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Research Article

Effects of vertical electric barrier on the behaviour of common carp

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Abstract

When managing invasive fishes, permanent barriers may be best in preventing spread; however, they may not be feasible due to costs and logistical constraints. Alternatively, non-permanent barriers using electricity, light, sound, pressure, bubbles, CO_2, and other stimuli are being developed and deployed in efforts to limit the spread of aquatic invasive species or to achieve fish guidance and conservation. However, the effectiveness of these barriers is quite variable and testing is often lacking for both target and non-target species. We conducted a series of laboratory trials to examine the effects of a vertical electric barrier on behaviour of common carp *Cyprinus carpio* (Linnaeus, 1758). In response to the electric field, common carp reduced passing the electric barrier significantly, exhibiting different behaviours when interacting with the electric barrier, and spent more time away from the electric barrier when it was turned on during the stimulus period compared to pre- and post-stimulus periods. Our results suggest that a relatively weak electric gradient (i.e., voltage gradient: 0.2–0.4 $V \cdot cm^{-1}$, power density: 3–42 $\mu W \cdot cm^{-3}$) can inhibit the movement of common carp. Our results also highlight the importance of detailed examination of behavioural responses of target species when evaluating and considering fish-deterrent technologies.

Key words: neptun, movement barrier, guidance, invasive species, Asian carps

Introduction

In recent years, bighead carp *Hypothalmichthys nobilis* (Richardson, 1845), silver carp *Hypothalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844), grass carp *Ctenopharyngodon idella* (Valenciennes in Cuvier and Valenciennes, 1844), and black carp *Mylopharyngodon piceus* (Richardson, 1845), collectively known as Asian carps, have become established in the Mississippi River basin and have had significant ecological and socio-economic impacts on its ecosystem (Kolar et al. 2005; Chapman and Hoff 2011). Potential movement of these invasive species from the Mississippi River basin into the Great Lakes basin has become a concern (Cudmore et al. 2012, 2017; Currie et al. 2017). Asian carps have a very high likelihood of successful establishment should they enter the Great Lakes system and their spread will negatively affect lake ecosystems in the long term (Cudmore et al. 2012, 2017). Similarly, common carp *Cyprinus carpio* (Linnaeus, 1758) is an introduced species in Canada, United States, and Australia (Weber and Brown 2009). The common carp are considered harmful to native fish populations as they increase the turbidity of the water and destroy submerged aquatic plants (Scott and Crossman 1973; Weber and Brown 2009). Due to ecological and environmental impacts caused by common carp, there have been substantial research and management efforts in the world, including North America (Sisler and Sorensen 2008; Huntingford et al. 2010; Zielinski et al. 2014; Kim and Mandrak 2016).

Deterrent systems are used in management applications as barriers to prevent fishes from spreading or to guide fishes away from sources of mortality (e.g. hydropower turbines; Adams et al. 2001). There are two main types of deterrent systems: physical and nonphysical barriers. Physical barriers (e.g. vertical or horizontal bars, screens, barrier nets, low-head dams) physically prevent fish movement (Taft et al. 2001). However, physical barriers are prone to fouling and, therefore, require regular cleaning and maintenance. In addition, depending on scale, barriers can be quite costly, may inhibit economic activities such as shipping, and may permanently alter landscapes and flow regimes. In contrast, nonphysical barriers use behavioural stimuli to divert fishes and may be species specific in some instances (e.g. Noatch and Suski 2012). A variety of nonphysical barriers have been developed and deployed to exclude fishes from undesirable locations using a combination of electricity, sound, strobe light, bubble, carbon dioxide, electricity, and pulse pressure (Maes et al. 2004; Noatch and Suski 2012; Kates et al. 2012; Ruebush et al. 2012; Johnson et al. 2014; Romine et al. 2015; Vetter et al. 2015; Murchy et al. 2017; Vetter et al. 2017; Kim and Mandrak 2017).

Use of electricity has a long history in fisheries management and has recently attracted more attention due to emerging issues of invasive species such as Asian carps (USACE 2015). Alternating current (AC) was first used to block and guide sea lamprey *Petromyzon marinus* (Linnaeus, 1758) (Baker 1928; Applegate et al. 1952), but resulted in excessive non-target fish mortality (Erkkila et al. 1956). Pulsed direct current (PDC) was subsequently used to block the upstream spawning migration of sea lamprey (McLain 1957). PDC is now typically used for fish blockage because the field is not continuous and polarities do not reverse, hence, the potential for human injury is reduced (Reynolds and Kolz 2012). Most PDC fields are now produced by horizontal electrodes mounted on the stream bottom to shelter electrodes from stream debris. The primary difference between vertical and horizontal electrodes is the plane in which the electric field varies (Johnson et al. 2014). Although electric barriers have been used to restrict movement of adult sea lamprey (Katopodis et al. 1994; Johnson et al. 2014), common carp (Verrill and Berry 1995), grass carp (Maceina et al. 1999), ruffe *Gymnocephalus cernua* (Linnaeus, 1758) (Dawson et al. 2006) and, more recently, Asian carps (Holliman 2011; Parker et al. 2015; USACE 2015), there are large information gaps on effectiveness of electric barriers, settings, target species, size, and behaviour (Reynolds 1996; Noatch and Suski 2012; Johnson et al. 2014; Parker et al. 2015; USACE 2015; DFO 2017).

To maximize the effectiveness of an electric barrier as a means to prevent fish movement, a comprehensive understanding of how target species interact with this barrier is required. For our research, common carp is used as a model organism for Asian carps as it is illegal to possess live Asian carps in Canada. Common carp is a good surrogate due to its biological similarity to Asian carps (both in family Cyprinidae, Page et al. 2013), its ecological impacts, its ongoing use in behavioural studies as the Asian carps, and the importance of testing in groups of three common carp (Huntingford et al. 2010; Sisler and Sorensen 2008). Laboratory trials were conducted on common carp to determine the effectiveness of a vertical electric barrier. We specifically tested to see if an electric barrier influences: (1) crossing rates of electric barrier zone; (2) type of behaviours exhibited when interacting with the electric barrier; and, (3) space use within the experimental tank of common carp.

Methods

Experimental subjects

Wild adult common carp were collected by boat electrofishing on August 4–6, 2015 in Hamilton Harbour on the western end of Lake Ontario. The individual fishes were visually inspected for good health upon capture and transported in live wells to several large aerated recirculating tanks (~700 to 1600 L) at the Aquatic Life Research Facility in the Canadian Centre for Inland Waters (CCIW), Burlington, Ontario, Canada. All fish were maintained in recirculating tanks with dechlorinated water (water temperature 12–15 °C; 12 h: 12 h light: dark photoperiod) and were fed ad libitum (0.5–1.0% of fish weight) daily of commercial fish food (Profishent Trout Chow, Martin Mills, Inc).

Fish tagging

Prior to each trial, all fish were individually marked using a numbered and coloured floy tag (FD-94, Floy Tag & Mfg. Inc., Seattle, USA). Fish were anaesthetized using a portable electroanaesthesia system (PES; Smith-Root, Inc., Vancouver, USA). The system includes a large portable cooler (100 cm × 46 cm × 38 cm) with anode/cathode plates at either end (distance between anode and cathode = 80 cm), both connected to a control system that is capable of regulating wave form supplied, duty cycle, and time. The electrosedation setting (Smith-Root, Inc. 2009; Kim et al. 2017) used to anaesthetize the fish was "burst of 3", duty cycle 62%, burst frequency 500 Hz, cycle frequency 30 Hz, and a voltage of 100 V. Seven to ten shocks were administered to each fish until stage IV of sedation was achieved (Summerfelt and Smith 1990). In general, fish were oriented at horizontal angles towards cathode or anode plates (0° or 180°, Rous et al. 2015; Kim et al. 2017). Stage IV sedation is associated with the total loss of equilibrium, muscle tone, and responsiveness to visual and tactile stimuli but maintenance of a steady, although reduced, opercular ventilation rate. Prior to tagging, all fish were measured, weighed, and photographed to ensure that fish would be similar in size for each trial. One of the four coloured floy tags was then inserted beside the dorsal fin between the pterygiophores using a floy-tag inserting gun (Floy Tag & Mfg. Inc., Seattle, USA). Following tagging, fish were placed in the recovery tank and monitored until they were able to maintain proper balance, before being returned to their holding tanks. All fish were given at least 21 days to fully recover from any effects of the tagging procedure before being used in experiments. In addition, this allowed fishes to recover and resume "normal activity" under the laboratory conditions after experiencing electric shocks during the collection and tagging procedures. Overall, both boat electrofishing and electroanaesthesia reduced handling stress and facilitated the logistics of this study (Summerfelt and Smith 1990; Kim et al. 2017). Furthermore, the addition of both pre- and post-stimulus periods allowed identification and accounting for any potential confounding effects of prior experiences of wild-caught fishes.

Experimental set-up

Experiments were conducted in a rectangular tank (3.56 m long, 1.1 m wide, and 0.39 m deep). The tank was evenly divided into six grids using nuclear-grade red duct tape for accurate positional scoring (Figure 1). During the acclimation period, air stones were left in the tub to provide sufficient oxygenation and a low flow was also left on to maintain a water temperature of around 14 °C and to prevent the build-up of waste products. Prior to testing, both aeration and flow were turned off to maximize the visibility of camcorders and minimize any interferences. Average ambient water conductivity was 250.44 µS cm^{-1} (± 3.73 µS cm^{-1}). Blinds were used to cover the experimental tanks and to prevent disturbance.

Electric barrier

A portable electric barrier system (neptun, Procom System S.A., Wroclaw, Poland) was used in the trials. The barrier consisted of two elements: a power control unit that supplies the electrical voltage, and the vertical electrodes in the water. Two electrode lines (one cathode and one anode) were placed in the centre of the experimental tank so that the electric field divided the tub into two "safe zones" of around 110 cm × 150 cm on either end (Figure 1). Two electrodes were attached to each line for a total of four electrodes in the whole system. The cathode (diameter = 4.13 cm) and the anode (diameter = 3.81 cm) were made of hollow, stainless steel rods. The electric field settings used in this experiment were 30 volts, 10 pulses, pulse length = 0.3 ms, gap length = 10 ms, repetition = 150 ms creating a duty cycle of 2% (neptun, Procom Systems, S.A.). These settings were selected with inputs from Procom Systems personnel, Fishways Global personnel, experienced biologists at Fisheries and Oceans Canada, and consideration of similar studies (Johnson and Miehls 2014; Johnson et al. 2014).

Voltage gradients ($V \cdot cm^{-1}$; peak values, not the average of one on-off cycle) within each location of experimental tanks (Figure 1) were measured with a 10 cm probe connected to an oscilloscope (Fluke 190 series Scopemeter, Mississauga, Canada) at depths of 15 and 39 cm (Johnson et al. 2014; Procom Systems S.A.). Voltages were measured over a 10 cm distance, so the measurements were divided by 10 (Johnson et al. 2014). Summary information are reported in Table 1 (see also Supplementary material Figure S1). In addition, the power density ($\mu W \cdot cm^{-3}$) was calculated as peak voltage gradient squared times ambient conductivity (Kolz 1989; Johnson et al. 2014). The power density ranged from 3.0 to 42.0 $\mu W \cdot cm^{-3}$ at the location 0 (Figure 1).

Behavioural experiments

Fifteen trials were conducted using a total of 45 common carp (mean weight ± standard deviation SD = 3.94 ± 1.19 kg, mean length ± SD = 584 ± 58 mm, n = 45) in November 3–25, 2015. Three individuals per replicate were used to reduce stress associated with captivity and testing for common carp (CCAC 2005; Huntingford et al. 2010; Sisler and Sorensen 2008) and provide sufficient amount of data for the study. Three individuals were introduced to the experimental tank the day before each trial, allowing the fish to acclimate to tank for at least 16 h. Each trial consisted of three consecutive phases of 30 min: pre-stimulus, stimulus, and post-stimulus. For each phase, video footage was captured for at least 30 minutes. The electric barrier was turned off for the pre-stimulus phase, followed by a stimulus phase with the electric barrier turned on. The electric barrier was then turned off for the post-stimulus phase. All three phases were continuously recorded using two methods: an overhead view using a camcorder (Canon, XA25) placed over one corner of the experimental tank; and, an underwater view recorded by a camcorder (GoPro, HERO4) fixed at the opposite end of the tub (Figure 1).

Fish behaviour was observed closely during each trial, especially during the stimulus phase where the fish could be shocked in a way that prevented escaping

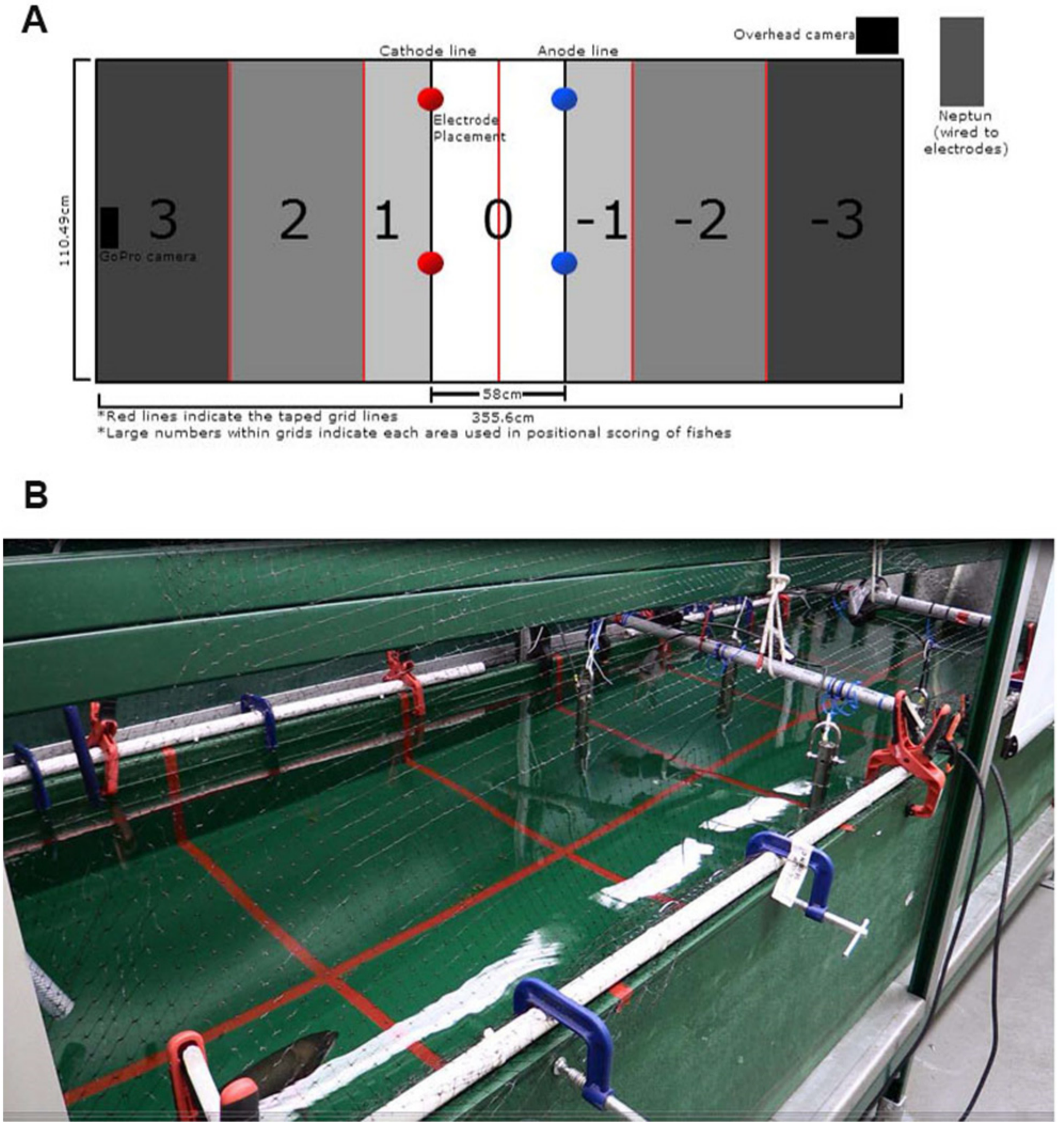

Figure 1. A) Experimental tank set-up and scoring grid, B) photo of experimental tank set-up.

from the electric field. To prevent the death and over-shocking of an individual in these cases, the electric barrier was turned off for a short period of time to allow for the individual's recovery and eventual exit of the barrier before the system was turned back on. Video recordings were extended to ensure at least 30 minutes of total recording time with the electric barrier turned on. If the fish did not recover within 15 minutes after failing to escape the electric field, the fish was manually removed after the electric barrier was turned off. This fish was considered "deceased" and no longer counted for future positional scoring.

Data analysis

Both overhead and underwater video recordings were used simultaneously by the scorer for each trial. Total positional occurrences and total barrier crossings were quantified for each of the three phases by recording a positional score for each fish at every 30-second interval. The scoring grid was divided into seven locations based on distance from the electric field (Figure 1). An individual was considered to have "crossed" the barrier if it moved from a negative to a positive location (or vice versa) when evaluating the summarized scoring results.

Table 1. Summary of electric gradient in the experimental tank.

Voltage (mean ± SD, $V \cdot cm^{-1}$)	Location 3	Location 2	Location 1	Location 0	Location -1	Location -2	Location -3
Ambient (electric barrier OFF)	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0	0.03 ± 0.01	0.03 ± 0.01
Electric barrier ON (depth of 15 cm)	0.03 ± 0.02	0.03 ± 0.01	0.05 ± 0.04	0.26 ± 0.08	0.03 ± 0.02	0.03 ± 0.01	0.02 ± 0
Electric barrier ON (depth of 39 cm; bottom)	0.02 ± 0.01	0.02 ± 0.02	0.05 ± 0.04	0.29 ± 0.09	0.02 ± 0.02	0.02 ± 0.01	0.02 ± 0

*water conductivity = 253.2 ± 3.89 $\mu S \cdot cm^{-1}$, water temperature = 14.13 ± 0.46 °C, and pH = 7.9

During the 30-min stimulus phase, every interaction with the electric barrier was recorded and classified as one of six categories (modified from Johnson et al. 2014): (1) **approach and retreat –** a slow approach towards the barrier and slow backward movement upon sensing of the electric field; (2) **deflected –** a quick approach towards the barrier and a strong turn away from the electric field; (3) **stunned and remained on the same side of the barrier –** the fish body goes rigid but does not ultimately cross the barrier; (4) **stunned and crosses the barrier –** the fish body goes rigid and crosses through the barrier; (5) **paralyzed –** a loss of equilibrium and motor functions when entering the barrier, recovery occurs within 2 min of the barrier being turned off to allow for the fish's escape; and, (6) **death/over-paralysis –** a loss of equilibrium and motor functions when entering the barrier, recovery does not occur within 2 min of the barrier being turned off and the individual may have to be manually removed from the electric field. These interactions were then tallied to determine how common carp could be expected to react when faced with an electric barrier.

We used repeated-measures ANOVA to test the effects of the electric barrier on the mean number of total crosses as within-subjects across pre-stimulus, stimulus, and post-stimulus periods. Scores of each behaviour category were examined using a one-way ANOVA to test whether the number differed among behaviour categories. Subsequently, pairwise post-hoc Fisher's LSD comparisons were completed for the behaviour category. We also used repeated-measures ANOVA to examine the effects of location as between-subject and proportion of time spent in each location across three time periods as within-subjects. Because not all locations were equal in size (Figure 1), the proportion of time spent for locations 1 and −1 were combined and repeated-measures ANOVA were completed using the total of six locations (i.e., 3, 2, 1 and −1, 0, −2, −3). Prior to data analyses, all data (e.g. mean number of total crosses, score of each behaviour, proportion of time spent) were transformed using $\log_{10}(x + 0.1)$ to meet the assumptions of parametric tests (Zar 1996). All statistical analyses were conducted using SPSS 12.0.1.

Results

Crossing of electric barrier

Number of crossings by common carp significantly differed among three periods (repeated-measures ANOVA: within-subject, quadratic: $F_{1,14} = 17.85$, $P = 0.001$; Figure 2). Initially, when the electric barrier was turned off, number of crossings were on average about 12 per trial (Figure 2). As expected, when the electric barrier was turned on during the stimulus period, the number of crossings decreased significantly to about one per trial (Figure 2). The number of crossings increased significantly again to about 15 per trial when the electric barrier was turned off during post-stimulus period, similar to pre-stimulus period (Figure 2).

Behavioural interactions with electric barrier

During the stimulus period when the electric barrier was turned on, the mean frequency of observed behaviours significantly differed between categories (ANOVA: $F_{5,84} = 18.06$, $P < 0.001$; Figure 3). The most frequently observed behaviours were stunned and stays on the same side of the barrier, approach and retreat, and deflected (Figure 3), which prevented fish from crossing the electric field from one side to the other side. The least observed behaviours were death/over-paralysis, paralyzed, and stunned and crossed the barrier (Figure 3). There was only one occurrence where a fish was considered "dead or over-paralyzed", and five instances where a fish was paralyzed (Figure 3).

Time spent at locations within experimental tank

Across the three periods, the proportion of time spent by all three fishes did not differ significantly between locations (ANOVA, between-subject: $F_{5,84} = 1.82$, $P = 0.12$; Figure 4). However, time spent differed significantly between three periods (ANOVA, within-subject quadratic, $F_{1,98} = 4.77$, $P = 0.032$; Figure 4), where time spent in each location was lower during the pre-stimulus period, then increased during stimulus period, and then decreased during post-stimulus period (Figure 4). As expected, there was a significant interaction between the three periods and location (ANOVA, within-subject, quadratic, $F_{5,84} = 22.28$, $P < 0.001$; Figure 4). Specifically, fish spent the most time in locations farthest from electric barrier (3 and −3, Figure 1) when it was on, compared to pre-stimulus and post-stimulus periods where electric barrier was turned off (Figure 4). In contrast, fish spent the most time in locations closest to the electric barrier (0, 1 and −1, Figure 1) when it was turned off (i.e. during pre-stimulus and post-stimulus periods) compared to the stimulus period when electric barrier was turned on (Figure 4). Time spent in moderately distant locations (2 and −2, Figure 1) did not vary significantly across the three periods (Figure 4).

Discussion

Our study found that the use of vertical electric barrier was effective in restricting the movement of common carp under laboratory conditions. The average number of crossings by fish significantly decreased when electric barrier was turned on. Most common carp turned away after encountering the electric field. Common carp responded to the electric barrier by spending significantly more time away from the location of electric barrier within the experimental tank. Similarly, pulsed direct current has been shown to prevent movement or guide freshwater fishes such as bighead carp, gizzard shad *Dorosoma cepedianum* (Lesueur, 1818), grass carp, rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792), juvenile and adult sea lamprey, silver carp, and walleye *Sander vitreus* (Mitchill, 1818) (Verrill and Berry 1995; Maceina et al. 1999; Holliman 2011; Johnson and Miehls 2014; Johnson et al. 2014; Parker et al. 2015; Weber et al. 2016). To our knowledge, this is the first laboratory study describing in detail how common carp responded behaviourally to fields of pulsed direct current using a relatively low-voltage gradient with portable vertical electrodes.

Our study showed that a low-voltage gradient (Range: 0.2–0.4 $V \cdot cm^{-1}$) would be sufficient to deter or block common carp. Moreover, this voltage gradient was sufficiently powerful to paralyze some fish and, in one instance, trap the fish, potentially leading to its death if we had not rescued it (Figure 3). In contrast, in the Chicago Sanitary Shipping Canal (CSSC), voltage gradients used were 0.79 to 0.91 $V \cdot cm^{-1}$ (Parker et al. 2015), which are two to four times higher than this study. Additionally, the power density in our

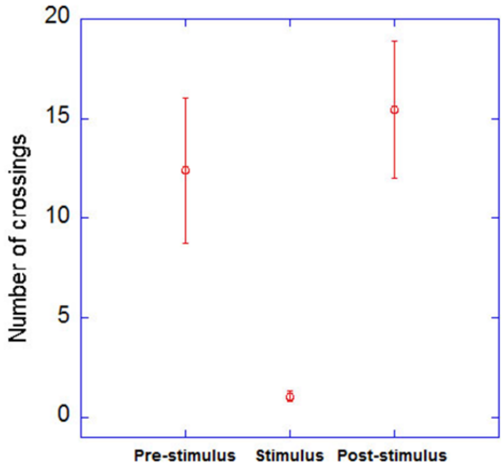

Figure 2. Mean (± SE) number of crossing the electric field during 30 minutes of pre-stimulus, stimulus, and post-stimulus periods (n = 15).

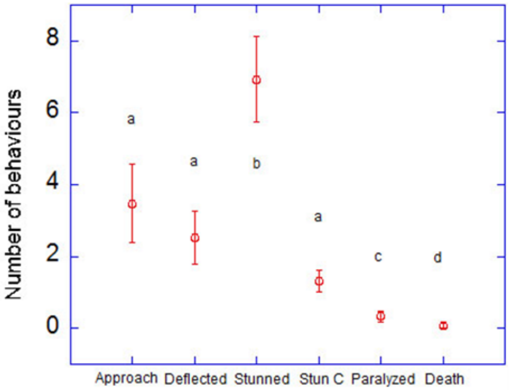

Figure 3. Mean (± SE) number of behavioural interaction with the electric field during 30 minutes of stimulus period (n = 15).

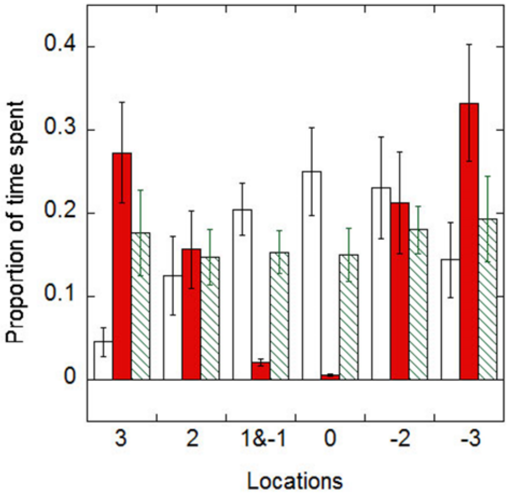

Figure 4. Mean (± SE) proportion of time spent in locations of experimental tank during 30 minutes of pre-stimulus (□), stimulus (■), and post-stimulus (dashed box) periods (n = 15).

study ranged from 3.0 to 42.0 $\mu W \cdot cm^{-3}$ whereas the power density estimates in the CSSC ranged from 418.1 to 960.6 $\mu W \cdot cm^{-3}$ (i.e., calculated using data from Parker et al. 2015), about ~10 to 20 times greater. Power density estimate could increase upto 3889.6 $\mu W \cdot cm^{-3}$ (i.e., calculated using data from Holliman 2011) during the winter period (December to March) when water conductivity ranges between 3049 and 4697 $\mu S \cdot cm^{-1}$. For the CSSC, higher voltages were selected to ensure that it would be able to stun smaller silver carp (i.e. 137 to 280 mm of total length, Holliman 2011) and account for varying field conditions. Depending on the management goals, use of weaker electric field to deter or guide invasive fishes from undesirable locations should be considered and tested to limit the potential impact on target and non-target species including species at risk (Johnson and Miehls 2014; Johnson et al. 2014).

Although our results showed that the vertical electric barrier was effective in restricting fish from crossing the barrier, it was not 100% effective in blocking all fish at all times. This may have been the result of size of our experimental tank and use of low-voltage setting. For instance, although our tank was sufficiently large to hold three adult common carp (i.e. tank was ~1.53 m^3 (~1530 L) with electric barrier zone as 0.25 m^3 (~250 L)), it was not possible to place a buffer zone of low electric field between safe areas and electric barrier zones (i.e., high electric field). A buffer zone may allow enough space and time for fish to avoid, or move away from, the electric barrier. We observed many instances where fish were stunned initially, but managed to cross the electric field either gliding or bursting through due to sudden shock. Electric barriers and guidance systems have been installed to block invasive fishes such as sea lamprey and Asian carps. Most applications for sea lamprey were decommissioned because they did not block 100% of sea lamprey, attributed to periodic floods, power outages or equipment failure, and limited the migration of non-target species (Swink 1999; Lavis et al. 2003; Clarkson 2004). In the CSSC, where series of large horizontal electric barriers have been set up to deter the movement of Asian carps, there are concerns about whether electric barriers are 100% effective considering there may potentially be periodic floods, power outages, and barges providing potential refuge under the metal hull (Holliman 2011; Parker et al. 2015; Davis et al. 2016). Vertical electric barriers may provide alternative solutions for dealing with periodic floods and strengthening the top portions of the water column compared to horizontal electric barrier.

In our study, we observed that, during the 30-min stimulus period, common carp kept actively re-approaching and challenging the electric barrier even after they felt mild shock, followed by active behaviour in the post-stimulus period (e.g. passing of electric barrier zone, spending more time). Similarly, fishes have been observed to continuously challenge the electric barriers in the CSSC (Holliman 2011; Parker et al. 2015). The fish may be unable to discern the directions or location of electric barrier (Stewart 1990a; Holliman 2011). Visible-marker or other novel stimuli may provide opportunity for fishes to identify, locate, and learn to avoid the electric barrier (Stewart 1990b; Holliman 2011). In addition, behavioural responses can vary depending on the size and species (Holliman 2011; Johnson and Miehls 2014; Johnson et al. 2014). Further research on how fishes interact with electric barriers over time, and whether and how fishes learn to avoid electric barrier in a field setting, would be useful for management and conservation applications.

Practical advantages of vertical electric barriers are that they are portable and can be installed quickly without major stream modification (Johnson et al. 2014). Installing the electric barrier in the testing tanks in this study was relatively easy, fast, flexible, and not permanent. This vertical electric barrier can be readily taken into the field to evaluate its effectiveness on native and non-native species. It is possible that vertical electric barriers may be more susceptible to floating debris compared to horizontal electric barriers and may require periodic maintenance depending on the conditions of study sites (but see Applegate et al. 1952; Johnson et al. 2014). Long-term field studies using improved designs are needed to evaluate their effectiveness and long-term feasibility in varying conditions such as high-flow environments. However, our study provides strong evidence that vertical electric barriers are effective in restricting the movement of common carp and can be easily implemented into management situations where the objectives may be to block, restrict, or guide fishes from undesirable locations (Johnson et al. 2014).

Overall, our study found that a vertical electric barrier was effective in preventing the movement of common carp under laboratory conditions. While our findings should not be extrapolated to other species, such as bighead carp and silver carp, or larger field scales until further research is conducted, our study provides valuable insights on how common carp responds behaviourally to an electric barrier, especially under relatively low-voltage settings. This is important to managers and researchers using the electric barriers solely or in combination of other barriers to prevent movement of fishes to undesirable locations, especially in situations where portable and flexible systems are needed.

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Supplementary material

The following supplementary material is available for this article:

Figure S1. Electric gradient in the experimental tank during A) ambient conditions at 15 cm depth and when electric barrier is on at B) 15 cm depth and C) max depth (39 cm).

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