Title: Evaluation of horizontally and vertically aligned bar racks for guiding downstream moving juvenile chub (*Squalius cephalus*) and barbel (*Barbus barbus*)

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Highlights

- Horizontally and vertically oriented bar racks were evaluated for fish screening
- Downstream movements of groups of chub and barbel were recorded and analysed
- Sweeping flows across the rack face to the bypass were not established
- Consequently, total guidance was low for both species under all treatments
- The bar racks used were not suitable for fish guidance under the tested conditions

Abstract

Bar racks are commonly installed to divert fish away from water intakes, such as those at hydropower stations or other abstraction points. In temperate regions their effectiveness has predominantly been assessed in relation to diadromous species, such as salmon and eel. This study compared the efficacy of horizontally and vertically oriented racks (5 mm diameter and 10 mm spacing) to guide downstream moving groups of five chub (*Squalius cephalus*) and barbel (*Barbus barbus*) to a bypass channel in a recirculating flume under two discharge regimes, and with the rack angled at either 30° or 45° to the direction of flow. Regardless of treatment, the bulk flow predominantly passed through the bars resulting in a lack of a well-established sweeping flow across the rack face, and consequently many instances of entrainment and impingement occurred. Total guidance (the number of bypass entries expressed as a percentage of the total number of approaches) was low and comparable between species with means of 21.3% and 24.8% for chub and barbel, respectively. Bar orientation had limited influence on all metrics, with the exception of the number of guidance events which was higher for the vertical treatment. Interspecific differences in the number of entrainments and guidance events and the exhibition of fine-scale avoidance behaviours were apparent, being higher for chub. In conclusion, the racks used here were not suitable for guiding juvenile cyprinids under conditions similar to those tested. Accounting for interspecific differences and reducing avoidance behaviour are important factors that should be considered in advancing guidance screens for multiple

species.

Keywords: Avoidance, Bar racks, Cyprinidae, Fish passage, Guidance

1. Introduction

Worldwide, river ecosystems are under threat due to the exploitation of water resources (Best, 2019, Vörösmarty et al., 2010). Intake structures are common along many rivers where they are used to abstract water for multiple purposes, including hydropower, irrigation and aquaculture. Unfortunately, such infrastructure can negatively impact fish communities (Kemp, 2016, Sabater, 2008), resulting in the need for mitigation reinforced by the requirements of a range of environmental legislation, including the Water Framework Directive (2006) in Europe, and the Clean Water Act (1972) in the US.

Fish run the risk of being entrained into intakes with the extracted water and removed from the system if no route of return is available in cases where abstraction is consumptive, e.g. for the purpose of irrigation, water supply, or aquaculture production. To protect fish, physical screens are commonly installed to block and guide them to bypass systems (Larinier and Travade, 2002), but the screens can themselves have undesirable impacts on those they were designed to protect. If screen apertures are too wide, fish other than the target life-stage / species may be lost to entrainment (Boys et al., 2013); if flow velocities at the face are too high to enable escape, then they may be impinged and suffer injury or death as a result of mechanical abrasion and suffocation

(White et al., 2007, Poletto et al., 2014). Furthermore, avoidance of hydrodynamic conditions, such as rapid accelerations of velocity or turbulence, encountered at the screen or bypass entrance may cause migratory delay (Ovidio et al., 2016, De Bie et al., 2018) and increased predation risk (Schilt, 2007). Improved screening is needed to minimise the unintended negative consequences of these structures and protect important fisheries resources and populations of those species of high conservation concern.

Bar racks are physical screens that typically consist of vertically aligned bars supported by a frame, with width and spacing determined by the dimensions of the target life-stage of the species they are intended to exclude. Previous evaluation of screen guidance efficiency highlights high intraspecific variability, usually for the downstream moving life-stages of those with diadromous life-histories, which are most frequently studied. For example, guidance efficiency ranged from 0% to 98% for European eel (*Anguilla anguilla*) (Russon et al., 2010, Gosset et al., 2005, Calles et al., 2012),17% to 73% for juvenile Atlantic salmon (*Salmo salar*) (Scruton et al., 2003, Croze, 2008, Calles et al., 2012), and 0% to 52% for juvenile brown trout (*Salmo trutta*) (Greenberg et al., 2012). Although less frequently studied, the guidance efficiencies for species with alternative life-histories (e.g. potamodromous) tend to be low. For example, for smallmouth (*Micropterus dolomieu*) and largemouth bass (*M. salmoides*), golden shiner (*Notemigonus crysoleucas*), walleye (*Stizostedion vitreum*), channel catfish (*Ictalurus punctatus*), shortnose (*Acipenser brevirostrum*) and lake sturgeon (*A. fulvescens*) efficiencies of less than 50% were frequently observed (EPRI, 2001). It is clear that to improve the performance of bar racks so that they provide a viable screening option for multiple species, the level of guidance, and consistency between sites, should be enhanced.

The angle at which the screens are placed relative to the oncoming flow, in addition to the spacing and shape of the bars (Katopodis et al., 2005, Rajaratnam et al., 2010), is an important determinant of the guidance efficiency (EA, 2009). By installing the screen at a gentle angle to the bulk flow, local sweeping velocities created parallel to the face enhance fish guidance, while the resulting escape velocity perpendicular to the screen should be sufficiently low as to prevent impingement or entrainment. In the UK, different thresholds for the escape velocity are prescribed in regulatory guidance (e.g. EA, 2009) to accommodate variability in swimming performance of different target fish species and life stages.

The orientation of the bars has recently gained some attention; in some cases, designs have shifted from vertical to horizontal alignment, albeit predominantly to enhance self-cleaning of debris rather than to improve fish guidance (Ebel, 2008, Ebel et al., 2015). Nevertheless, given the oval cross-section of many species it is not an unreasonable assumption that horizontally oriented bar screens will block smaller fish than those that are vertically aligned assuming spacing is equal. Alternatively, the ability to exclude fish of the same size with larger spaced screens is likely to be of interest to the operators of water intakes if they are consequently able to abstract more water and reduce capital and maintenance costs, e.g. due to lower accumulation of debris. Furthermore, horizontal screens may facilitate the escape of fish that become temporarily impinged because their pectoral fins might be less restricted under this orientation (Horsfield and Turnpenny, 2011). Despite the logical advantages of employing horizontally aligned bar screens from the perspective of improved fish guidance, direct comparison between the two designs is limited, with only one recent study that focused on wedge-wire screens and downstream moving chub (*Squalius cephalus*) (De Bie et al., 2018).

The primary aim of this study was to compare the effectiveness of vertically and horizontally oriented bar racks under different experimental settings. This was expressed through metrics for guidance to a bypass channel, and instances of entrainment and impingement. To address the bias towards consideration of diadromous fish, two potamodromous cyprinid species, the chub and barbel (*Barbus barbus*), were selected because they exhibit different body morphologies and behaviours, with barbel being adapted to a more benthic lifestyle than chub (EA, 2004, Kottelat and Freyhof, 2007). To investigate the influence of hydrodynamics on screen effectiveness, two discharge regimes were used, each creating their own hydrodynamic conditions at the rack and bypass entrance. The influence of differences in the angle of the bar rack was investigated using racks angled at 30° and 45°.The 45° angled rack was tested under both discharge regimes and a comparison between 30° and 45° investigated under the higher discharge regime only. The secondary aim of this study was to determine how variation in interspecific avoidance behaviour (expressed through metrics for rejection of the racks and holding station in close proximity to them) might explain differences in screen performance. Due to the gregarious nature of the juveniles of the test species, small groups of five individuals were released under the experimental conditions created.

2. Materials and Methods

2.1 Experimental setup

Experiments were conducted in a large recirculating flume (21.4 m long, 1.38 m wide and 0.6 m deep) at the International Centre for Ecohydraulics Research (ICER) facility, University of Southampton, UK. A centrally located 10.3 m long section of the flume was isolated upstream from the rest of the channel by a flow straightener (10 cm wide polycarbonate honeycomb-structured screen) and downstream by a 0.5 cm x 0.5 cm square mesh panel to prevent escape of fish from the experimental area. The flume was illuminated by fluorescent lighting (2.5 m above the channel floor), and six overhead cameras (1.6 m above the channel floor) recorded fish movements in the observation zone (50 cm upstream of the start of the bar rack to the bypass entrance, Fig. 1). The bypass was separated from the rest of the channel by a Perspex sheet (4 m long, 50 cm high and 1 cm thick). Black screens were installed on both sides of the flume to prevent visual disturbance by the observer during trials.

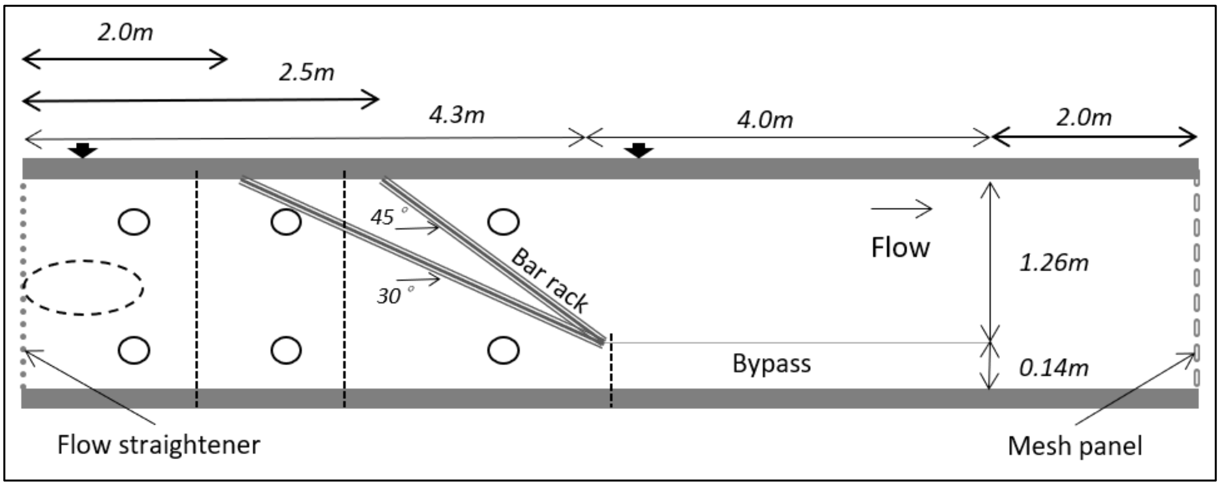

Figure 1. Plan view of an experimental section of a large re-circulating flume at the ICER facility (University of Southampton). Each bar rack was placed against the true left side of the flume and connected to a bypass channel downstream. Closed circles represent locations of six overhead cameras. The dashed oval represents the location of release. Thick black arrows denote locations of overhead tube lights. Fish movements were recorded in the observation zone (dashed lines), which ranged from 50 cm upstream of a bar rack to the bypass entrance.

Two different discharge regimes were used, defined as low (L: 0.09 $m^3 s^{-1}$) and high (H: 0.15 $m^3 s^{-1}$). The resulting mean upstream velocity ($m s^{-1}$) was approximately twice as high under high compared to low discharge. Discharge was controlled by adjusting the pump valves and an overshot weir at the downstream end of the flume. Resulting mean ± SD flow velocities (mid-channel and mid-depth) were 0.19 ± 0.01 $m s^{-1}$ and 0.36 ± 0.01 $m s^{-1}$ under low and high discharge, respectively (Table 1). Fish behaviour was studied under six treatments: low horizontal (LH45), low vertical (LV45), high horizontal (HH30, HH45) and high vertical (HV30, HV45). These abbreviations consist of the first letter denoting the discharge regime as defined above, the second denoting bar orientation (H for horizontal or V for vertical), and two numerals denoting the angle of the rack relative to the oncoming flow (Table 1). Under high discharge, either a 1.78 m (short rack) or 2.52 m long (long rack), 0.5 m high rack with vertically or horizontally aligned bars was used. As a result, the screen angle ($\boldsymbol{\alpha}$) relative to the oncoming flow was either 45° (short rack) or 30° (long rack). Under low discharge, only short racks were used. During each treatment, one of four different bar racks extended between 2.5 m (short rack) or 2.0 m (long rack) and 4.3 m downstream of the flow straightener and placed perpendicular to the channel floor against the true left side of the flume and connected to the bypass entrance on the right wall (Fig. 1). The magnitude of the sweeping velocity was expected to be at least similar to (for the 45° racks) or exceed (for the 30° racks) the escape velocity required to promote fish guidance (Fig. 1, 2). Under the high discharge, the corresponding escape velocity at the screen was below the published recommended maximum value for coarse fish of 0.25 m s^{-1} (EA, 2009). Under both discharge regimes the magnitude of the resulting mean upstream velocities were similar to those typically encountered by juvenile chub and barbel in their natural habitat, but lower than the maximum they could encounter from time to time (EA, 2004, Kottelat and Freyhof, 2007). Water depth (D) across the width of the flume, 0.5 m downstream of the flow straightener, was 0.38 m and 0.27 m under the low and high discharge, respectively. All bar racks had a 5 mm bar width, circular in cross-section, and 10 mm bar spacing, with square 2.5 cm thick support bars (Fig. 2).

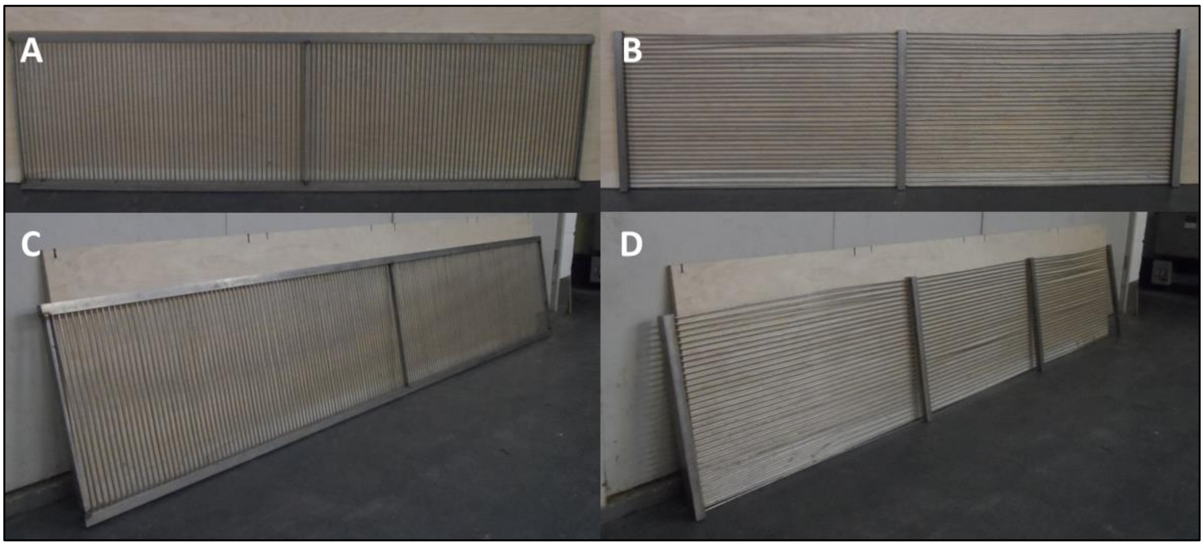

Figure 2. Bar racks used during the study. A) and B): short vertical and horizontal bar racks, respectively, used in the low horizontal (LH45), low vertical (LV45), high horizontal (HH45) and high vertical (HV45) treatments. These were installed at an angle of 45° to the oncoming flow and tested under two discharge regimes (low: 0.09 $m^3 s^{-1}$ and high: 0.15 $m^3 s^{-1}$). C) and D) long vertical and horizontal bar racks, respectively, used in the high horizontal (HH30) and high vertical (HV30) treatments. These were installed at an angle of 30° to the oncoming flow and tested at high discharge only.

Treatment	**Date**	**Mean (± SD) velocity upstream (m s^{-1})**	**Mean (± SD) velocity in middle of bypass (m s^{-1})**	**Mean (± SD) water temperature (°C)**	**Mean (± SD) total length chub/ barbel (mm)**	**#Replicates chub/barbel**	***N* chub/barbel**
LH45	5-8 December 2013	0.19 (± 0.01)	0.21 (± 0.01)	11.1 (± 0.8)	85.3 (± 6.1)/ 93.1 (± 5.7)	10/10	50/50
LV45	9-12 December 2013	0.19 (± 0.01)	0.19 (± 0.01)	10.3 (± 0.8)	83.9 (± 5.6)/ 89.3 (± 7.1)	10/10	50/50
HH30	17-18 February, 3 & 7 March 2014	0.36 (± 0.01)	0.35 (± 0.01)	10.6 (± 0.7)	88.3 (± 7.5)/ 84.2 (± 7.1)	18/19	90/95
HH45	21,22 & 27 February, 5 March 2014	0.36 (± 0.02)	0.37 (± 0.01)	10.9 (± 0.7)	86.2 (± 8.2)/ 81.7 (± 7.5)	16/19	80/95
HV30	19-20 February, 2 & 6 March 2014	0.36 (± 0.02)	0.44 (± 0.02)	11.1 (± 0.6)	84.4 (± 7.2)/ 83.7 (± 8.4)	17/19	85/95
HV45	23, 24 & 28 February, 4 March 2014	0.36 (± 0.01)	0.42 (± 0.01)	11.2 (± 0.7)	84.8 (± 6.7)/ 81.3 (± 7.6)	18/19	90/95

Table 1. Hydrodynamic conditions encountered by chub and barbel during downstream passage in a recirculating flume under low discharge (LH45, LV45) treatments in 2013 and high discharge (HH30, HH45, HV30 & HV45) treatments in 2014. *N* is the total number of fish used per treatment.

The flow vector field was quantified using an Acoustic Doppler Velocimeter (ADV) (Vectrino+, Nortek) along an eight-point transect 8 cm (~1 BL) upstream and perpendicular to the face of each rack. Sampling locations remained constant for horizontal and vertical short racks but differed between the long racks due to the presence of vertical support bars. Sampling volume and frequency were set at 0.28 cm^3 and 50 Hz, respectively. Sampling depth was 0.2*D*, 0.4*D* and 0.8*D* under the two discharge regimes. At each sampling point, three thousand velocity readings were obtained over a period of 60 s, which was deemed sufficiently long under the steady and uniform flow resulting from discharge settings of the flume and the placement of the flow straightener (Fig. 1). Raw ADV data was filtered following the protocol of Cea et al. (2007) and the mean velocity vector (***V***) was calculated as:

$$V = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}, \quad (1)$$

where $\overline{\boldsymbol{u}}^{\boldsymbol{2}}$, $\overline{\boldsymbol{v}}^{\boldsymbol{2}}$ and $\overline{\boldsymbol{w}}^{\boldsymbol{2}}$are the mean velocities in the longitudinal (***x***), lateral (***y***), and vertical (***z***) direction, respectively. Sweeping ($\boldsymbol{V_s}$) and escape velocities ($\boldsymbol{V_e}$) at every sampling point were calculated following the methods described in De Bie et al. (2018).

Vector plots of ***V*** at the three sampling depths were similar and are shown only for the 0.2*D* case, as both species were predominantly associated with the channel floor during trials (Fig. 3). Under low discharge, ***V*** was directed through the bar racks, regardless of orientation, at each sampling point (Fig. 3). Vector arrow length did not change with position towards the bypass, indicating that the amount of flow diverted was minimal. Under high discharge, diversion of ***V*** was also minimal, and ***V*** was not consistently directed to the bypass channel (Fig. 3). There were no discernible differences in the direction of ***V*** between horizontal or vertical bar racks, regardless of whether these were angled at 45° or 30° to the oncoming flow. Under the HH45 and HH30 treatment, diversion of ***V*** seemed to take place where the vertical support bars were located (Fig. 2). The magnitude of the sweeping velocities at each rack did not change with decreasing distance to the bypass, confirming that little flow was diverted under both low and high discharge (Fig. 4A, C). Escape velocities showed no clear patterns, but generally changed little in magnitude along the rack among treatments (Fig. 4B, D).

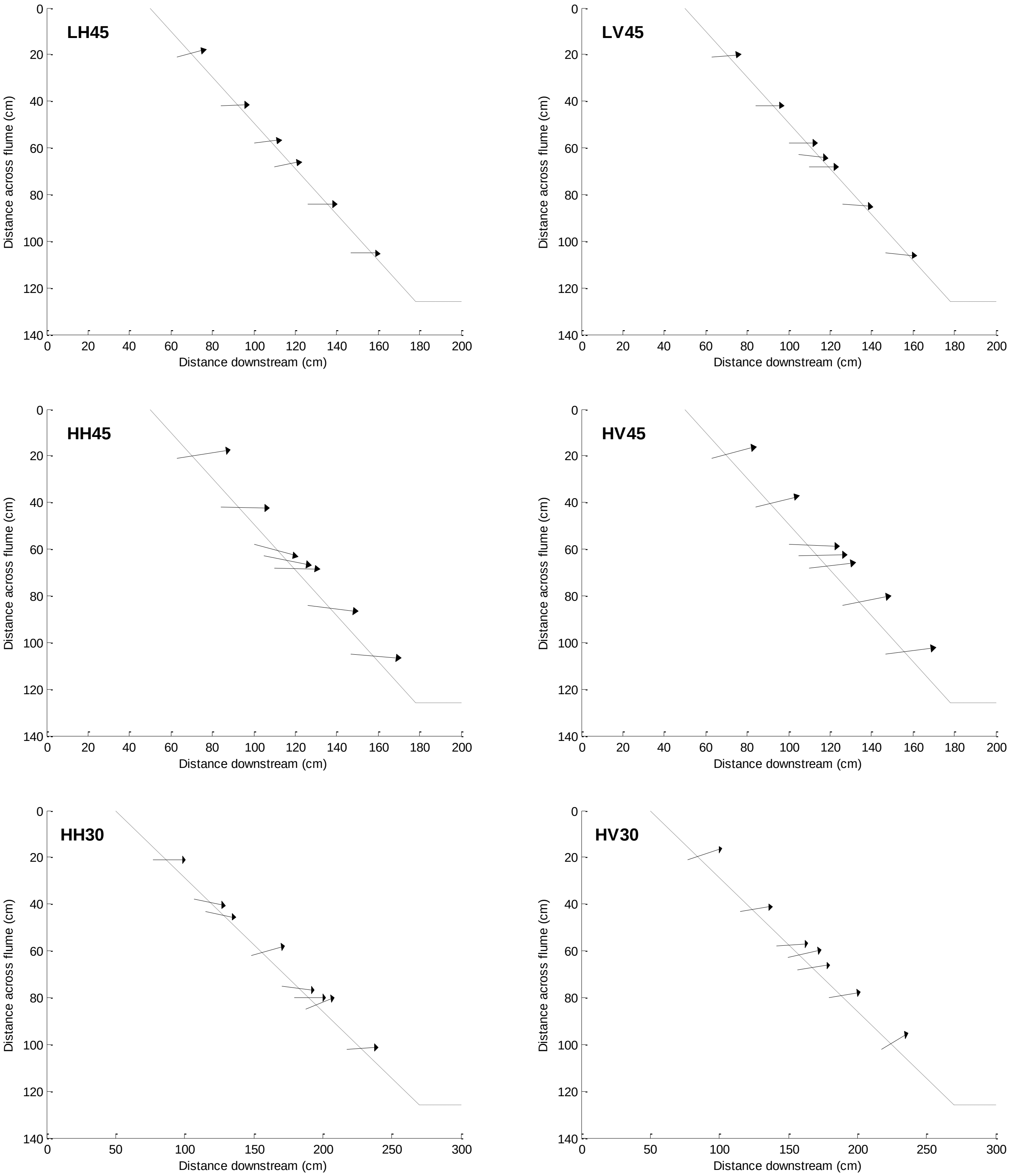

Figure 3. Quiver plots of the mean velocity vector (**V**) close to the channel floor (0.2D) in the vicinity of the bar rack under each treatment. Top row: low horizontal (LH45) and low vertical (LV45); middle row: high horizontal (HH45) and high vertical (HV45); bottom row: high horizontal (HH30) and high

vertical (HV30). The two numerals denote the angle of the rack relative to the oncoming flow. Arrow length is scaled by the freestream $\boldsymbol{V}$ upstream of the rack in each treatment. Note the differences in x-axis values for the HH30 and HV30 treatments.

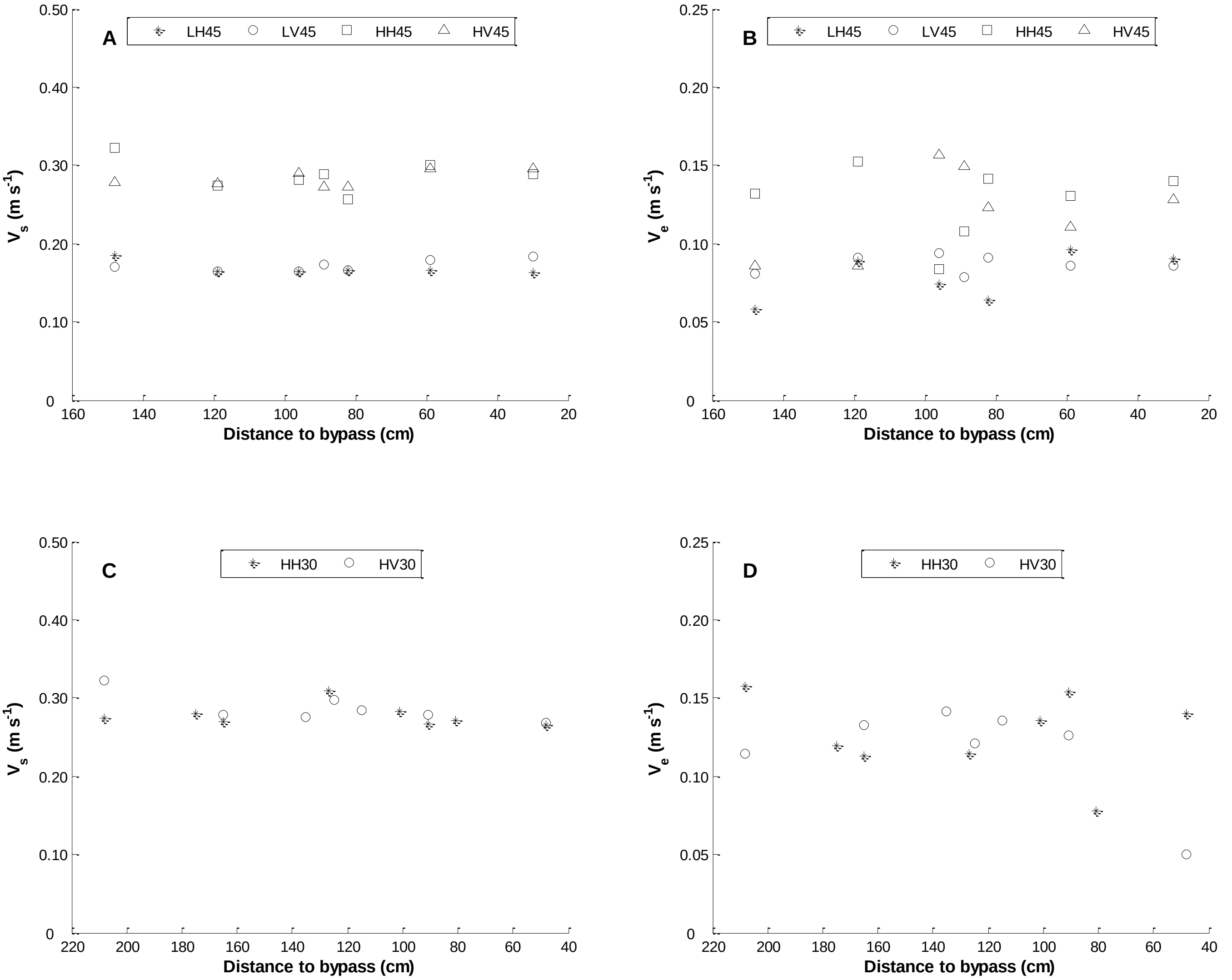

Figure 4. Sweeping velocity $\boldsymbol{V_s}$ (left) and escape velocity $\boldsymbol{V_e}$ (right) close to the channel floor (0.2*D*) in the vicinity of bar racks. A-B) 45°-angled racks under both discharge regimes. C-D: 30°- angled racks under the high discharge regime.

2.2 Experimental procedure

A total of 150 subyearling chub (mean ± SD total length [TL] and wet mass [M] = 84.8 ± 7.1 mm; 5.3 ± 1.4 g, respectively) and 150 subyearling barbel (mean ± SD TL and M = 91.0 ± 8.0 mm; 6.4 ± 1.6 g) were collected from an Environment Agency fish farm at Calverton, UK, (53°2'1.3" N, -1°3'7.0" W) on 12 November 2013. A further 475 subyearling chub (mean ± SD TL and M = 86.2 ± 7.9 mm; 5.7 ± 1.7 g) and 475 subyearling barbel (mean ± SD TL and M = 83.0 ± 8.0 mm; 4.9 ± 1.3 g) were sourced from the same place on 5 February 2014. Fish were transported to the ICER facility in sealed plastic bags filled with oxygen saturated water. All fish were maintained in three (2013) and four (2014) 3000 L outside holding tanks (mean ± SD water temperature: 7.0 ± 1.0 °C in 2013; and 7.4 ± 1.1 °C in 2014) containing dechlorinated and oxygenated water for two weeks prior to use in trials. Water quality (pH, and levels of NH_3, NO_2^-, and NO_3^-) was monitored throughout the duration of the experiment, with 50% water changes when NH_3 and NO_2^- levels exceeded 0.25 ppm. Chub were separated from barbel throughout the duration of the experiment. Fish were fed twice daily, at least two hours before use in trials.

All trials were conducted during hours of daylight. A total of 40 trials were conducted under the low discharge regime with the 45° racks from 1 - 15 December 2013 (Table 1). The test species used was alternated daily, and bar orientation changed after 10 trials per species were completed. A further 152 trials were conducted under high discharge from 15 February- 7 March 2014 (Table 1). Due to the greater number of treatments under this discharge and the requirement for more test fish, species was alternated between trials. Similar to December 2013, treatments were initially alternated every two days (i.e. after 10 trials per species were completed), and then alternated daily until completion of the experiment.

Each day, a total of 40 chub or barbel were randomly selected from the indoor holding tank and transported to 150 L containers filled with aerated flume water for a minimum of one hour. Prior to the start of each trial, five fish were randomly selected from the container and placed into a rectangular mesh (length: 53 cm, width 33 cm, height 20 cm) box placed at the upstream end of the flume for a minimum of twenty minutes to acclimate. A clear absence of erratic startle behaviour at the end indicated that the duration of acclimation time was sufficient. Each trial commenced when the fish were released in the middle of the upstream section and allowed to volitionally explore the experimental area. Trials lasted until all fish had passed downstream of the bar rack, or after one hour had elapsed. At the end of each trial fish were removed from the flume and measured and weighed. Each fish was used once only during the study.

Despite random selection of the test fish, mean TL differed among treatments (chub were longer under HH30 compared to LV45, HV45 and HV30, ANOVA $F_{5,474} = 4.27$, $p = 0.001$; barbel were longer under the low flow than the high flow treatment, Kruskal-Wallis $H = 92.86$, $df = 5$, $p < 0.001$, Table 1). Nevertheless, as differences in TL were less than 1 cm, they were not deemed sufficient to impact the results of the study because all test fish were small enough to pass through the bars.

2.3 Bar rack performance

Every entrance to the observation zone was categorised as an *approach*. After an approach, three different routes of passage were possible and categorized as either: (1) guided along the bar rack into the bypass; (2) passed along the true right wall into the bypass without direct interaction with the bar rack; (3) entrainment through the bar rack. Fish were allowed to freely move up and down the experimental area and return upstream after *entrance* into the bypass or back through the rack following *entrainment*. As a result, each fish could pass via the three alternative routes multiple times. *Total guidance* per trial was defined as the number of bypass entries expressed as a percentage of the total number of approaches. The total number of times a single fish passed through a bar rack (*entrainments*), was guided along the bark rack into the bypass (*guidance events*) or impinged on the bar rack (*impingements*) were combined for each fish and recorded per trial.

2.4 Fish behaviour

A fish returning upstream after leaving the observation zone without entering the bypass was deemed to have displayed a *rejection*. If a fish halted downstream movement and maintained position during the first 30s following a successful approach, it was deemed to have *held station* near the bar rack.

The total number of times a single fish displayed *rejections* and *held station* was combined for all fish and recorded per trial.

2.5 Statistical analysis

Tests of normality and homogeneity of variance were performed using the Shapiro-Wilk and Levene's test, respectively. Percentage data was transformed using the arcsine square-root method prior to statistical analysis. Non-parametric count data were log-transformed. Where transformation failed, either non-parametric tests were used, or parametric test results were reported together with bootstrapped (1000 iterations) 95% confidence intervals (***CI***) of the mean, to display general trends.

Total guidance was compared among treatments using Kruskal-Wallis tests, and compared between species using Student's *t*-tests or Mann Whitney U tests. The effect of rack angle was assessed for the high discharge treatments. Since no differences were found, the associated data was pooled for each species (e.g. HH30 + HH45). The influence of rack orientation and species (fixed factors) on total number of: (1) *entrainments*, (2) *guidance events*, (3) *rejections*, and (4) instances where fish *held station* (dependent variables) were assessed using bootstrapped (1000 iterations) univariate two-way ANOVA tests. Because of an unbalanced treatment design, discharge level was not used as a fixed factor in this analysis. *Impingements* were compared among treatments using Kruskal-Wallis tests, and compared between species using Mann Whitney U tests or Student's *t*-tests. Statistical analysis was performed using IBM SPSS Statistics 20/22 software. A significance level of 0.05 was used.

3. Results

3.1 Bar rack performance

For chub, the mean *total guidance* when all treatments were aggregated was 21.3%. Total guidance differed among treatments (Kruskal-Wallis: $H = 15.04$, $df = 5$, $p < 0.05$) (Fig. 5A), being higher under the HH30 (median = 38%) than LV45 (median = 9%). For barbel, mean *total guidance* was 24.8% for all treatments and differed among treatments (Kruskal-Wallis $H = 11.29$, $df = 5$, $p < 0.05$) (Fig. 5B), being higher under LV45 (median = 49%) compared to HH45 (median = 0%). Interspecific differences in *total guidance* were found only under the LV45 treatment, being higher for barbel (mean = 47%) than for chub (mean = 10%) (t (18)= -2.74, $p < 0.05$).

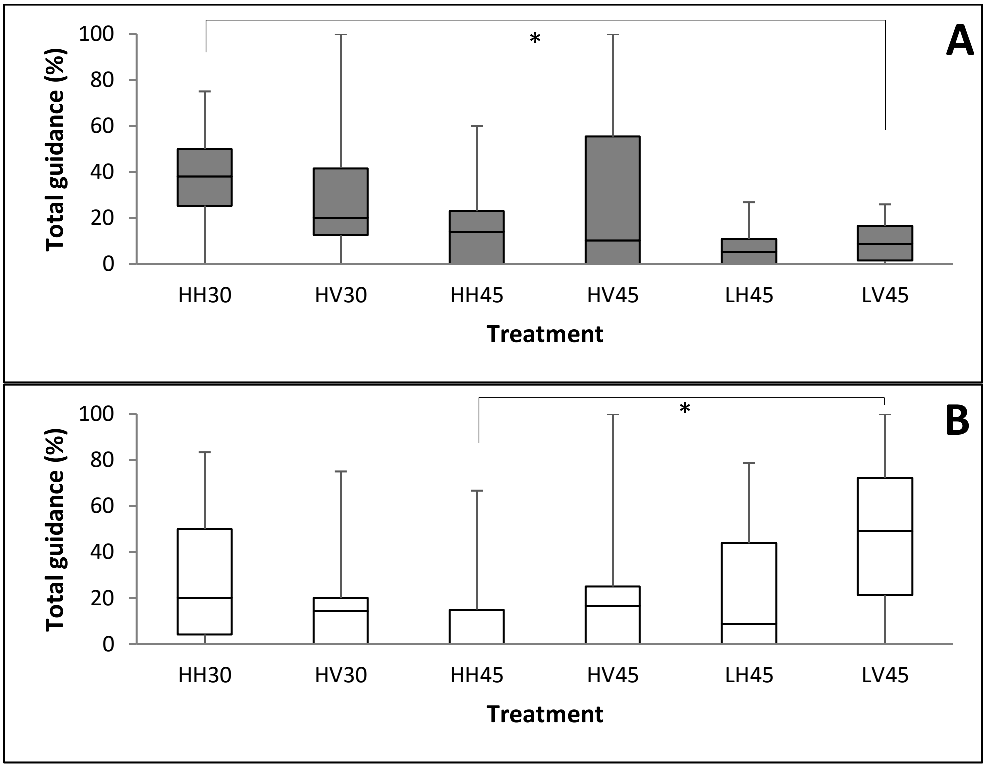

Figure 5. Total guidance for chub (A) and barbel (B) under high horizontal/ vertical (HH, HV) or low horizontal/ vertical (LH, LV) treatments with 30° or 45° angled bar racks in a large flume. Boxes represent the IQR, and whiskers denote maximum and minimum values. Medians are denoted by a horizontal line and may overlap with the IQR. Asterisks denote a statistical difference between treatments.

Under high discharge, the number of *entrainments* was higher for chub (mean ± S.E. = 1.9 ± 0.19) than barbel (mean ± S.E. = 0.6 ± 0.14) (Table 2 for test statistics). There was no effect of rack orientation and no interaction (Table 2). Under low discharge, an interaction indicated that the number of *entrainments* was higher and lower for vertical compared to horizontal bar racks for barbel and chub, respectively. Rack orientation and species had no effect (Table 2).

Under high discharge, an interaction indicated that the number of *guidance events* was higher and lower for vertical compared to horizontal bar racks for barbel and chub, respectively. However, the effect of species was stronger than that of rack orientation, as indicated by an overlap in 95% CI across both species (Table 2). The main effects of rack orientation and species confirmed that the number of *guidance events* was higher for vertical (mean ± S.E. = 0.6 ± 0.12) compared to horizontal (mean ± S.E. = 0.3 ± 0.07) and higher for chub (mean ± S.E. = 0.8 ± 0.14) than barbel (mean ± S.E. = 0.1 ± 0.04). Under low discharge, the number of *guidance events* was higher for vertical (mean ± S.E. = 2.0 ± 0.48) compared to horizontal (mean ± S.E. = 0.6 ± 0.28). No species and interaction effect were observed (Table 2).

The number of *impingements* differed between treatments for chub (Kruskal-Wallis: H = 22.722, df = 4, p < 0.001), being higher under HH30 (median = 2.0) than HV45 (median = 0.0) (Mann Whitney post-hoc test, p < 0.001, Fig. 6). For barbel, the number of *impingements* differed between treatments (Kruskal-Wallis: H = 32.762, df = 5, p <0.001) (Fig. 6), being higher under LH45 (median = 8.0) and LV45 (median = 6.0) than HH45 and HV45 (medians = 0.0) (Mann Whitney post-hoc tests, all p < 0.001). The number of *impingements* was consistently higher for barbel than chub under HV30 (median = 3.0 versus 1.0; Mann-Witney U: U = 83.00, W = 236.00, Z = -2.563, p = 0.01); HV45 (median = 0.0 versus 0.0; Mann-Witney U: U = 111.50, W = 282.50, Z = -2.403, p < 0.05); and LH45 (median = 8.0 versus 0.0; Mann-Witney U: U = 1.00, W = 56.00, Z = -3.786, p < 0.001).

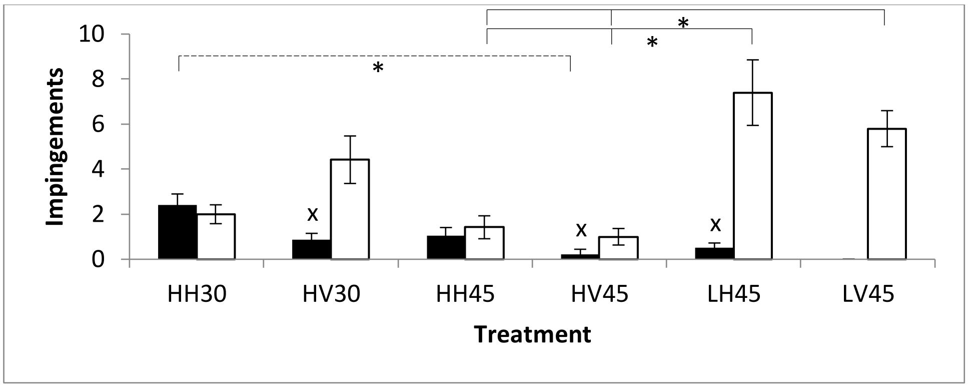

Figure 6. Number of impingements of chub (black bars) and barbel (white bars) on bar racks under high horizontal/ vertical (HH, HV) or low horizontal/ vertical (LH, LV) treatments, angled 30° or 45° to the oncoming flow. Error bars denote ± S.E; asterisks denote a statistical difference among treatments within species with a dashed and solid line for chub and barbel respectively; and crosses denote a statistical difference among treatments between species.

3.2 Fish behaviour

For both species, the total number of *approaches* did not differ between high and low discharge treatments (mean ± S.E. = 48.8 ± 8.04 and 14.2 ± 3.39 for chub under low and high discharge, respectively; mean ± S.E. = 7.9 ± 1.16 and 5.47 ± 0.88 for barbel under low and high discharge, respectively). Under both discharge regimes, *rejections* were influenced by species, with chub rejecting more often than barbel (Table 2). Under high discharge, an interaction between rack orientation and species indicated that *rejections* were higher and lower under vertical than horizontal bar rack orientation for chub and barbel, respectively (Fig 7A, Table 2). An overlap in 95% CI across both species indicated that this was caused by chub rejecting more often than barbel (mean ± S.E. = 9.7 ± 2.39 and 2.8 ± 0.53 for chub and barbel, respectively). Under low discharge, no influence of rack orientation or interaction between this and species was found, but rejections were higher for chub (mean ± S.E. = 43.0 ± 8.13) than barbel (mean ± S.E. = 2.5 ± 0.92) (Fig. 7B, Table 2).

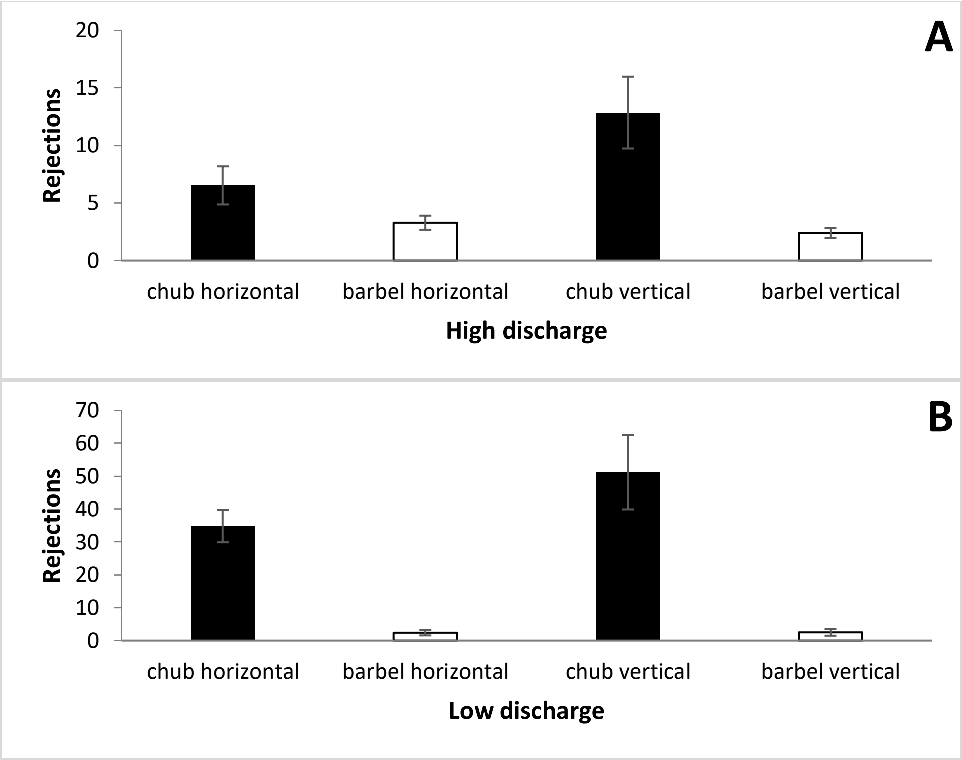

Figure 7. Number of rejections exhibited by chub and barbel after approaching racks with horizontal or vertical bar orientation under high (A) and low (B) discharge. For the high discharge treatments, data for those with a 45° rack was pooled with those for a 30° rack, as angle had no effect. Error bars denote ± S.E.

Under high discharge, the number of instances fish *held station* was influenced by species, being higher for chub (mean ± S.E. = 5.8 ± 1.31) than barbel (mean ± S.E. = 2.8 ± 0.42). This was also the case under low discharge (mean ± S.E.

= 11.9 ± 2.82 and 3.7 ± 0.75 for chub and barbel, respectively) (Table 2, Figure 8A, B). No influence of rack orientation or interaction between rack orientation and species was observed (Table 2).

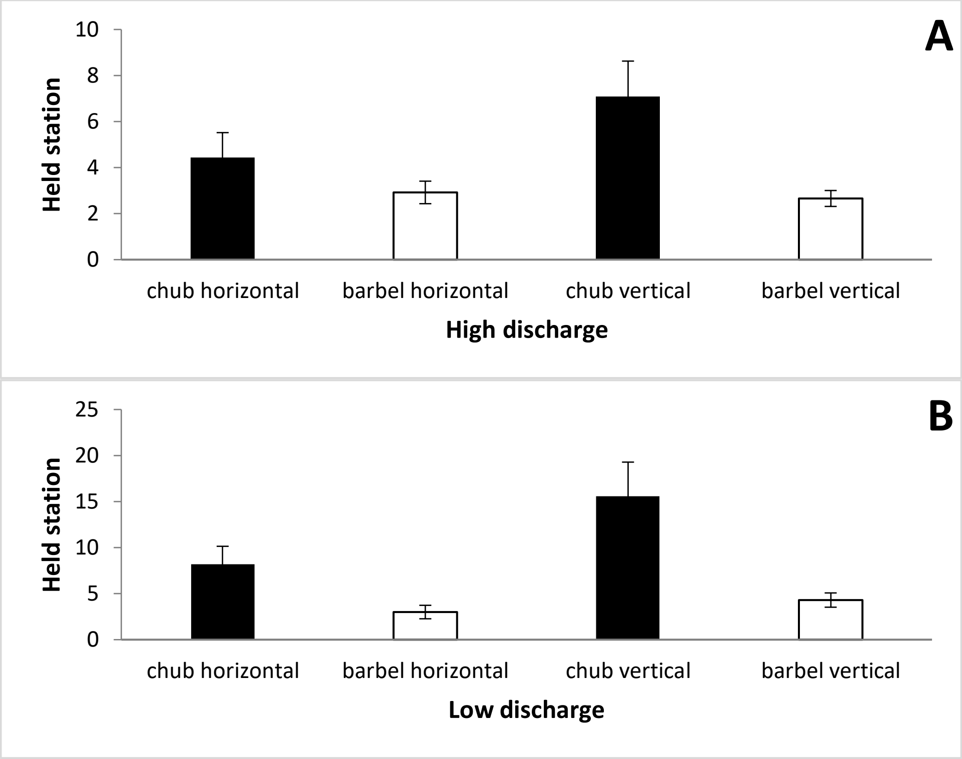

Figure 8. Number of instances chub and barbel held station after approaching racks with horizontal or vertical bar orientation under high (A) and low (B) discharge. For the high discharge treatments, data for those with a 45° rack was pooled with those for a 30° rack, as angle had no effect. Error bars denote ± S.E.

Dependent variable	**Discharge**	**Rack orientation**				**Species**				**Interaction**			
		df	***F***	***p***	**95% *CI***	**df**	***F***	***p***	**95% *CI***	**df**	***F***	***p***	**95% *CI***
(1) Entrain-ments	High	1, 141	2.216	>0.05		1, 141	29.127	<0.001*	Chub [1.50, 2.24] Barbel [0.39, 0.93]	1, 141	3.108	>0.05	
	Low	1, 36	1.027	>0.05		1, 36	1.027	>0.05		1	10.142	<0.01*	Chub-H [2.00, 6.60] Barbel-H [0.50, 2.36] Chub-V [0.57, 2.36] Barbel-V [1.67, 4.00]
(2) Guidance events	High	1, 141	6.972	<0.01*	H [0.16, 0.44] V [0.42, 0.87]	1, 141	27.528	<0.001*	Chub [0.56, 1.07] Barbel [0.05, 0.19]	1, 141	4.158	<0.05*	Chub-H [0.26, 0.79] Barbel-H [0.00, 0.18] Chub-V [0.69, 1.55] Barbel-V [0.05, 0.29]
	Low	1, 36	5.781	<0.05*	H [0.12, 1.24] V [1.02, 3.05]	1, 36	1.340	>0.05		1, 36	0.008	>0.05	
(3) Rejections	High	1, 141	2.429	>0.05		1, 141	15.453	<0.001*	Chub [6.44, 13.38] Barbel [2.16, 3.66]	1, 141	4.293	<0.05	Chub-H [3.66, 10.12] Barbel-H [2.24, 4.62] Chub-V [7.23, 19.66] Barbel-V [1.57, 3.34]
	Low	1, 36	1.764	>0.05		1, 36	42.623	<0.001*	Chub [31.98, 55.70] Barbel [1.30, 3.71]	1, 36	1.722	>0.05	
(4) Held station	High	1, 141	1.558	>0.05		1, 141	9.722	<0.01*	Chub [4.06, 7.74] Barbel [2.23, 3.42]	1, 141	2.232	>0.05	
	Low	1, 36	4.089	>0.05		1, 36	14.707	<0.001*	Chub [8.13, 16.04] Barbel [2.51, 4.65]	1, 36	2.010	>0.05	

Table 2. Bootstrapped two-way ANOVA results, comparing the influence of rack orientation (‘H’ = horizontal, ‘V’ = vertical) and species on the total number of entrainments, guidance events, rejections and instances where fish held station in a large recirculating flume. Data from the high discharge treatments were pooled by rack orientation. Significant results are indicated by *, and the 95% confidence interval (CI) of the mean in that case reported.

4. Discussion

Physical screens intended to block fish from entering water intakes, and guide those moving downstream to alternative bypass routes, have suffered from variability in efficiency, often achieving lower than expected performance, and negatively impacting species they are designed to protect. In many cases their design criteria are biased towards those species exhibiting diadromous life-cycles. Here we tested the effectiveness of two alternative screen configurations (vertically and horizontally oriented bar racks) to guide groups of two seldom studied cyprinid species to a bypass channel under experimental settings. The tests were performed under two discharge regimes and with the screen installed at different angles to the oncoming bulk flow.

Total guidance to the bypass, expressed as a percentage of the total number of approaches to the racks, was generally low for both species, with mean values between 20-25% for the treatments. This reflected a combination of a high degree of avoidance and the loss of individuals that were entrained through the racks (especially chub) or impinged on them (especially barbel). Poor guidance and high entrainment and impingement were likely a result of a lack of sweeping flow across the screen face that was expected to direct the fish towards the bypass. In this study the bulk flow predominantly passed through the racks, regardless of orientation and discharge, and the resulting sweeping flow to the bypass was weak. The bars used were circular in cross-section, which may provide a partial explanation for our results, as bars with round or streamlined edges induce lower head losses than those with rectangular ‘bluff’ edges under a variety of bar spacing and screen angles of vertical bar racks (Tsikata et al., 2014, Albayrak et al., 2018, Raynal et al., 2013). A recent study by Meister et al. (2020a) evaluated head losses near horizontal bar racks with different bar spacing, shape and angle to the flow. The used bar shapes included a rectangular and three hydrodynamic ones of which the rectangular bar with a circular tip, would be most similar to the circular bars used in our study. Again, head losses were highest with rectangular bars in place and could be reduced by using foil-shaped bars instead of circular tip ones.

While horizontal bar racks have been suggested to offer benefits in terms of reduced debris accumulation (e.g. Ebel et al. 2015) or improved probability of fish escape after impingement (Horsfield and Turnpenny, 2011, Ebel et al., 2015), more fish were guided to the bypass under the vertical configuration, suggesting a disadvantage of the horizontal design. Guidance with a vertically oriented rack could have been aided by the support bar located at the bottom of the frame. This bar may have provided the test fish with shelter from the flow field that also led to the bypass channel. This is plausible as the test fish of both species were predominantly observed to swim near the channel floor. Indeed, Meister et al. (2020b) found that the effect of a bottom overlay of height 20% of the water depth had a governing effect on the velocity field near horizontal bar racks, more pronounced than the effect of bar shape, spacing, or angle to the oncoming flow, and suggested this may enhance guidance efficiency.Previous studies with fish found that guidance of benthic species, such as lake sturgeon (*Acipenser fulvescens*) and American eel (*Anguilla rostrata*), is improved when an overlay covers the lower 30 cm of a bar rack (Amaral et al., 2002, Amaral et al., 2003).

Under high discharge rack angle did not appear to influence probability of entrainment, guidance, rejection and number of fish that held station. The high discharge data was pooled accordingly for both species before investigating the influence of rack orientation and species (Table 2), but the resulting data violated normality and homogeneity of variance after transformation. Therefore, the bootstrapped parametric test results are used here to illustrate trends but these should be interpreted with caution (see Vowles and Kemp, 2012 for a similar approach for downstream moving fish). Trends predominantly indicated a species effect, i.e. chub counts exceeded those of barbel under at least one discharge regime for all test variables. This may be explained by morphological differences between the species and resulting differences in behaviour when encountering the bar racks.

Fish avoidance of the local hydrodynamics associated with bar racks and other types of screens, such as sudden changes in velocity or turbulence, has been observed for a range of migratory species, including European eel (Russon et al., 2010), American eel (Brown et al., 2009), and more recently for chub (De Bie et al., 2018). In this study, barbel were less likely to avoid the racks, either by rejecting them and moving back upstream or holding station, than chub. Barbel were, therefore, more likely to make contact, increasing the probability of impingement. Conversely, chub approached the racks more frequently and either exhibited stronger avoidance (rejection or holding station) or entrainment when they followed the bulk flow. In the wild, both these outcomes are unwanted as it causes mortality or greater delay and associated costs, e.g. energy expenditure or predation risk (e.g. Castro-Santos and Haro, 2003, Nyqvist et al., 2016).

To facilitate the development of sustainable and resilient river infrastructure systems that adequately mitigate environmental risk, there is a need to further develop the techniques for screening of water intakes to block and guide multiple species of fish (Kemp, 2016). This requires an understanding of the variability in fish behaviour, both within and between species, in response to hydrodynamics commonly encountered at screens so that appropriate design criteria can be formulated. This considers less frequently studied potamodromous European species, which are important indicators of water quality and ecosystem health (e.g. Britton and Pegg, 2011) and of value to recreational fishing. Ultimately, both orientations of the bar racks were relatively ineffective under the conditions tested in which velocities were not challenging, while interspecific variation in avoidance behaviour to fine-scale hydrodynamics created at the screen further influenced effectiveness. Further experiments are warranted to ascertain whether the bar racks used here are an appropriate screen design to protect a wider range of species.

Declaration of interest: none

Data availability

Data supporting this study are available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D1836.

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