, d) their mean latency (±SE) to passage with different louver configurations under light and dark conditions. Grey bars: light guidance device control; red bars: red light strobing at 1 Hz; green bars: green light strobing at 20 Hz [Colour figure can be viewed at wileyonlinelibrary.com]

migratory movement of sturgeon at night (Poletto et al., 2014). These results may show benefits to the use of integrated behavioural guidance systems and how they may enhance desired outcomes through mutual reinforcement.

Behavioural guidance techniques in the past have primarily focused on avoidance by using different strategies to deter organisms from passing into a certain area, whereas our approach also examined the possibility of attracting fish towards safe passages. Based on our observations, using red light as a repellent from the louver was less effective than using green light to attract fish towards the bypass. Attraction to safe areas may be more beneficial to fish protection because fish may become habituated to the negative stimuli, attenuating the repulsive effect and increasing the risk of harm over repeated exposures. Although our observed trends of slower approaches to the bypass and decreased likelihoods of downstream movement during the red light treatments may not be completely attributed to the repulsion setting, these could benefit from further exploration under field conditions. Repulsion strategies also can become a problem as fish do not respond consistently to the same stimuli depending on time of day (Poletto et al., 2014), as illustrated by reports of fish numbers increasing around an illuminated dam during night compared to day (Simmons et al., 2004). If fish react differently depending on individuals and diel period, then it may be possible that attraction would serve best to reinforce travel around hazards and decrease the number of encounters with harmful objects such as physical barriers.

The present research has shown promise for the use of integrated behavioural guidance systems. The advantage of the LGD during the day and the louver during the night has shown that age-0 white sturgeon can be guided towards safe passage in a laboratory setting through attraction. The use of an integrated guidance system to simultaneously repel (louver) fish from a danger area and to attract (LGD) fish towards safety could lead to applications around many waterway developments where single behavioural guidance techniques may not be sufficient to guide the majority of fish. It is important to note that this research was done in a laboratory, and if at all possible should be followed up with a study under fully natural conditions to confirm these results. Findings from this study may help lower risk of entrainment and impingement of white sturgeon, aiding populations that are threatened from many different stressors and thus improving population numbers. The use of integrated diversion systems could lead to better protection for many other imperilled fish and aquatic species.

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