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River-Scale Evaluation of a Floating LED Light Array for Behavioral Guidance of American Eel

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ABSTRACT

Exploiting the sensory physiology of migratory fishes to guide them away from hazards like hydroelectric turbines is of interest to regulatory agencies and hydropower operators to achieve conservation and management goals. Here we describe a river-scale experiment where out-migrating adult American eel (*Anguilla rostrata*) were tracked downstream via acoustic telemetry as they encountered a 216 m long floating LED light array on the St. Lawrence River. Eel ($N = 51$) spatial responses to light were compared to eels detected on control (no light) nights with the expectation that light would cause eels to deflect laterally along the light array toward the river-right shore. Eels generally swam near the surface at night, and 39.5% of eels that encountered the light altered their downstream trajectories consistent with lateral deflection, although those responses were relatively modest. However, 76.7% of eels demonstrated diving responses of ≥ 4 m, consistent with seeking darker passage under the light field. Although we observed some degree of light avoidance, additional research is needed to optimize use of light for effective behavioral guidance in large rivers.

1 | Introduction

The American eel (*Anguilla rostrata*) is a semelparous, facultatively catadromous species that engages in panmictic spawning (Avise et al. 1986; Oliveira 1999; Castonguay and Durif 2016) at the end of its lifecycle in the marine environment of the Sargasso Sea. Young eels migrate throughout the eastern Atlantic Ocean into freshwater, brackish (estuarine), or nearshore habitats (Cairns et al. 2009) throughout the Caribbean islands and the eastern coasts of North and Central America (Rypina et al. 2014) where they grow and mature for many years before out-migrating upon attaining some age-independent minimum size threshold (Jessop et al. 2008). Historically, the upper St. Lawrence River and Lake Ontario (USLRLO) provided growth habitat for large numbers of juvenile and subadult eels that constituted an important subsistence fishery for some First Nations in Canada (Castonguay and Durif 2016; Giles et al. 2016) and Indigenous communities in the United States (Casselman 2003; MacGregor et al. 2009; Miller and

FIGURE 1 | Map of the study area. White pins indicate the locations of (left–right) the acoustic tag implantation and release site at the OMNRF Glenora Fisheries Research Station in Prince Edward County, ON, on Lake Ontario; the Iroquois Water Control Dam (IWCD) and Moses-Saunders Generating Station (MS GS) spanning the St. Lawrence River between ON and NY. The yellow line indicates the USA-Canada border. [Color figure can be viewed at wileyonlinelibrary.com]

Casselman 2014). Due to stock declines driven in part by turbine mortality as well as reduced juvenile recruitment into the USLRLO by as much as 95%–99% since the early 1970s (Castonguay et al. 1994; Casselman 2003; Verreault and Dumont 2003; Cairns et al. 2014; Doyon 2015; DFO 2025), American eels are identified as Threatened on the IUCN Red List (Jacoby et al. 2015), and were recommended for listing as Threatened under Canada's federal Species-at-Risk Act (COSEWIC 2012).

American and European eels (*A. anguilla*) experience turbine mortality at hydroelectric generating stations on their downstream outmigrations. In the USLRLO, out-migrating eels pass through two generating stations on the St. Lawrence River that are separated by ~130 km (Moses-Saunders Generating Station spanning the river between Cornwall, ON, and Massena, NY, and the Beauharnois Generating Station at Beauharnois, QC; Figure 1). Cumulative mortality from turbine encounters at these two stations has been estimated at 40% (Verreault and Dumont 2003). Despite widespread interest in providing safe downstream passage at hydroelectric projects, identifying solutions has proven to be challenging, particularly at big facilities with large volumes of water (> 100 m^3/s) and wide reaches of turbines (Pratt et al. 2021). Notably, the negative rheotaxis and preferences for faster water currents of eels during downstream migration pose challenges for protecting them from passing through turbines and guiding them away to alternative safer passage routes (Piper et al. 2015) or concentrating them to stream sections upstream of dams to facilitate their collection for trap and transport programs. Mitigation options for eel protection and passage that may be feasible at some smaller facilities are problematic for large plant operators due to the protracted, episodic nature of eel outmigration (between July and early October in the USLRLO for naturally migrating eels) and the lack of effective guidance technologies that do not interfere with hydroelectric generating potential.

To reduce or mitigate mortality in downstream migrating eels from turbines at the Moses-Saunders Generating Station, Ontario Power Generation (OPG) began operating a trap and transport program in 2008 (Béguer-Pon et al. 2014, 2018; Stanley 2022) wherein large yellow-stage eels (> 2.2 kg or > 80 cm total length TL) are transported from the Ontario Ministry of Natural Resources (OMNR) Glenora Fisheries Station on Lake Ontario (Figure 1) downstream past the generating stations. Eels are then released into the St. Lawrence River with the expectation that they will continue their spawning migration or continue to develop and outmigrate in subsequent years (see also Piper et al. 2020 for a description of a similar program involving European eels). Although the trap and transport program has successfully translocated tens of thousands of eels (Stanley 2022), a more efficient solution that can guide, bypass, and/or concentrate and collect eels in larger numbers before they encounter hydroelectric turbines is needed.

Previous work on the St. Lawrence River has demonstrated that underwater debris transport and accumulation are significant challenges to conventional fish screening and protection structures (K. McGrath, unpublished data, reviewed in Versar Inc. 2009). Technologies that exploit the sensory physiology and behavior of target species may provide non-physical options for behavioral guidance that both avoid debris accumulation problems and enhance conservation success for target species (EPRI 2018; Elmer et al. 2021). Light has been identified as a promising tool for effectively guiding eels to capture locations (EPRI 2017a, 2017b, 2018; Pratt et al. 2021; MacLeod et al. 2025) based on their nocturnal migration patterns, captive laboratory studies of responses to submerged LED (light emitting diode) devices (Elvidge et al. 2018), and earlier projects in the St. Lawrence River by the New York Power Authority (NYPA) that used submerged incandescent light

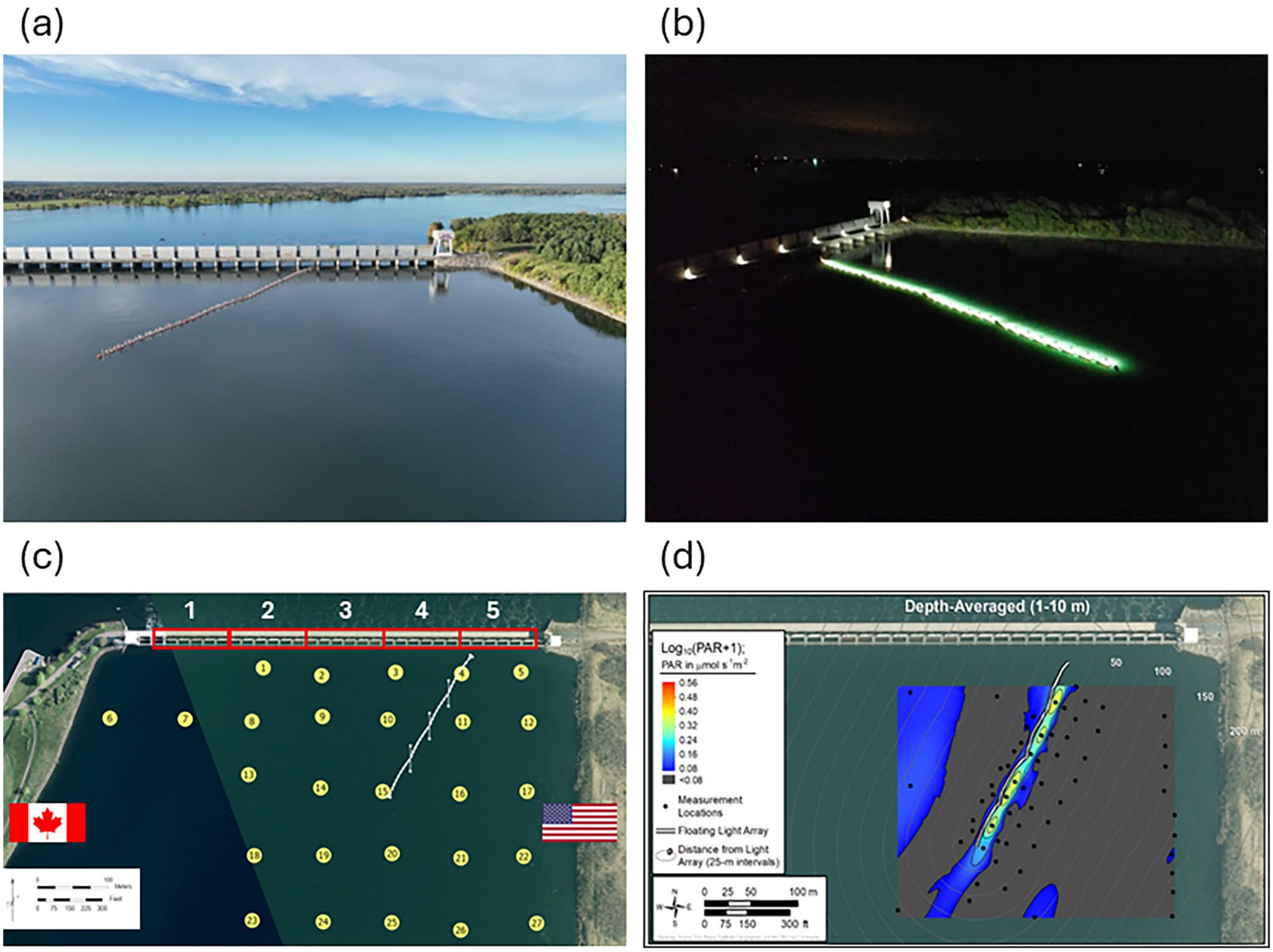

FIGURE 2 | The study site at the Iroquois Water Control Dam (IWCD) on the St. Lawrence River between Iroquois, ON, and Waddington, NY. (a) The 216 m long floating LED light array installed ~30 m upstream from the dam at a 30° angle to the stream axis seen during the day and (b) at night. Both images are aimed roughly downstream with the US shore pictured. White arrows indicate the predicted routes followed by out-migrating American eels (*Anguilla rostrata*) deflecting away from the downstream end of the light field. Images provided by A. Weinstock (NYPA). (c) Locations of $N = 27$ Innovasea HR2-180 kHz receivers (numbered circles) that detected eels implanted with acoustic transmitters between 24 August and 5 December 2022. The floating light array is the white diagonal line with positions of its anchor lines indicated. Red squares illustrate the five gate groups (six gates each) numbered from the river-left to the river-right shore. (d) Depth-averaged (1–10 m; 1 m bins) distance of the light field produced by the floating light array (white scalloped diagonal line) showing the locations of vertical sampling transects (black dots in the grey area). Image reproduced from EPRI (2023). [Color figure can be viewed at wileyonlinelibrary.com]

columns on smaller scales to deflect eels away from illuminated fields (Versar Inc. 2009; EPRI 2016). These St. Lawrence River studies are bolstered by results involving the European eel, notably a long-term research and mitigation program at the Killaloe Weir on the River Shannon in Ireland that has described lower numbers of out-migrating eels caught in nets on nights when the bridge-mounted navigation lights were operating compared to unilluminated control nights (Cullen and McCarthy 2000). More recently, European eels demonstrated avoidance of illuminated gates and higher passage rates through control gates at the same weir (Lenihan et al. 2025). While these studies demonstrated that submerged lights have some promise for deflecting migrating eels away from illuminated fields at night (Versar Inc. 2009; EPRI 2025) and that overhead lights have been associated with lower numbers of detected eels (Cullen and McCarthy 2000; Lenihan et al. 2025), the effectiveness of above-water lights at guiding or deflecting eels throughout the water column is unknown.

Here, we tested the effectiveness of a large floating LED light array installed at 30° to the river axis shining downwards on the water surface at the Iroquois Water Control Dam (IWCD; Figure 1) at deflecting American eels toward the river-right shore of the St. Lawrence River (Figure 2a,b). Precise three-dimensional positioning of eels via acoustic telemetry was used to evaluate in situ light performance at eliciting behavioral (avoidance) responses of eels to artificial light fields in the form of lateral deflections along the downstream, illuminated length of the light array and causing them to pass through the dam gates (gate group 5; Figure 2c) closest to the river-right shore. Effective experimental guidance of eels by inducing a majority (≥ 80%) of those encountering the light field to follow the intended route

TABLE 1 | Schedule of control nights when the light array installed at the Iroquois Water Control Dam (IWCD) was not operating between sunset and sunrise during fall 2022.

Week	Number of nights off	Off	Off	On
26-Sep	2	28 September	29 September	30 September
03-Oct	1	05 October		06 October
10-Oct	2	12 October	13 October	14 October
17-Oct	1	19 October		20 October
24-Oct	2	26 October	27 October	28 October
31-Oct	1	31 October		01 November
07-Nov	2	08 November	09 November	10 November
14-Nov	1	16 November		17 November
21-Nov	2	22 November	23 November	24 November
28-Nov	1	01 December		02 December
05-Dec	2	05 December	06 December	07 December

Note: "Off" date refers to the evening when the lights were not activated.

may support the potential development and adoption of a full-sized, river-wide eel protection system.

2 | Materials and Methods

2.1 | Eel Selection and Transmitter Implantation

Previous telemetry studies involving USLRLO American eel found that eels > 90 cm TL were more likely to outmigrate through the St. Lawrence River during the fall period (Johnson et al. 2018), independent of morphometric changes associated with silvering (Durif et al. 2009). Measurements from a sample of American eels ($N = 117$) from the fall 2021 trap and transport program were used to estimate a threshold mass at which eels should exceed 90 cm TL based on a logarithmic length-weight regression ($y = 2.784x—11.2103$; $r^2 = 0.859$, $p < 0.0001$). An eel total length of 90 cm corresponded to a mass of 1.78 kg, with 95 cm corresponding to 2.07 kg. Based on these relationships, eels ≥ 1.8 kg in good condition based on visual inspections by OMNR technicians were selected for acoustic transmitter implantation.

During the spring (10 May—3 June) and fall (9–23 September) trap and transport activities in 2022, $N = 199$ eels per period ($N = 398$ total; 1.89–4.92 kg [mean 2.62 ± 0.44 kg] and 92–121 cm [mean 104.0 ± 5.44 cm] TL) were implanted with internal acoustic telemetry transmitters (details provided in Supporting Information 1) within 48 h of their arrival at the Glenora facility. We selected Innovasea V9P-2x-180 kHz HR acoustic transmitters (9 mm diameter; 2.8–3.2 s signal frequency) equipped with depth sensors (34 m max depth, 0.15 m intervals, ±0.5 m accuracy), programmed to high power output levels with expected minimum battery life of ~6 months. After a post-implantation recovery period (≤ 15 min), eels were released directly back into Lake Ontario and all eels swam out of the detection range of an acoustic receiver deployed at the release site to verify their initial survival within minutes.

2.2 | Light and Acoustic Receiver Array Design and Operation

We selected the IWCD ~50 km upstream of the Moses-Saunders generating station (Figure 1) as the location to test the effectiveness of light for eel guidance at the river scale due to it not conflicting with shipping interests in St. Lawrence Seaway system, the relatively narrowness, canalization, and consistent depth (~13 m) of the river at this site, characteristics that make it attractive for potential deployment of a full-scale guidance and collection system. A 216 m long light array was installed starting ~30 m upstream of the IWCD at a 30° angle to the river axis (Figure 2a). The light array consisted of 32 individual 6 m long floating ice barrier sections that extended ~20 cm below the water surface when installed, each equipped with a single high-output light fixture consisting of DuraBrite standard-series LED flood lights rated at 35,000 lm and 5000 K color temperature with 76° beam angle. The light emitted from each fixture was focused using an aluminum shroud with a 45° angled top and bottom and 60° angled sides, forming a linear array of continuous white light aimed downward toward the water surface at an approximate angle of 40° on the river-right side of the array (Figure 2b). The light array operated continuously from sunset to sunrise between 17 August—12 December 2022, except for systematically determined control nights (two consecutive nights 1 week and one night the following week; $N = 17$ nights; Table 1) when the array was not activated to evaluate any effects of the physical structure on eel downstream swimming behavior. Previous acoustic telemetry studies around the IWCD found that ~50% of implanted eels that were detected were passing through the river-right side of the dam (S. Schlueter, pers. comm.; EPRI 2025, Supporting Information 1), concentrated in gate groups 4 and 5 (Figure 2c). The position of the light array was selected with the goal of achieving encounters with the light field in ~50% of migrating eels in this study and deflecting a majority (≥ 80%) of those eels toward the river-right shore and through gate group 5 (Figure 2a–c).

Mapping of the artificial light field during normal nighttime operations took place on 28 October 2022, three nights after a new moon, under relatively low lunar luminosity (13% illumination, 17% relative luminosity; https://nextfullmoon.org/moon-phase-any-date). Light measurements were taken by lowering a light meter (LI-COR spherical underwater quantum sensor model LI-193SA and a LI-COR 2009S lowering frame) equipped with depth sensor (YSI EXO2 multiparameter sonde) and GPS locator at 61 different points around the light array (at a rate of 0.3 m/s to depths of 10 m) and recorded with a LI-COR LI-1400 logger. Light levels were measured as photosynthetically active radiation (PAR, μmol s^{-1} m^{-2}) and averaged over 1 m depth intervals (Figure 2d). Full details of the measurements and analytical approach are provided in EPRI (2023). Although we did not collect turbidity measures as part of this study, the upper St. Lawrence River generally has very low levels of turbidity (e.g., independent measurements of water clarity at IWCD have recorded daytime Secchi depth of 4.9 m in July 2021: https://data.waterrangers.com/locations/iroquois-dam; historic Secchi depths of 6–8 m: Farrell et al. 2010) as it is the outflow for the morphometrically oligotrophic Lake Ontario (Twiss et al. 2022; Dordoni et al. 2024). Previous monitoring has not identified any significant diel variation in plankton abundance in the St. Lawrence River downstream of Lake Ontario (Twiss et al. 2010).

Innovasea HR2-180 kHz receivers (N = 27) and three reference tags were deployed in a grid pattern (~100 m spacing) intended to maximize detection efficiency of acoustic tag signals from implanted eels in the vicinity of the light array while providing coverage throughout the width of the river near the dam (Figure 2c). Receiver deployments and retrievals were performed by USFWS on 24 August and 5 December 2022, respectively. Signals detected by multiple (≥ 3) stationary receivers were geospatially positioned (GPS latitude and longitude, with depth measurements for each position in 0.15 m intervals) via hyperbolic triangulation by Innovasea using their Vemco Positioning System (VPS) software.

2.3 | Light Guidance Analysis

VPS positions (see Supporting Information 1 for description of data filtering criteria) for each individual eel were plotted in Google Earth Pro and color-coded by 2 m depth intervals. Nearest distances (m) to both the light array and the IWCD structure were measured for each detected eel. The inter-position linear distances and depth estimates from the integrated pressure sensors in the acoustic tags provided three-dimensional (XYZ) coordinates for individual acoustic signals in addition to associated timestamps. Inter-position changes were calculated using trigonometry based on the XYZ coordinates and depth measurements to obtain vector lengths (m) and speeds (m/s, in 2-, and 3-dimensions). Vectors were converted into degrees, with the absolute value of the difference between vector degree heading of each position and 90° calculated such that 0° indicated travel parallel to the river axis (directly downstream) and 90° indicated travel toward either shore (perpendicular to the river axis). These inter-position changes were examined for effects of the light array using linear mixed-effects models (LMEs) with light treatment, tagging season, and distance from the array as explanatory variables and eel tag number as a random error term to account for individual variability in movement behavior (Wilson et al. 2010). If an LME returned a singular model fit, the model was simplified to a general linear model by removing the random error term. Additionally, individual positioning maps were examined to identify whether or not the eel demonstrated a diving response to light (if depth increased by ≥ 4 m for two or more successive positions), ostensibly to avoid higher illumination levels, and at what distance from the light array each dive began.

Two χ^2 contingency tests were used to evaluate the relative frequencies of qualitative responses of guidance candidate eels to the light array (diving or horizontal deflections) based on visual inspections of their individual traces. Diving responses consisted of: (i) no apparent response (Figure SM1-1a); (ii) changes in depth of 2 m or more (Figure SM1-1b); and (iii) diving under the array (Figure SM1-1c). Horizontal deflection responses consisted of (i) no apparent response (Figure SM1-1a); (ii) equivocal responses (Figure SM1-1d); (iii) crossing (swimming under) the array (Figure SM1-1b,c); (iv) swimming parallel to the array (Figure SM1-1e); and (v) apparent horizontal deflection consisting of a notable change in approach angle to avoid the array and/or the illuminated field (Figure SM1-1f). In addition, whether or not guidance candidate eels demonstrated dives under the array (binary outcome) was examined in a generalized linear model (GLM) against treatment with a binomial error distribution while distances from the array at which diving was observed were examined with Welch's two-sample *t*-test.

All analyses used R version 4.3.1 (R Core Team 2023). LMEs were constructed and analyzed with 'lme4' (Bates et al. 2015) and 'lmerTest' (Kuznetsova et al. 2017), general and generalized linear models with the 'car' package (Fox and Weisberg 2019), and data figures were generated with 'ggplot2' (Wickham 2016), 'cowplot' (Wilke 2020), and the 'viridis' color package (Garnier et al. 2023).

3 | Results

3.1 | Light Field Mapping, VPS Analysis, and Light Treatment Groups

Light was detected at greater than ambient levels at a depth-averaged distance of ~25 m from the array (Figure 2d), up to 51 m from the array in the 4–5 m depth interval, and receded below ambient light levels at 25 m or less from the array at depths greater than 5 m (illustrated in Figure 3a). We selected 25 m as the threshold distance from the light array to classify an eel as having encountered the light stimulus and designated these eels as light guidance candidates.

The acoustic receiver array at IWCD recorded a total of N = 201,926 detections from N = 201 unique tags (out of 398 tags deployed). Individual transmissions were detected by as many as 21 out of 27 receivers with most signals (59%) detected by 6–10 receivers, far exceeding the three concurrent detections required to position the location of a signal. From these detections, a total of N = 23,078 VPS positions (Figure SM1-2a) were calculated for N = 193 eels (92–121 cm TL, mean 104.6 cm ± 5.4 cm SD; 1.95–4.28 kg, mean 2.58 kg ± 0.42 kg SD).

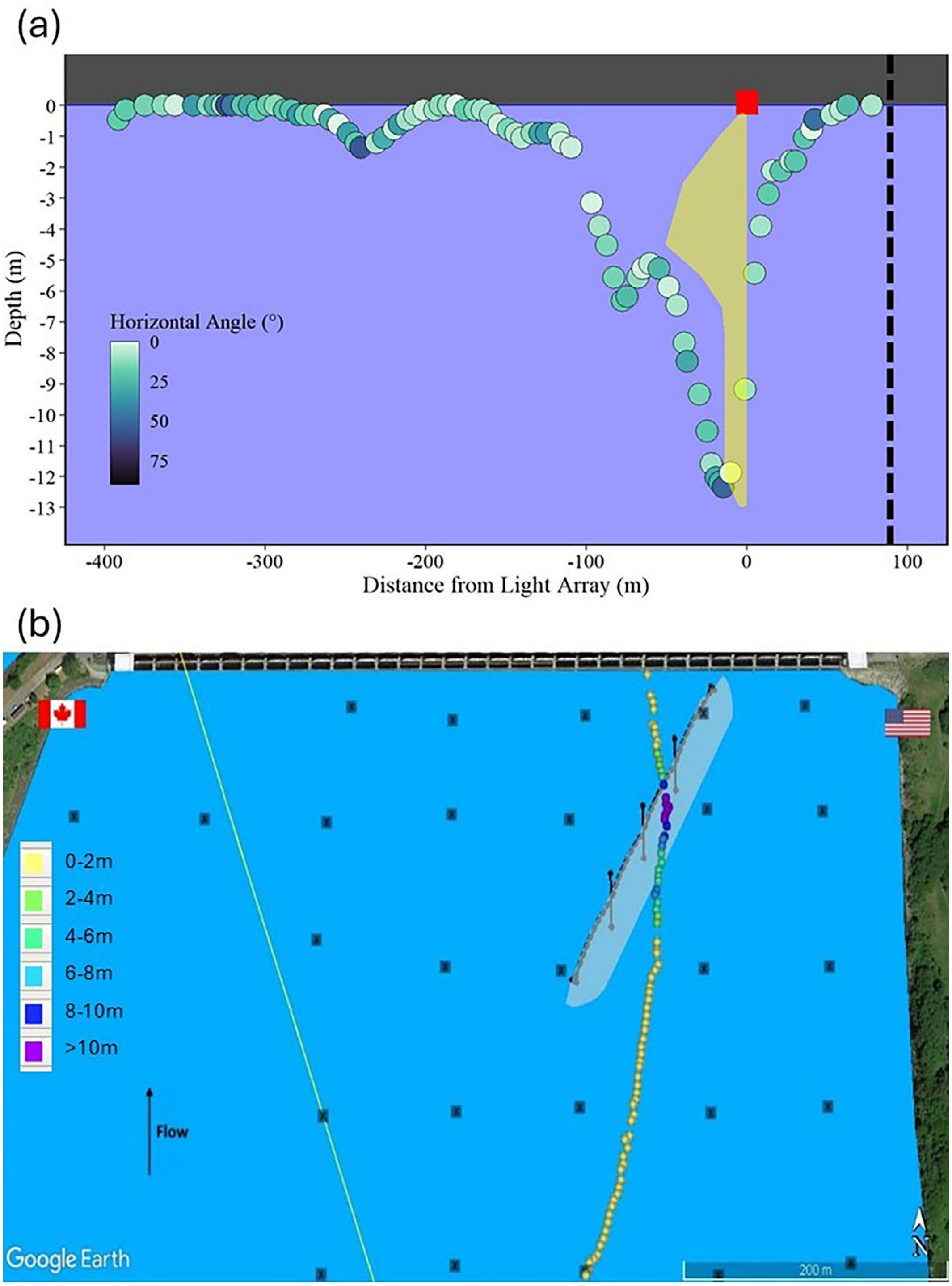

FIGURE 3 | Example out-migration path of one American eel (*Anguilla rostrata*; tag ID 1922) surgically implanted with a V9P-2x-180 kHz acoustic transmitter. (a) The eel's depth profile as it approached the floating light array (red square) and the putative light field (yellow polygon) with downstream swim angles (0° = parallel to stream axis, 90° = perpendicular to stream axis) indicated by the point colors. The upstream face of the Iroquois Water Control Dam (IWCD) is represented by the vertical dashed line. (b) Top view of the eel's path detected by stationary HR2-180 kHz acoustic receivers (black squares) with positions color-coded by depth, the 216 m long floating light array indicated by the diagonal black line, and the putative light field by the white polygon. [Color figure can be viewed at wileyonlinelibrary.com]

Applying an HPE filter of 0.4 (i.e., ≤ 4 m displaced between successive positioned signals [average 3 s], or 1.33 m/s swim speed) retained 63.34% of positions (N = 14,619; Figure SM1-2b) while applying the RMSE filter of < 2 retained 89.22% of positions (N = 20,590; Figure SM1-2c). Applying both filters retained 60.48% of positions (N = 13,958; Figure SM1-2d), with positions that were filtered out tending to cluster at the upstream and downstream peripheries of the receiver array (Figure SM1-2a–c). A concurrent visual evaluation of all points for each individual eel found these filtering thresholds retained positions that generated reasonable tracks for each fish (Figure 3b; Supporting Information 2). A secondary visual inspection of the tracks of each individual fish found a total of 20 additional positions among all individuals (< 0.01%) that deviated from biologically reasonable movement patterns (i.e., positions varying laterally from the path indicated by preceding and following points that would require swim speeds greater than observed throughout the rest of the path). These 20 outlier positions were distributed across 13 different eels and were removed from the dataset for analysis. Filtered positions for each eel were plotted and color-coded by depth (2 m intervals). A complete set of depth profile plots (Figure 3a) and VPS positions (Figure 3b) for each eel is provided in Supporting Information 2.

Among the positioned eels, 74.5% ($N=144$) were detected at night when the light array was operating. The remaining 25.5% ($N=49$) were detected on nights when the array was not operating (20.8%; $N=40$) or during the daytime (4.7%; $N=9$) and were assigned to the control treatment (Table 2). Although we could not assign fish to treatment groups a priori due to the variability and uncertainty in outmigration timing, we planned control nights to account for ~20% of the operating period with the goal of detecting a corresponding percentage of out-migrating eels, which matched well with the observed treatment distributions. A full summary of the sample sizes of potential guidance candidates based on light array proximity is presented in Table 2.

3.2 | Qualitative Light Field Responses: Vertical (Diving) and Horizontal (Deflection) Outcomes

Within the subset of eels ($N=51$) that passed within 25 m of the light array, 84.3% ($N=43$) did so when the array was operating (light treatment) and the remainder ($N=8$) when it was not (Table 2). Among the control eels, 50% ($N=4$) passed through the receiver array during daytime. Visual inspection of depth changes indicated by the 2 m interval bins on the individual positioning maps (Figure 3b; Supporting Information 2) indicated that the frequency of categorical depth responses (dive, uncertain, none) differed significantly between the light and control treatments (contingency test: $\chi^2=8.903$, df $=2$, $p=0.012$; Figure 4a). A greater percentage of control treatment eels demonstrated no response and did not dive or deviate direction than light treatment eels (50% vs. 9%, respectively). Conversely, a greater percentage of light treatment eels dove (≥ 4 m) under

TABLE 2 | Sample size summary of American eel (*Anguilla rostrata*) light guidance candidates at the Iroquois Water Control Dam (IWCD) based on light treatment, VPS positioning, and measured nearest distance (m) to the floating light array overall and divided by treatment (whether or not the light array was operating).

	Nearest distance from the array (m)						
Number of eels	**0**	**25**	**40**	**51**	**Total detected with VPS**	**Total detected during the day**	**Total detected at night**
Total	32	51	65	73	193	9	184
Light	25	43	53	61	144	0	144
Control	7	8	12	12	49	9	40

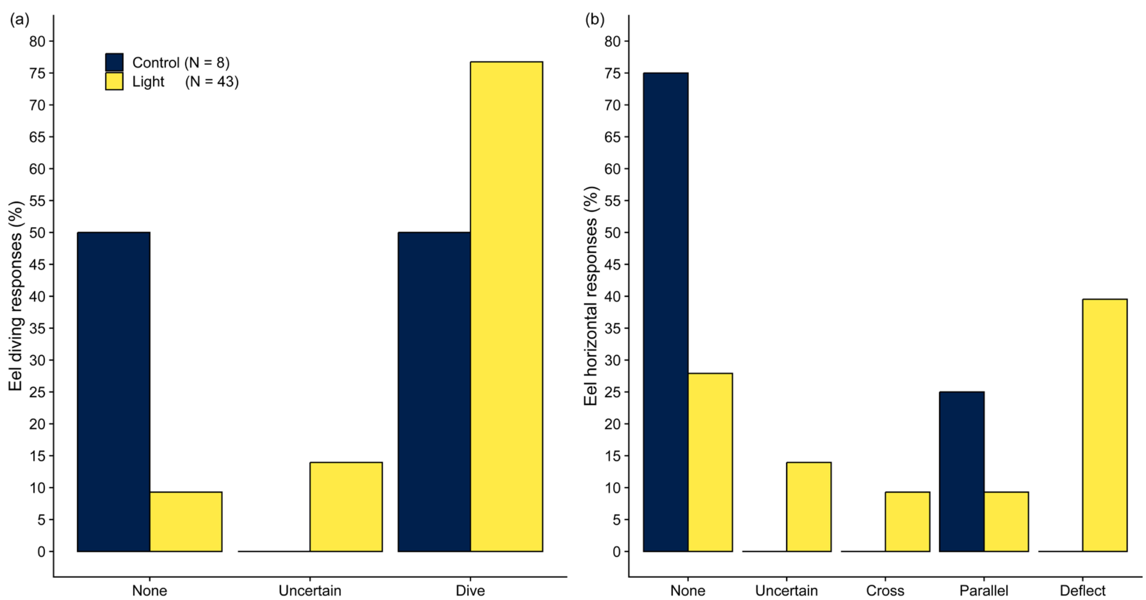

FIGURE 4 | Frequencies (%) of qualitative (a) diving and (b) horizontal responses of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the light array at the Iroquois Water Control Dam (IWCD) when it was turned off (control) or operating (light). Examples of each response category are illustrated in Figure SM1-1. [Color figure can be viewed at wileyonlinelibrary.com]

the array than control eels (76.7% vs. 50%; Figure 4a). In the light treatment, however, 90.7% (N = 39) of eels dove by at least 2 m ("uncertain" and "dive" responses together; Figure 4a). Light treatment eels were significantly more likely to demonstrate diving responses than control fish (binomial GLM: LRT $\chi^2 = 6.607$, df = 1, $p = 0.01$). During the day, however, in $N = 4$ control eels, 50% also demonstrated diving responses ≥ 4 m, suggesting that some eels may have been responding to the floating structure itself independent of the light treatment. Distance from the array to the beginning of the dives when they did occur at night did not differ significantly between treatments (Welch's two-sample t-test: $t_{0.05(2),4.18} = -1.924$, $p = 0.124$), although dives generally started at a greater distance in the light treatment (mean 51.8 m) than in the control treatment (mean 27.2 m; Figure 5).

Guidance candidate eels demonstrated significant differences (contingency test: $\chi^2 = 11.35$, df = 4, $p = 0.023$) in frequencies of the five horizontal deflection response categories (none, equivocal response, swimming parallel to the array, changing direction to cross the array, and horizontal deflections; Figures SM1-2 and 4b). In the control group, 25% swam parallel to the array, while 75% demonstrated no apparent response. In the light treatment group, 39.5% of eels demonstrated putative horizontal deflections, while 9.3% swam parallel to the array, and 13.9% demonstrated equivocal responses (Figure 4b). However, 27.9% demonstrated no apparent horizontal deflection response, and 9.3% changed direction to swim toward and under the operating light array (Figure 4b). Overall, a greater percentage of eels in the light treatment demonstrated some degree of horizontal guidance or deflection (including "parallel" and "deflect") by the light array than control fish (48.8% vs. 25%, respectively; Figure 4b), while none of the control eels demonstrated "uncertain" or "cross" responses (Figure 4b).

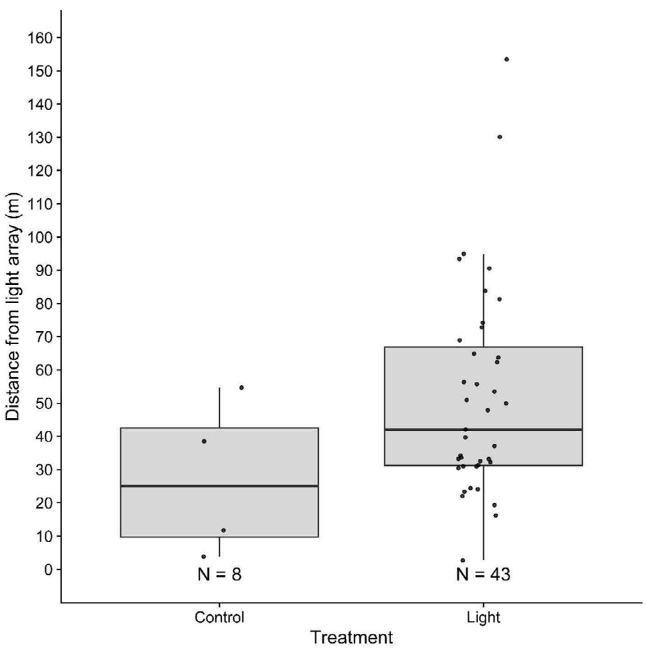

FIGURE 5 | Distances at which each out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the light array at the Iroquois Water Control Dam (IWCD) started their dive. Diving was defined as an increase in depth of at least 2 m and distance was measured to the nearest point of the light array in Google Earth. 50% (N = 4) of control eels and 9.3% (N = 4) of light treatment eels did not demonstrate any diving behavior under the floating light array and were excluded from this analysis.

3.3 | Quantitative Light Field Responses: LMEs Of Guidance Candidates

Mean swimming depth increased as eels approached the light array when it was operating, with mean depth for light treatment eels > 9 m at their closest distance from the array (Figure 6a). Control treatment eels also dove slightly to a mean depth of ~2 m as they approached the array structure, and this smaller response occurred closer to the array than in the light treatment (within 25 m of the array; Figures 5 and 6a). Eel depths varied significantly between treatments (deeper in the light treatment) and with distance from the light array (farther in the light treatment), with a concurrent significant two-way interaction between treatment and distance and a three-way interaction between treatment, tagging season, and distance, as well as between individual eels as a random error term (Table 3).

Forward swimming speed (parallel to stream flow) was significantly influenced by light treatment, distance from the array, the treatment × distance interaction, and individual eels as the random error term (Table 4). Forward speed increased slightly in control treatment eels as they moved downstream, but decreased sharply as eels approached the light array and then returned to previous levels as they approached the water surface downstream of the array (Figure 6b). Horizontal swimming speed (perpendicular to the river axis or toward either shore) varied significantly with distance to the array but was not influenced by any other model term (Table 5). Although light treatment did not have a significant effect on horizontal speeds as a main effect, light treatment eels did demonstrate marked decreases in horizontal speeds as they approached within 100 m of the light array (Figure 6c).

In contrast to the horizontal and forward swim speed responses, diving speed (rate of depth change) increased notably in both light (~0.125 m/s) and control (~0.025 m/s) treatment fish (Figure 6d) as they approached the array, followed by returns to baseline depth and swim speeds after they passed the array. Statistically, diving speed was significantly influenced only by the distance from the light array and the treatment × distance interaction (Table 6). A visual inspection of the results (Figure 6d) suggests diving speed response of the control treatment eels more closely resembled that of the light treatment eels than did the other responses, reflecting the non-statistically significant differences between treatments (Table 6). Including individual eel as a random error term created a singular model fit, so this response was analyzed in 3-way factorial ANOVA with the same model structure (excluding the random error term) as the LMEs.

Light treatment eels demonstrated mean horizontal deviations (i.e., deflections) of ~5° overall from their original trajectories as they approached the array and then returned to their approximate initial trajectories, while control treatment eels demonstrated consistent approach angles throughout their range of

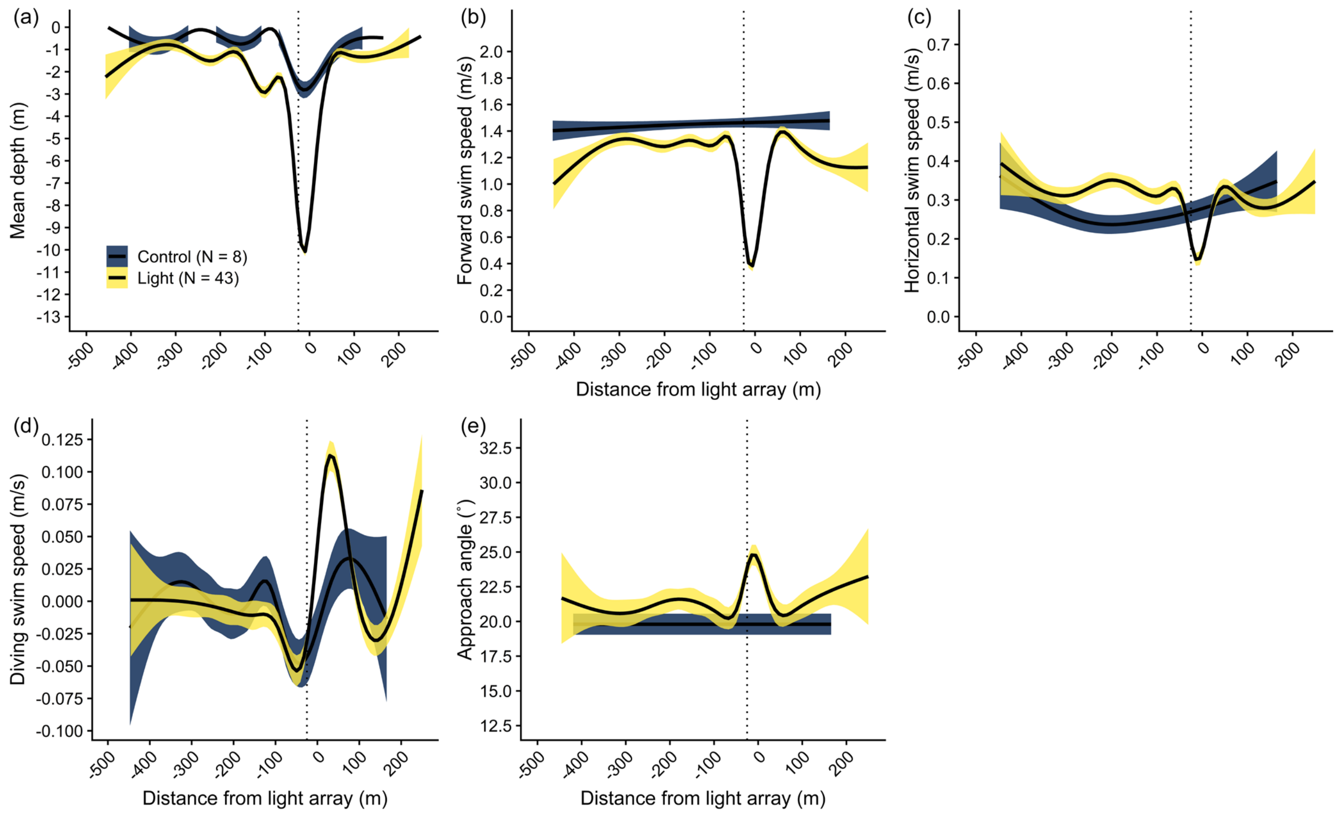

FIGURE 6 | Mean (a) depths, (b) forward swim speeds, (c) horizontal swim speeds, (d) diving swim speeds, and (e) angles of approach (0° = parallel to river axis, 90° = perpendicular to river axis) of out-migrating American eels (*Anguilla rostrata*) approaching the Iroquois Water Control Dam (IWCD) within 25 m of the 216 m long floating light array when the array was operating (light, yellow) or not (control, grey) during fall 2022. Shaded areas represent standard errors and the vertical dashed lines indicate 25 m upstream distances. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 | LME results for depth (m) of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the floating light array at the Iroquois Water Control Dam (IWCD) during fall 2022. Bold font indicates statistical significance at $\alpha = 0.05$.

Predictor	F	df	*p*
Treatment	**5.440**	**1, 48.9**	**0.0226**
Tagging Season	0.296	1, 48.9	0.589
Distance from the light array	**197.288**	**1, 4645**	**< 0.0001**
Treatment × Season	0.399	1, 48.9	0.531
Treatment × Distance	**20.906**	**1, 4645**	**< 0.0001**
Season × Distance	0.846	1, 4645	0.358
Treatment × Season × Distance	**8.407**	**1, 4645**	**0.00375**
Eel ID (random)	**LRT $\chi^2 = 2988.1$**	**1**	**< 0.0001**

TABLE 4 | LME results for forward swim speed (m/s) of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the floating light array at the Iroquois Water Control Dam (IWCD) during fall 2022. Bold font indicates statistical significance at $\alpha = 0.05$.

Predictor	F	df	*p*
Treatment	**6.860**	**1, 56.5**	**0.0113**
Tagging Season	0.269	1, 56.5	0.606
Distance from the light array	**39.479**	**1, 4581.4**	**< 0.0001**
Treatment × Season	1.517	1, 56.5	0.223
Treatment × Distance	**11.838**	**1, 4581.4**	**< 0.001**
Season × Distance	1.419	1, 4581.4	0.234
Treatment × Season × Distance	0.270	1, 4581.4	0.603
Eel ID (random)	**LRT $\chi^2 = 1194.8$**	**1**	**< 0.0001**

detection (Figure 6e). The light treatment itself did not have a significant effect on the change in angle of approach, but distance from the array and the treatment × distance interaction did (Table 7).

3.4 | Gate Usage at IWCD

Eels ($N = 193$) demonstrated some overall patterning in their usage of different gate groups at IWCD (contingency test:

TABLE 5 | LME results for horizontal swim speed (m/s, perpendicular to the river axis) of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the floating light array at the Iroquois Water Control Dam (IWCD) during fall 2022. Bold font indicates statistical significance at α = 0.05.

Predictor	F	df	*p*
Treatment	0.0093	1, 57.0	0.923
Tagging Season	0.0704	1, 57.0	0.792
Distance from the light array	**4.174**	**1, 4487.8**	**0.0411**
Treatment × Season	0.951	1, 57.0	0.334
Treatment × Distance	**9.753**	**1, 4487.8**	**0.00180**
Season × Distance	0.199	1, 4487.8	0.655
Treatment × Season × Distance	3.366	1, 4487.8	0.0666
Eel ID (random)	**LRT $\chi^2 = 323.38$**	**1**	**< 0.0001**

TABLE 6 | ANOVA results for diving speed (m/s, toward the substrate) of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the floating light array at the Iroquois Water Control Dam (IWCD) during fall 2022. Bold font indicates statistical significance at α = 0.05.

Predictor	F	df	*p*
Treatment	0.483	1, 4608	0.487
Tagging Season	0.927	1, 4608	0.927
Distance from the light array	**16.102**	**1, 4608**	**< 0.0001**
Treatment × Season	0.134	1, 4608	0.714
Treatment × Distance	**4.776**	**1, 4608**	**0.0289**
Season × Distance	0.539	1, 4608	0.463
Treatment × Season × Distance	0.0052	1, 4608	0.942

Note: Model was singular with the random error term so a GLM was used for this response.

TABLE 7 | LME results for angle of approach (where 0° = parallel to the river axis and 90° = perpendicular to the river axis) of out-migrating American eel (*Anguilla rostrata*) that passed within 25 m of the floating light array at the Iroquois Water Control Dam (IWCD) during fall 2022. Bold font indicates statistical significance at α = 0.05.

Predictor	F	df	*p*
Treatment	3.246	1, 55.2	0.0771
Tagging Season	0.612	1, 55.2	0.437
Distance from the light array	**4.788**	**1, 4557.5**	**0.0287**
Treatment × Season	0.0084	1, 55.2	0.927
Treatment × Distance	0.194	1, 4557.5	0.659
Season × Distance	1.831	1, 4557.5	0.176
Treatment × Season × Distance	0.689	1, 4557.5	0.407
Eel ID (random)	**LRT $\chi^2 = 607.97$**	**1**	**< 0.0001**

$\chi^2 = 22.02$, df = 5, $p < 0.001$), with most eels detected in the river-right half of the river channel (gate groups 3–5; 77%) and the largest number of eels seeming to use gate group 5 (30%), nearest the river-right shore (Figures 2c, 7a). In eels detected during the day ($N = 9$), the most-frequented gate groups were 4 and 5 (each 33%; Figure 7b) followed by group 3 (22%) although there was no statistically significant patterning detected ($\chi^2 = 3.78$, df = 4, $p < 0.437$). At night, light treatment eels demonstrated the same general pattern of gate group usage ($\chi^2 = 23.36$, df = 4, $p < 0.001$) as all eels (77% in the river-right half of the river and 31% using gate group 5; Figure 7a vs. Figure 7c), reflecting the large sample size in this group ($N = 144$). Control treatment eels detected at night ($N = 40$), however, demonstrated equivocal preferences between gate groups ($\chi^2 = 2$, df = 4, $p = 0.736$), with similar passage rates across the dam (Figure 7d) but more eels detected in the river-left portion of the river than in light treatment eels (65% vs. 23%, respectively). Qualitatively, the light treatment (Figure 7c) did not differ from the all-eels grouping (Figure 7a) and appeared to result in similar usage patterns of the gate groups. However, if the non-specific gate group usage of control eels (Figure 7d) is indicative of typical movement patterns, the light treatment may have been the cause of the shift toward groups 3–5 (Figure 7c). While this gate usage patterning is consistent with concentrating eel passage toward the river-right half of the dam but not moving a majority of all eels through gate group 5. In the 25 m guidance candidate light treatment ($N = 43$), 28% of eels used gate group 5, 58% gate group 4, and 14% gate group 3, with none passing through groups 1 or 2. The control treatment guidance candidates ($N = 8$), however, used only gate groups 4 (75%) and 5 (25%), indicating that light was not influencing the movement of eels that passed within 25 of the array toward the river-right gates.

4 | Discussion

Despite widespread efforts to exploit the sensory physiology and behavior of wild animals to achieve behavioral guidance away from anthropic hazards, there is increasing evidence that responses are highly variable among individual organisms and often yield only modest levels of attraction or repulsion (Elmer et al. 2021). Indeed, that is exactly what was observed here, with eels demonstrating considerable variability in their responses to a light field produced by a floating LED array on the St. Lawrence River. Light appeared only marginally effective at laterally deflecting out-migrating eels toward the intended target area on one side of the river with regard to both frequency and magnitude of eel responses, with 39.5% of light treatment eels demonstrating some degree of horizontal deflection. When eels encountered the operating light array,

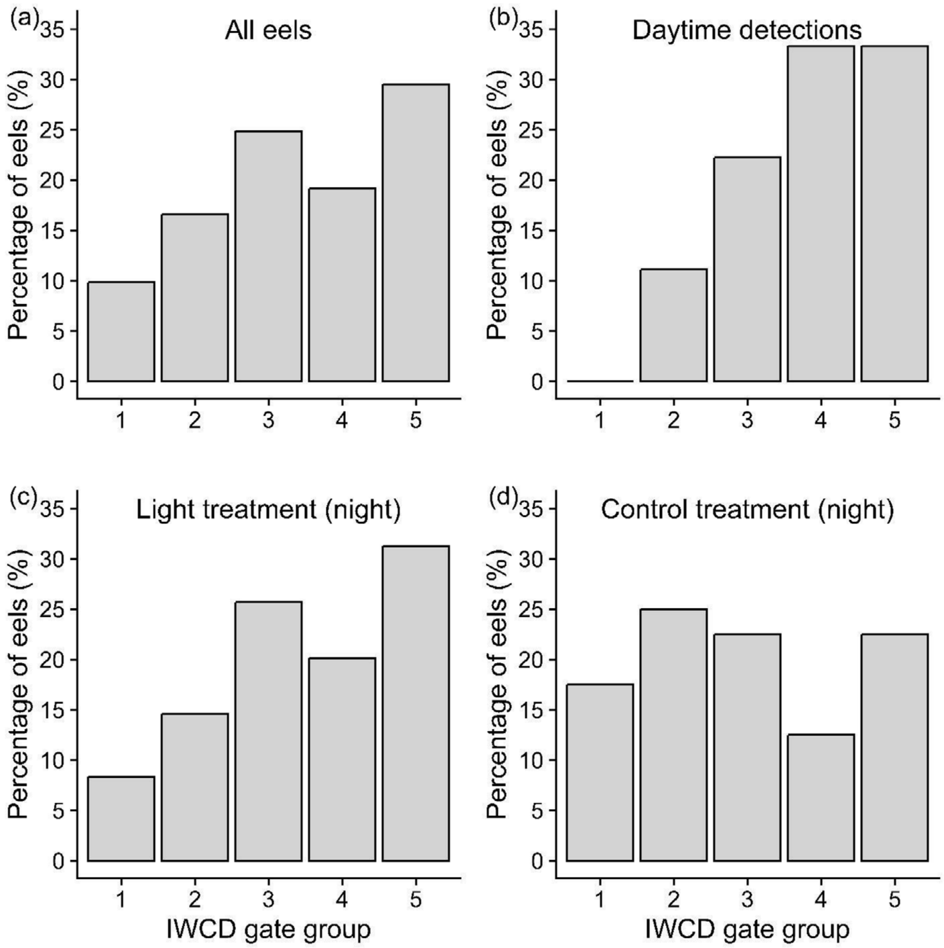

FIGURE 7 | Frequencies of gate group usage at the Iroquois Water Control Dam (IWCD) (where 1 = river-left shore and 5 = river-right shore; Figure 4) by VPS-positioned out-migrating American eel (*Anguilla rostrata*) during fall 2022. (a) All eels ($N = 193$); (b) eels detected during the day ($N = 9$); (c) eels detected at night while the light array was operating ($N = 144$); (d) eels detected on control nights when the light array was not operating ($N = 40$).

they decreased forward swim speeds and demonstrated minor angular changes in their forward swim paths while 76.7% of them dove toward the substrate and tended to pass under the array itself instead of swimming away horizontally. Control eels, by contrast, made much more shallow dives that started significantly closer to the array structure than the dives of light treatment eels. Together, these patterns suggest that the artificial light field played a greater role in eliciting the deep dive responses observed under the array than the physical presence of the array itself.

While the light treatment was associated with a general tendency to use the river-right side of the river (gate groups 3–5) to move downstream compared to the control treatment, the effect was insufficient to achieve the desired guidance outcomes (≥ 80% of guidance candidate eels using gate group 5) for the purpose of bypassing or concentrating and subsequently collecting out-migrating eels. The observed responses may reflect individual variability in behavioral responses to light, although the results of the light field mapping indicate that the light stimulus was applied unevenly along the length of the array and throughout the water column. There was also an unexpected amount of illumination from the IWCD itself along with reflections from the river-right shore that may have contributed to different exposure levels between eels, providing an alternative explanation for the observed variability in responses.

Despite the rather equivocal effects of the light array, acoustic telemetry was highly successful at positioning eels detected by the receiver array at IWCD, with more than 200,000 tag detections yielding close to 14,000 unique positions for $N = 193$ eels. Although acoustic transmitters were only implanted into large eels that surpassed the migratory size threshold in this system and all of the implanted eels ($N = 398$) swam out of detection range within minutes of their release, only half ($N = 201$) were subsequently detected downstream at IWCD. The planned control nights (~20% of the operating period) effectively captured ~22% of out-migrating eels in the control treatment but only 8% of those control eels passed within the 25 m guidance threshold of the light array, highlighting the challenge of studying the behavior of free-swimming fishes in a large river system using an impact and control experimental design.

Our acoustic telemetry data was, however, inconsistent with visual observations (videos) of eels approaching a light array recorded in earlier attempts at light guidance of eels in the St.

Lawrence River upstream of IWCD (K. McGrath, unpublished data, reviewed in Versar Inc. 2009; reproduced in EPRI 2025, Supporting Information 1). Those videos, recorded from above the water surface, show eels swimming downstream at or near the water surface as they approached a light field. Those eels tended to continue to swim downstream at consistent depths but alter their horizontal trajectories to follow the margin of the light field, which was positioned at an angle to the stream current. An important difference in lights used in the earlier study was that they were attached to 28 columns spanning an 80 m length that extended vertically throughout the water column, instead of floating above the water surface in the present study. In general, it seemed difficult for those earlier eels to increase their tail beats or change their approach angles to move perpendicularly away across the river width to avoid the light stimulus. When an eel swims downstream in a fast-flowing environment and changes its direction angle laterally, it becomes positioned more perpendicular to the flow and consequently may be carried downstream by the current, impeding lateral movement over longer distances. This may explain their demonstrated diving responses to the floating light array in this study in that it may be easier to dive than to divert laterally in a strong river current, whereas illuminated columns may have disrupted water flow enough to allow eels to change their horizontal direction (Piper et al. 2015). Further, the submerged light columns presented their visual stimulus throughout the water column, whereas illumination from above the water surface decreased toward the substrate.

A laboratory-based study of LED effectiveness at downstream guidance of juvenile white sturgeon (*Acipenser transmontanus*) in an artificial stream flume presented fish with a submerged LED light, a reversed louver array, and the combination of the two (Ford et al. 2017). LED light alone had no guidance effect on white sturgeon (Ford et al. 2018), while the louver array alone significantly increased the rates of simulated bypass use by sturgeon moving downstream, and pairing the LED light with the louver array further increased bypass usage (Ford et al. 2017). Similar to Ford et al. (2017), McGrath (unpublished data) tested without the lights on and the accompanying supporting structures remaining in the water; they deployed nets downstream of their array on both treatment (lights on) and control (lights off) nights and reported capture of greater numbers of deflected eels on light treatment nights. Likewise, an 80.6% deflection efficiency for European eel was observed using LED lights mounted on an in-water structure (Lenihan et al. 2025). Cullen and McCarthy (2000), in contrast, reported fewer European eels captured in nets deployed at an eel weir on the River Shannon when bridge-mounted navigation lights were operating, suggesting that eels can avoid top-mounted lights in the absence of hydraulic cues.

During spawning migrations back to the Sargasso Sea, American eels have demonstrated diel vertical migrations to depths up to 240 m over the Scotian Shelf (Béguer-Pon et al. 2015). Farther south, silver-stage eels generally migrate at depth, moving even deeper during the day (up to ~1000 m: Aarestrup et al. 2009; Béguer-Pon et al. 2017). Here, we detected eels diving under the light array on control nights although to lesser depths than on light nights (~2 m vs. ~8 m, respectively), indicating that some eels were responding to the hydraulic cues from the floating structure independent of light with dives deeper than required to avoid the ~20 cm of submerged float sections, and that the addition of light elicited greater diving responses. Collectively, the current study and earlier attempts (K. McGrath, unpublished data; Ford et al. 2017, 2018; Elvidge et al. 2018) in eels and white sturgeon point to a complementary effect of visual and hydraulic cues on fish guidance. In the case of eels that demonstrate a tendency to dive to greater depths during the day, light alone may be insufficient for guidance systems aimed at eliciting horizontal avoidance movements when light intensity is not uniform throughout the water column.

Based on these observations and uncertainties, we cannot definitively conclude whether, under the conditions and with the apparatus tested here, light as a stand-alone technology is an effective tool for guiding eels away from hazards (e.g., turbines) or toward safer downstream migration paths (e.g., bypasses) or collection devices in large systems like the St. Lawrence River. Several recent studies on behavioral guidance of eel recommend multimodal systems that exploit more than one sense (notably light, sound, hydrodynamics, and electricity: Piper et al. 2015; EPRI 2016; EPRI 2017a, 2017b; EPRI 2018; Piper et al. 2019; Pratt et al. 2021; MacLeod et al. 2025), and potentially incorporating physical screening (Versar Inc. 2009; Piper et al. 2019; Deleau et al. 2020; Meister et al. 2021; Miller et al. 2022). We deliberately chose to deviate from an earlier study at IWCD that used submerged lights (K. McGrath, unpublished data; reviewed in Versar Inc. 2009) to avoid the frequent maintenance required because of debris accumulation on underwater light supports. However, illuminating the water column from above the water surface may not have delivered the stimulus as effectively to the target eels as submerged lighting that delivered stimulus at the eels' eye level, suggesting that different light technologies and configurations warrant continued study of their effectiveness as behavioral guidance tools in the St. Lawrence River.

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Ethics Statement

All work reported here was consistent with the Canadian Council on Animal Care guidelines and approved by the Carleton University Animal Care Committee (protocol nos. 102935 and 102925).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data and code for the analysis and figures are archived and publicly available through the Open Science Framework (DOI: 10.17605/OSF.IO/E6T3S) at https://osf.io/e6t3s/.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information 1:** Detailed description of surgical implantation of acoustic transmitters and VPS data filtering criteria for light guidance analysis. Two figures consist of (1) six example qualitative responses of out-migrating American eels to the floating LED light array (Figure SM1-1), and (2) visualizations of all VPS data points before and after filtering for HPE and RMSE thresholds (Figure SM1-2). **Supporting Information 2:** Filtered VPS positions on a map image for each American eel detected in the acoustic receiver array accompanied by a data box summarizing key individual characteristics (eel size, tagging season, light treatment, time/length of detection, moon phase at time of detection, qualitative response to the floating light array, putative gate passage at the Iroquois Water Control Dam, etc.). Immediately following each map image we present side-view images of the eel's downstream migration throughout the entire range of detection and zoomed-in to focus on the 50 m immediately upstream of the floating light array, illustrating individual swim depth and trajectory changes, with VPS points color-coded by downstream swim angle. Eel images are grouped by treatment (Light treatment passing within 25 m of the light array; Light treatment within 26–40 m of the array; Light treatment within 41–50 m of the array; Control treatment passing within 25 m of the array; Control treatment within 26–40 m of the array; Control treatment within 41–50 m of the array; Light treatment passing > 51 m from the array; Control treatment passing > 51 m from the array).