**Title:** Effectiveness of horizontally and vertically oriented wedge-wire screens to guide downstream moving juvenile chub (*Squalius cephalus*).

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Declaration of interest: none

# **Abstract**

Physical screens are commonly installed to prevent downstream moving fish from entering dangerous areas (e.g. intakes to hydropower turbines, irrigation canals, and fish farms), and divert them to preferred alternative routes (e.g. bypass systems). In northern temperate regions, assessments of the functioning of screens have largely focused on diadromous species (e.g. salmon and eel), while ignoring those with other life history characteristics. Recent developments in physical screens include the usage of horizontally aligned bars as opposed to traditional vertical ones, but a direct comparison in terms of guidance remains untested. To address this and aid in the development of successful screens for the wider fish community, this study compared the efficacy of wedge-wire screens with horizontally and vertically oriented bars to block and divert downstream moving groups of five chub (*Squalius cephalus*) to a bypass channel installed in a recirculating flume under two discharge regimes. Hydrodynamics differed between horizontal and vertical screens under both flows; the vertical configuration created a higher velocity gradient towards the bypass. Total guidance (the number of bypass entries as a percentage of the number of approaches) was generally low (mean = 17.3% for all treatments), the highest being recorded for the horizontal screen under low discharge (25.3%). Rejections and holding station events, both proxies for fish exhibiting avoidance of the hydrodynamic conditions created by the screen, were lowest under this treatment. Horizontal performed better than vertical screens in guiding fish to the bypass under low but not high discharge. The results confirm that screen functioning is dependent on hydrodynamic conditions as well as the fish’s behavioural response.

**Keywords:** Fish passage, Cyprinidae, groups, wedge-wire screen, guidance

# **Introduction**

Widespread engineering of European rivers and high densities of infrastructure (e.g. dams and weirs) reflect a long historic legacy of water resource development and management (Demirbas 2007; Paish 2002). It is estimated that there are more than 55,000 large (>15 m high) dams present worldwide (International Commission on Large Dams, 2017), and over half the large rivers in Europe are affected by them (Nilsson and others 2005). Many thousands of smaller structures, such as weirs and sluices, further exacerbate the impacts (EA 2010; Lucas and Baras 2001), which include the disruption of flow regimes (first order) that alters channel morphology and physical and chemical processes (second order), and leads to ecological shifts (third order), including changes in community composition and species abundance (Kemp 2016; Petts 1980). Depending on the type of impounding structure, fish movements can be completely blocked or impeded, while those that enter intakes may be lost (e.g. to irrigation and water supply systems), or risk injury and mortality if they pass through turbines (Kemp 2016; Larinier and Travade 2002). As longitudinal movements are essential to the completion of their life cycles (Lucas and Baras 2001), habitat fragmentation as a result of river impoundment threatens the sustainability of many fish populations (Liermann and others 2012).

 Often driven by legislation, environmental impact mitigation technologies are developed to protect fish at impounding river infrastructure (Kemp 2016). For example, fishways are installed at barriers to fish movements to help fish negotiate them, while physical and mechanical screens are designed to block fish that would otherwise enter intakes (O'Keeffe and Turnpenny 2005; Taft 2000) and guide them to safer alternative routes, such as bypass channels (Katopodis and Williams 2012). However, previously published research tends to focus more on fish passage than on screens, with a few notable exceptions (e.g. Gessel et al. 1991 and Skalski et al. 1996 for Pacific salmonid [*Oncorhynchus* spp.] smolts in North America; Russon et al. 2010 and Calles et al. 2013 for eel [*Anguilla anguilla*] in Europe). Furthermore, those studies that evaluate the effectiveness of screens often do so for diadromous species that are of economic and conservation concern (e.g. salmonids and eel), while benefits for the wider fish community are infrequently considered (Williams and others 2012).

 Evaluation of the efficiency of screens to guide fish to bypass channels (‘guidance efficiency’) yields variable results, reflecting differences in local site-specific characteristics (e.g. hydrodynamics) and variation in behaviour exhibited among species and life-stage. Nevertheless, it is clear that when upstream velocities adjacent to the screen are high relative to swimming capabilities, fish may be injured through excessive mechanical abrasion if they make contact, or suffocate if they become impinged and unable to escape from the screen face (Swanson and others 1998; 2005; White and others 2007). For fish that exhibit strong thigmotactic behaviour, such as downstream moving European eel, this is particularly problematic because they tend to show an avoidance response only after contacting the screen (Russon and others 2010), thus increasing the probability of injury, impingement, and mortality. Several species also exhibit avoidance behaviour to the hydrodynamic conditions created at the bypass entrance, as observed for American shad (*Alosa sapidissima*) (Kynard and Buerkett 1997) and Atlantic salmon (*Salmo salar*) (Larinier and Travade 1999), delaying downstream passage. Improving the functioning of screens requires detailed knowledge of the behaviour of the species under consideration.

 To improve the performance of screens there is a need to revisit guidance on their design and operation. Current design criteria focuses primarily on placement of screens and the need to provide a suitably high sweeping flow parallel to the face to enhance fish guidance towards a bypass, while minimising perpendicular escape velocities to reduce probability of impingement (EA 2009). As a result, it is advised that screens should be placed at an angle of 45° or less to the oncoming flow (Courret and Larinier 2008; Raynal and others 2013), while critical escape velocities vary depending on the target species of interest (e.g. 0.25 m s-1 for coarse fish, EA, 2009). Further, the hydrodynamic conditions adjacent to screens are influenced by a range of factors, including their shape and bar spacing (e.g. Katopodis and others 2005; Tsikata and others 2014). It is recommended that at screens and bypass entrances abrupt hydraulic transitions, such as rapid accelerations of velocity and increasing turbulence, should be minimised because these may induce undesirable avoidance behaviour and delay fish passage (Russon and Kemp 2011; Vowles and Kemp 2012) .

 Recently, the influence of bar orientation on screen effectiveness has received attention, as there is some suggestion that horizontal alignment, rather than the traditional vertical configuration, is beneficial because it improves passive “self-cleaning” of debris (Ebel 2008; Ebel and others 2015) and enables escape of impinged fish through facilitating movements in the horizontal plane (Horsfield and Turnpenny 2011). Whilst horizontal screens have currently been installed in Europe, an empirical comparison between bar orientations has not been made in the context of fish guidance.

 This study aimed to compare the effectiveness of wedge-wire screens, with bars oriented either horizontally or vertically, to guide downstream moving fish to a bypass entrance. To address the bias towards diadromous species, juvenile chub (*Squalius cephalus*), a potamodromous cyprinid, was selected here as the representative model. They are widely distributed in Europe and an important species for recreational angling. As chub are gregarious, especially during the juvenile stage (Kottelat and Freyhof 2007), the study used groups of five fish in an effort to induce natural behaviours under the experimental conditions presented. Trials were conducted under two discharge regimes (‘High’ and ‘Low’), creating distinct flow fields at the screen and entrance to the bypass. The objectives of the study were to quantify: (1) the guidance of the screen configurations under different settings; and (2) fish behaviour in response to the hydrodynamic conditions encountered.

# **Materials and Methods**

## **Experimental setup**

Experiments were conducted in a large recirculating flume (21.4 m long, 1.4 m wide and 0.6 m deep) at the International Centre for Ecohydraulics Research (ICER), University of Southampton, UK. A centrally located 8.2 m long section was isolated upstream from the rest of the channel by a flow straightener (10 cm wide polycarbonate honeycomb-structured screen) and downstream by a square mesh (0.5 cm x 0.5 cm) panel, both of which prevented fish from escaping the experimental area (Fig. 1). The flume was illuminated with fluorescent lighting installed 2.5 m above the channel floor. Five cameras mounted 1.6 m above the floor recorded fish movements in an observation zone that spanned from 50 cm upstream of the screen to the bypass entrance (Fig. 1). Black screens were installed on both sides of the flume to prevent visual disturbance to the fish.

Under treatment conditions a 2.5 m long wedge-wire screen was placed, perpendicular to the channel floor, at an angle of 30° to the oncoming flow and spanned a distance of 2.0 to 4.2 m downstream of the flow straightener between the flume wall and bypass entrance (Fig. 1; Fig. 2). The screen consisted of five 50 cm x 50 cm stainless steel wedge-wire panels (3 mm bar width and 6 mm bar spacing) which were rotated to alternate between a horizontal and vertical alignment. The width of the bypass was 10% of that of the flume channel and was longitudinally separated by a Perspex screen (4 m long, 50 cm high and 1 cm thick).

Trials were conducted under two discharge regimes, defined as low (L = 0.09 m3 s-1) and high (H = 0.15 m3 s-1), controlled by adjusting the centrifugal pumps and an overshot weir at the downstream end of the flume. Discharge levels are lower than the natural environment in which chub occurs, which includes streams and rivers with discharge up to 50 m3 s-1 (Kottelat and Freyhof 2007). Chosen discharge levels were also such that resulting escape velocities at the screen would not exceed the critical value of 25 cm s-1 for coarse fish proposed by the EA (2009). Average water depth across the width of the flume at 1.5 m upstream of the screen, was 0.38 m and 0.27 m under the low and high discharge, respectively. By altering the orientation of the screen, a total of four treatments were created: low horizontal (LH), low vertical (LV), high horizontal (HH) and high vertical (HV) (Table 1).

**Table 1. Hydrodynamic conditions encountered by groups of chub passing downstream through a flume under low (L) or high (H) discharge and on encountering either a horizontally (H) or vertically (V) oriented screen. *N* is the total number of fish used per treatment.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Treatment – discharge and screen type** | **# Replicates** | **Mean (± SD)****velocity****upstream (m s-1)** | **Mean (± SD) velocity in middle of bypass (m s-1)** | **Mean (± SD) water temperature (°C)** | ***N*** |
| LH | 14  | 0.17 (± 0.01) | 0.24 (± 0.01) | 10.7 (± 0.7) | 70 |
| LV | 13 | 0.18 (± 0.01) | 0.27 (± 0.01) | 10.3 (± 1.1) | 65 |
| HH | 12  | 0.36 (± 0.02) | 0.49 (± 0.02) | 11.1 (± 1.1) | 60 |
| HV | 12  | 0.35 (± 0.01) | 0.57 (± 0.02) | 10.7 (± 1.4) | 60 |

## **Experimental procedure**

A total of 750 subyearling chub were collected from the Environment Agency fish farm at Calverton, UK (53°2’1.3” N, -1°3’7.0” W), on 7 November 2014 and transported to the ICER research facility. Fish were maintained in two outdoor 2000 L holding tanks filled with dechlorinated and oxygenated water (mean ± SD water temperature: 9.5 ± 2.9 °C) prior to their use in the trials. Fish were acclimated to ambient indoor water temperatures by moving them to a 1000 L holding tank (mean ± SD water temperature: 10.7 ± 1.2 °C) one day before the trials commenced. Fish were fed twice daily. Water quality parameters (pH, $NH\_{3}$, $NO\_{2}^{-}$, and $NO\_{3}^{-}$) were monitored throughout the duration of the experiment, with 50% water changes employed when necessary. Fish total length (mean ± SD TL) and wet mass (M) were 107.9 ± 5.7 mm and 11.3 ± 2.0 g, respectively. Water temperature (mean ± SD) in the flume at the beginning of trials was 10.7 ± 1.1 °C.

Fifty-onetrials were conducted during hours of daylight between 29 November and 16 December 2014. A total of 40 chub were randomly selected each day from the indoor holding tank and transported to a 150 L container 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 in a circular mesh enclosure at the upstream end of the flume (Fig. 1) and allowed to acclimate for twenty minutes. Each trial commenced when the enclosure was raised and the fish were released into the experimental area which they could volitionally explore. Each trial lasted until all five fish had entered the bypass, or in cases where they did not, after 2 h 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.

## **Hydrodynamics**

Distinctly different hydrodynamic conditions were created upstream of the screen under the four treatments. These were quantified using an Acoustic Doppler Velocimeter (ADV) (Vectrino+, Nortek - set with a 50 Hz sampling frequency, 0.28 cm3 sampling volume, and recorded over a 60 s duration) at a depth of 5 cm above the channel floor, as pilot trials indicated fish tended to remain close to the channel floor when moving downstream. Raw ADV data was filtered following the protocol of Cea and others (2007) and the mean velocity vector (***V***) was calculated as:

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

where$ \overline{u}^{2}$, $\overline{v}^{2}$ and $\overline{w}^{2}$represent mean velocities in the longitudinal (*x*), lateral (*y*), and vertical (*z*)direction, respectively. Resulting density contour and vector maps (Fig. 3, Fig. 4) of ***u****,* ***v****,* and ***V*** under all treatments were created using Matlab (2014b). Changes in ***w*** were negligible in comparison and are not illustrated here.

 The screens effectively diverted flow (***u***, ***v***) to the bypass entrance, but this was most pronounced when vertically oriented (Fig. 3). The gradient of ***V***was lower along the horizontal compared to the vertical screen, and lowest under the LH treatment (1.2 cm s-1 m-1, Table 2). High similarities between the profiles of ***u***and ***V*** suggested thatthe predominant direction of flow was through the screen, and flow divergence occurred primarily where the screen met the channel wall (Fig. 4).

**Table 2. Magnitude of the mean velocity (**$V$**), 5 cm above the channel floor, at the start of either a horizontally (H) or vertically (V) oriented wedge-wire screen and bypass entrance under low (L) and high (H) discharge. The velocity gradient along the screen was obtained by calculating the quotient of** $∆V$ **and screen length (2.5 m).**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatment – discharge and screen type** | **Mean ± SD *Vscreen wall******(cm s-1)*** | **Mean ± SD *Vbypass* entrance*****(cm s-1)*** | ***V Gradient ± SD along screen******(cm s-1 m-1)*** |
| LH | 16.2 ± 0.5 | 20.9 ± 0.1 | 1.8 ± 0.2 |
| LV | 17.0 ± 1.2 | 23.2 ± 1.0 | 2.5 ± 0.6 |
| HH | 34.5 ± 1.5 | 47.4 ± 0.1 | 5.1 ± 0.6 |
| HV | 34.3 ± 1.1 | 50.0 ± 0.1 | 6.3 ± 0.4 |

Using the longitudinal and lateral components of the velocity, the divergence angle (***β1***) at which flow is diverted at the screen, the sweeping (***Vs***) and escape (***Ve***) velocities were calculated(Fig. 5):

$\tan(β\_{1}= \frac{v}{u})$, (2)

$β\_{2}= α-β\_{1}$, (3)

$V\_{s}=V\*cos(β\_{2})$, (4)

$V\_{e}=V\*sin(β\_{2})$, (5)

where ***α***is the angle of the screen to oncoming flow (= 30°).

Under all treatments, ***β1*** decreased towards the bypass entrance (Fig. 6a). There was no difference between treatments. ***Vs*** and ***Ve*** increased towards the bypass entrance and were lower under the low compared to the high discharge (Fig. 6b, c). Horizontal screens induced slightly lower ***Vs*** than vertical ones (Fig. 6b), while there was no discernible difference in ***Ve*** between horizontal and vertical screens, regardless of discharge (Fig. 6c).

## **Total and screen guidance**

A downstream moving fish was considered to have approached the screen area when it entered the observation zone. Thereafter, routes to the bypass were categorised as being either guided along the: (1) screen, or (2) true right wall (without direct interaction with the screen). Fish were allowed to freely move up and downstream through the observation zone and return upstream after *entrance* into the bypass channel. As a result, multiple approaches and entries per fish were possible.

*Total guidance* per trial was defined as the number of bypass entries as a percentage of the number of approaches (*total approaches*).

*Screen guidance* per trial was defined as the number of bypass entries along the screen as percentage of the number of approaches that occurred on the screen side of the flume (*screen approaches*).

## **Fish behaviour**

Whenever a fish left the observation zone by returning upstream after an approach without entering the bypass, it was deemed to have displayed a *rejection*. The number of *rejections* made by all five fish was recorded per trial.

In the first 30 s following a successful approach to the screen, the number of instances all five fish *held station* in response to the screen was recorded per trial.

Fish were deemed to belong to a group when a loosely aggregated structure was formed in which individuals maintained a distance no more than 4 body lengths apart (e.g. Hensor and others 2003). The number of *approaches* and bypass *entrances* made by solitary individuals and groups (cases totalled for a group size of up to five) was recorded for each trial.

## **Statistical analysis**

A Shapiro-Wilk and Levene’s test was used to evaluate data for normality and homogeneity of variance. Percentage and non-parametric count data were arcsine square root and log transformed, respectively, prior to statistical analysis. Where normality or homogeneity of variance was violated, and in the event that transformation was unsuccessful, non-parametric tests were used.

The influence of discharge and screen configuration (fixed factors) on the: (1) *total guidance*, and number of (2) *approaches* (as solitary individuals or groups) and (3) *rejections* (dependent variables) were tested using univariate two-way ANOVA. Tukey HSD post-hoc tests were used to determine where differences between treatments occurred. *Screen approaches* and s*creen guidance* were evaluated using a Kruskal- Wallis test.

A Chi-squared test of independence was used to determine the influence of treatment on the number of instances fish *held station*.

The effect of treatment on the number of bypass *entrances* of solitary individuals or groupswas analysed using a Kruskal-Wallis test.

# **Results**

## **Total and screen guidance**

An interaction between discharge and screen configuration indicated that *total guidance* was positively and negatively related to discharge for the vertically horizontally oriented screens, respectively (*F1,47* = 5.92, *p* < 0.05). *Total guidance* was highest under the LH treatment (Fig. 7a), which differed significantly from the HH treatment (Tukey HSD post-hoc test: *p* < 0.05). *Screen guidance* differed between treatments (Kruskal- Wallis: H = 8.881, df = 3, *p* < 0.05), being higher under LH than HH (*p* < 0.05) (Fig. 7b).

## **Fish behaviour**

*Screen approaches* did not differ between treatments. There was a positive relationship between *total approaches* and discharge (*F*1,47 = 8.87, *p* < 0.01), being higher under HH compared to both LH and LV treatments (*p* < 0.01 and *p* < 0.05, respectively). The number of *rejections* was positively related to discharge (*F1,47* = 7.53, *p* < 0.05), although an interaction (*F*1,47 = 4.29, *p* < 0.05) between discharge and screen configuration was apparent, with *rejections* being highest (mean ± S.E.: 115.8 ± 14.8) and lowest (mean ± S.E.: 40.4 ± 5.3) for the horizontal screen under high and low discharge, respectively (Tukey HSD post-hoc: *p* < 0.01) (Fig. 8). For the vertical screen the difference was small (Fig. 8).

The number of *station holding* events was influenced by discharge and screen configuration (*X*2 [1,519] = 14.4, *p* < 0.001, *V* = 0.17), being lowest for the LH (*n = 95*), and highest for the HH treatment (*n* = 192).

The number of *approaches* was higher under the high discharge treatments for both *solitary individuals* (*F1,47* = 5.21, *p* < 0.05) and *groups* (*F1,47* = 11.55, *p* < 0.01) of fish (Fig. 9a). The number of bypass *entrances* differed between treatments for *solitary individuals* only (Kruskal- Wallis: *H* = 17.20, *df* = 3, *p* = 0.001), being lower under the LV than HV (*p* < 0.001) and HH (*p* < 0.001) (Fig. 9b).

# **Discussion**

Screens are commonly installed at river abstraction points, e.g. intakes to hydropower turbines, irrigation systems, or fish farms, with the intention that they block ingress and guide fish to more benign routes, such as bypass systems at dams and weirs. There exists a large variety of screens, including physical ones and behavioural barriers, reflecting decades of attempts to improve downstream passage for a variety of species and life stages under different site-specific conditions (Kemp 2016; Noatch and Suski 2012). While wedge-wire panel screens are considered the best solution for protection of fry and juvenile life-stages (O'Keeffe and Turnpenny 2005), evaluation through experimentation is limited (but see Danley and others, 2002, for splittail (*Pogonichthys macrolepitodus*, and Poletto and others, 2014, for green and white sturgeon (*Acipenser medirostris/ A. transmontanus*).This study investigated the effectiveness of two wedge-wire screen configurations, vertically and horizontally oriented, to guide groups of chub, to a bypass entrance under experimental settings. Fish behaviour played an important role in influencing screen efficiency. Although the screens, particularly when vertically oriented, created sweeping flows along their face towards the bypass, the fish were not easily guided to the entrance as expected (Swanson and others 2004). Indeed, when considered as a percentage of the total number of approaches, which were numerous indicating high levels of activity and motivation, total and screen guidance were generally low, with mean and median values being equal to or less than approximately 25% and 20%, respectively. Rejections, however, were high under all treatments (mean >80%) as fish encountered and then frequently avoided the abrupt velocity gradient by moving back upstream. Holding station, a form of avoidance to velocity gradients (Vowles and others 2014), was furthermore commonly observed. The horizontal screen under low discharge proved to be most efficient with highest and lowest percentage guidance and rejections, respectively.

The results presented highlight the importance of avoidance behaviour induced by abrupt accelerations of velocity in juvenile chub. This potamodromous species is known to migrate variable but sometimes considerable distances within rivers (Fredrich and others 2003; Penczak 2006), but is yet to be considered in the context of screening.. Such behaviours are common for multiple species, including Pacific salmon smolts (Kemp and others 2005) and brown trout (*Salmo trutta*) (Vowles and Kemp 2012) under experimental settings, and Atlantic salmon smolts (Ovidio and others 2016) and European eel (*Anguilla anguilla*) in the wild (Piper and others 2015). When viewed from the perspective of screening and fish passage, avoidance is undesirable because it results in reduced efficiency and delay, and potential increased energetic expense and predation risk (Larinier and Travade 2002; Schilt 2007). Being gregarious in nature, juvenile chub were released in small shoals. Besides well-known advantages of group formation in fish, such as anti-predatory and foraging benefits (Krause and Ruxton 2002), enhanced navigational accuracy could also be gained from an increasing group size (Couzin and Krause 2003; Simons 2004). However, chub had a weak propensity to shoal after release and under high flow individual approaches and bypass entrances, and group approaches were significantly higher, suggesting that shoal cohesion was negatively impacted under more demanding conditions. In the context of fish passage, the breakup and reformation of shoals has previously been reported for Atlantic salmon and American shad (*Alosa sapidissima*) at bypass weirs (Haro and others 1998) and for juvenile palmetto bass (*Morone chrysops* x *M. saxatilis*) negotiating Louver screens (Lemasson and others 2014). Ensuring shoal maintenance could prove valuable in successful guidance of gregarious species and life stages and future research should focus on a better understanding of how this is influenced by hydrodynamics near screens.

 Where they have been installed (e.g. Germany, Ebel and others 2015) horizontal screens have been promoted as superior to the traditional vertical configuration because they may facilitate more efficient downstream transport of debris (Ebel, 2008) and enhance probability of escape for impinged fish (Horsfield and Turnpenny, 2011). In this study we compared the hydrodynamic performance of horizontally and vertically oriented wedge-wire screens under two relatively moderate discharge regimes. The sweeping flow associated with the horizontal screen was less pronounced than for the vertical orientation, resulting in a less abrupt velocity gradient which somewhat improved guidance under low flow for the reasons described above. Furthermore, under the conditions presented, a greater proportion of the flow passed through the horizontal screens, suggesting that in the field such a configuration may enable more water to be abstracted to the benefit of the operators compared to changing the bar spacing or screen angle for vertical ones (Katopodis and others 2005; Raynal and others 2013). Diversion of a greater proportion of flow to the bypass under the vertical treatment may have reflected higher flow separation at each individual wire so that the cumulative effect along the entire length of the 2.5 m screen was substantial. Thus, the benefit of horizontal screens may be primarily related to improved water abstraction, with some beneficial consequences for fish guidance. This study, however, did not consider fish and debris response under higher velocity conditions in which impingement will become a factor, and so further investigation is needed to test alternative designs under a greater range of flows in both the laboratory and field, whilst adhering to sweeping and escape velocity guidelines (EA 2009).

Screens that effectively prevent fish from entering intakes and guide them to alternative routes are an important component in the arsenal of technology designed to mitigate environmental impacts of river infrastructure (Kemp 2016). Nevertheless, such technology can itself have substantial negative effects on downstream moving fish if inappropriately installed and maintained. Physical abrasion or suffocation of fish that become impinged on screens when water velocities are higher than their escape velocities are perhaps the most noticeable (e.g. Calles and others 2010; Swanson and others 2005). However, the unseen costs of increased energetic expense and probability of predation (e.g. Evans and others 2016) of fish that are delayed as a result of avoiding hydrodynamic gradients are also likely to be as equally damaging, if not more so, at the population level. Methods are needed to improve screen guidance efficiency by reducing the probability of avoidance. This may be achieved by changing the hydrodynamic environment to create gentle velocity gradients at screens and bypass entrances, or by using alternative stimuli to either mask or compete (e.g. through deterring or attracting fish) with hydrodynamic signals encountered. To date, the use of hydrodynamic disturbance (e.g. turbulence) to mask velocity gradients (Kerr et al. under review) and acoustic fields to enhance the guidance performance of screens (e.g. Deleau et al. under review) provide an interesting way forward in efforts to advance combined low-cost solutions to improve fish screening.

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**Figure 1. Plan of the experimental section used to investigate the response of groups of five chub (*Squalius cephalus*) to conditions encountered at a wedge-wire screen oriented either in a horizontal or vertical configuration within a large recirculating flume at the University of Southampton. The wedge-wire screen was placed against the true left side of the flume, leading to the bypass entrance. Closed circles represent positions of overhead cameras. The dashed circle represents the location of fish release. Thick black arrows denote locations of 60W bright white fluorescent tube lights that were suspended perpendicular above the flume. Fish behaviour was recorded in the observation zone that extended between the dashed lines.**

**Figure 2. Details of wedge-wire panels used during the study. a) close-up of single panel with 3 mm bar width and 6 mm wire spacing; b) a single 50 cm x 50 cm panel; c) wedge-wire screen (horizontal bar orientation) comprising a frame with five slotted panels installed in a large recirculating flume. The bypass channel was located at the far right.**

**Figure 3. Colour density contour plots of *u* (top row) and *v* (bottom row), 5 cm above the channel floor upstream of either a horizontally (H) or vertically (V) oriented wedge-wire screen under low (L) and high (H) discharge. Positive and negative values for *v* indicate flow to the left and right, respectively. The black line denotes the location of the screen and bypass channel, the black dots indicate points where velocity was recorded using the ADV. Note that the colour bars across treatments are similar, but the ranges of values vary depending on discharge.**

**Figure 4. Colour density contour and vector plots illustrating the mean velocity (**$V$**) profile 5 cm above the channel floor upstream of either a horizontally (H) or vertically (V) oriented wedge-wire screen under low (L) and high (H) discharge. For illustrative purposes, the screen and bypass channel are not shown here. Note that the colour maps across treatments are similar, but the ranges of values vary depending on discharge.**

**Figure 5. Velocity components at a measurement point 2.0 m (left) and immediately upstream of a wedge-wire screen (right). At 2.0 m upstream of the screen, the magnitude and direction of the mean velocity (**$V$**) mainly results from the longitudinal component (*u*) as the lateral component (*v*) is comparatively small. The presence of the screen diverts** $V$ **by angle *β1*.** $V$ **can be decomposed into a sweeping (*Vs*) and escape (*Ve*) component. These can be computed using *β1* and *α* = 30°.**

**Figure 6. Divergence angle *β1*(a), sweeping velocity *Vs* (b), and escape velocity *Ve* (c) 5 cm above the channel floor at either a horizontally (H) or vertically (V) oriented wedge-wire screen under low (L) and high (H) discharge.**

**Figure 7. Total guidance (a) and screen guidance (b) for horizontally (H) and vertically (V) oriented wedge-wire screen under low (L) and high (H) flow. Error bars denote ± S.E. Boxes represent the interquartile range, and whiskers represent maximum and minimum values.**

**Figure 8. Number of rejections exhibited by chub after approaching either a horizontally (H) or vertically (V) oriented screen under low (L) and high (H) discharge. Error bars denote ± S.E.**

**Figure 9. Number of approaches (a) and entrances (b) to a bypass by solitary individuals or groups (totalled for groups of 2-5 fish) of chub at either a horizontally (H) or vertically (V) oriented screen under low (L) and high (H) discharge. Error bars denote ± S.E.**