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Impact of hydrokinetic turbines on rainbow trout behaviour

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Abstract

Hydrokinetic turbines are an emerging technology to supply reliable and renewable energy by harnessing kinetic energy from river or tidal flows. They are a potential alternative to current hydropower schemes that impound rivers, cause habitat fragmentation and fish mortality. To-date there is limited knowledge available about fish behaviour in the vicinity of hydrokinetic turbines and their effects on shoaling. In this study, juvenile rainbow trout (*Oncorhynchus mykiss*) were allowed to swim either individually or as a shoal of three fish in a laboratory flume with five turbine configurations of single and paired turbines. Results show the turbines did not reduce fish passage when in operation, and blade strikes were rare, none causing significant harm. Fish were more likely to swim in the turbine's downstream wake and upstream of the turbine (known as bow wake) when two turbines were operating because of the generation of larger areas of low velocity. Fish approached the turbines more often in shoals than alone and were overall bolder in shoals. This study suggests that hydrokinetic turbines do not significantly affect fish movement, thus supporting their utilisation as a suitable technology to extract renewable energy from rivers.

Introduction

Reliable power supply is essential to modern society, and affordable and clean energy is one of the United Nations Sustainable Development Goals (SDGs) ¹. Most large cities and settlements have access to national energy grid networks and power plants that deliver a stable power supply to homes and industry through a mixture of fossil, nuclear, and renewable energy. Remote communities, however, still struggle with reliable power supply and may depend on renewable resources that may not be predictable. The SDGs aim for a reduction in fossil fuel usage ¹, favouring an increase in renewable and low carbon resources, ideally using resources that do not damage the natural environment.

40 Freshwater watercourses are a valuable resource of energy which has a long history
41 of being exploited by humans. The most common form of energy extraction from rivers
42 in modern times is by impounding large volumes of water with a dam and forcing it
43 through turbines to generate power. Such hydropower plants generate 14.3% of the
44 world's electricity, but their contribution varies widely by country and region, ranging
45 from 0% to 100%^{2,3}. Hydropower plants are considered a low carbon energy source
46 but they still have a negative effect on the rivers, causing fragmentation, preventing
47 and/or delaying fish migration, disrupting natural sediment transport characteristics,
48 and causing fish mortality^{4,5}. Over 3,000 new hydropower plants are planned⁶,
49 particularly in relatively untapped rivers such as the Amazon, Congo, and Mekong⁷,
50 home to a third of freshwater species, some found nowhere else. Hydropower plants
51 installations without any technical or natural fish passage solution, however, can cause
52 up to 100% mortality in freshwater fish migrating through turbines⁸ and block the
53 migration of others⁵, with small dams having the largest ecological impact relative to
54 capacity^{6,9}.

55 For remote communities, not connected to the wider grid and in need of a reliable
56 source of power, hydrokinetic turbines are emerging as an alternative and less
57 environmentally-damaging alternative to hydropower plants¹⁰. Hydrokinetic turbines
58 use the flow velocity of rivers to generate power. They do not impound rivers or form
59 a barrier that spans the full river width¹¹. Hydrokinetic turbines are also easier and
60 cheaper to install than hydropower plants with potentially fewer environmental
61 drawbacks and predictable power delivery^{11,12}, making them suitable for use in remote
62 regions^{9,12}. Several small hydrokinetic turbines exist and currently operate in countries
63 like Brazil and Malaysia^{10,13-15}. These are used to provide power to small communities
64 and are effective in shallow but fast flowing streams. The designs are of various types
65 but mainly consist of horizontal and vertical axis turbines and sizes range from
66 diameters of 0.36 to 4.4 m¹³⁻¹⁸.

67 Although hydrokinetic turbines potentially have less impact on river hydrodynamics
68 and geomorphology¹⁹, they still block part of the watercourse, and therefore we must
69 seek to understand how they alter the flow field and associated habitats before this
70 technology is widely adopted. Vertical Axis Turbines (henceforth referred to as VATs)
71 are a typology of hydrokinetic turbines^{20,21} that can generate energy from relatively
72 low flow velocities of 1.5 m/s or lower²². VATs have little effect on the flow when
73 stationary, making them suitable for a wide range of rivers while their horizontal axis
74 counterparts operate at higher rotational speeds and require velocities above 2.0 m/s.
75 The effects of full-scale operating turbines on the flow have been studied, e.g. with a
76 turbine deployed in Alaska which created an induction zone upstream where the
77 upstream velocity decreased while turbulence increased compared to the surrounding
78 flow²³. Downstream of this turbine, the near wake had a fast recovery, quickly turning
79 into a low energy far wake²³.

80 Numerical and experimental studies of VATs have characterised the wake behind a
81 varied range of turbine configurations; a single turbine featured a small stagnation
82 point upstream of the turbine²⁴⁻²⁶ with a downstream wake that expanded laterally
83 bounded by regions of high vorticity, which started to converge at 2.5 turbine diameters
84 (2.5D) downstream with vortices reaching a maximum size of 0.85D²⁴. A VAT wake

85 can be categorised into three main regions: the near wake extending 2D from the
86 turbine featuring low momentum and bounded by high energy vortices, a transition
87 region between 2D-5D downstream of the turbine where there is momentum recovery
88 but still maintains a high level of turbulence and where the wake expands vertically,
89 and the far wake beyond 5D where the rotor-averaged velocity is recovered to 90-95%
90 with some minor fluctuations²¹. Using twin VATs (TVAT) can generate a synergistic
91 effect that potentially generates more energy compared to a single turbine. The
92 interactions between the wakes of the two turbines depends on their relative rotational
93 direction. When rotating in the same direction (co-rotating), there is a reduced velocity
94 in the wake compared to a single turbine and there is the largest lateral expansion of
95 the wake, whereas counter-rotating turbines will have the fastest wake velocities and
96 momentum recovery by 5D if counter-rotating forwards or a wake with a large vertical
97 extension if counter-rotating backwards²⁷.

98 The limited knowledge of fish behaviour around hydrokinetic turbines is based on
99 laboratory flume, river, and tidal turbine studies. In flume trials and rivers, salmon and
100 rainbow trout avoided the turbine when operational, but passage remained unaffected
101 ²⁰²⁹⁻³³. In tidal channels, a 35% decrease in turbine interactions was observed when
102 the turbine was operational³⁴. Other field studies, however, reported attraction to the
103 turbines and increased presence of fish in the wake^{34,35} and a 378% increase in
104 shoaling behaviour³⁵. Such aggregations can create predation hotspots³⁶. Mostly,
105 fish prefer to pass to the side^{31,37,38} or above the turbine when spatially constrained
106 ³⁹. In a narrow flume³¹ or in a tidal channel⁴⁰, turbine presence did produce a
107 movement barrier for rainbow trout. Survival rates for turbine exposure are generally
108 reported as being above 95%^{29-31,33,37,41} but blade strike risks can vary widely in
109 laboratory and numerical studies from 0-1.3%^{38,42} to 6-68.9%^{41,43}. Injury rates from
110 hydrokinetic turbines also vary, with maximum values reaching 20% with bruising and
111 descaling being the most common form of injury³⁰. While the hydrokinetic turbine
112 sound does not appear to impact fish responses, visual cues and turbine visibility do
113 affect behaviour^{34,37,42}.

114 Few studies have analysed the effects of fish shoaling near a hydrokinetic turbine^{34,35},
115 even though most fish species are shoaling. Hence, this effect should be considered
116 when evaluating fish behavioural responses to the presence of hydrokinetic turbines.
117 The primary drivers of fish shoaling are well understood to be predation avoidance⁴⁴⁻
118 ⁴⁸, foraging⁴⁷, social interactions⁴⁵, and hydrodynamic benefits^{49,50}. However, the
119 interplay between these factors is debatable^{45,46,49} and this balance will shift according
120 to context. With regard to hydrokinetic turbines and moving flow, shoaling might bring
121 a primarily hydrodynamic benefit^{49,50}. Fish can reduce their energy expenditure by up
122 to 53% in shoaling Giant danio (*Devario aequipinnatus*)⁵¹. Experimental studies⁵²⁻⁵⁵,
123 a fish and a flapping foil^{56,57}, and numerical studies^{58,59} have also found energetic
124 benefits of shoaling, but the driving mechanism of the energy reduction of shoaling is
125 unclear. The leading fish in a shoal can also benefit from shoaling due to the reduced
126 pressure difference generated by the fish behind⁵⁸. A more common explanation for
127 the hydrodynamic benefits, however, is that following fish can exploit the lower drag
128 force and the reverse Karman street vortices in the wake of the leading fish. They
129 achieve this by swimming directly behind the fish in front^{56,60} or in a staggered or

130 diamond formation^{49,59}. Fish in a shoal could occupy any position and gain energetic
131 benefits. As positioning is dynamic, this has led to arguments against fish shoals
132 'drafting' in the vortex street^{53,61}. There are studies, however, that have not found any
133 metabolic difference caused by shoaling in rainbow trout⁵², demonstrating that the
134 principles discussed may not be universally transferable among species and flow
135 conditions. Other factors affecting shoaling are the familiarity and geographic origin of
136 the fish with its shoal mates^{62,63}, infection status^{48,64,65}, and presence of predators⁴⁸.

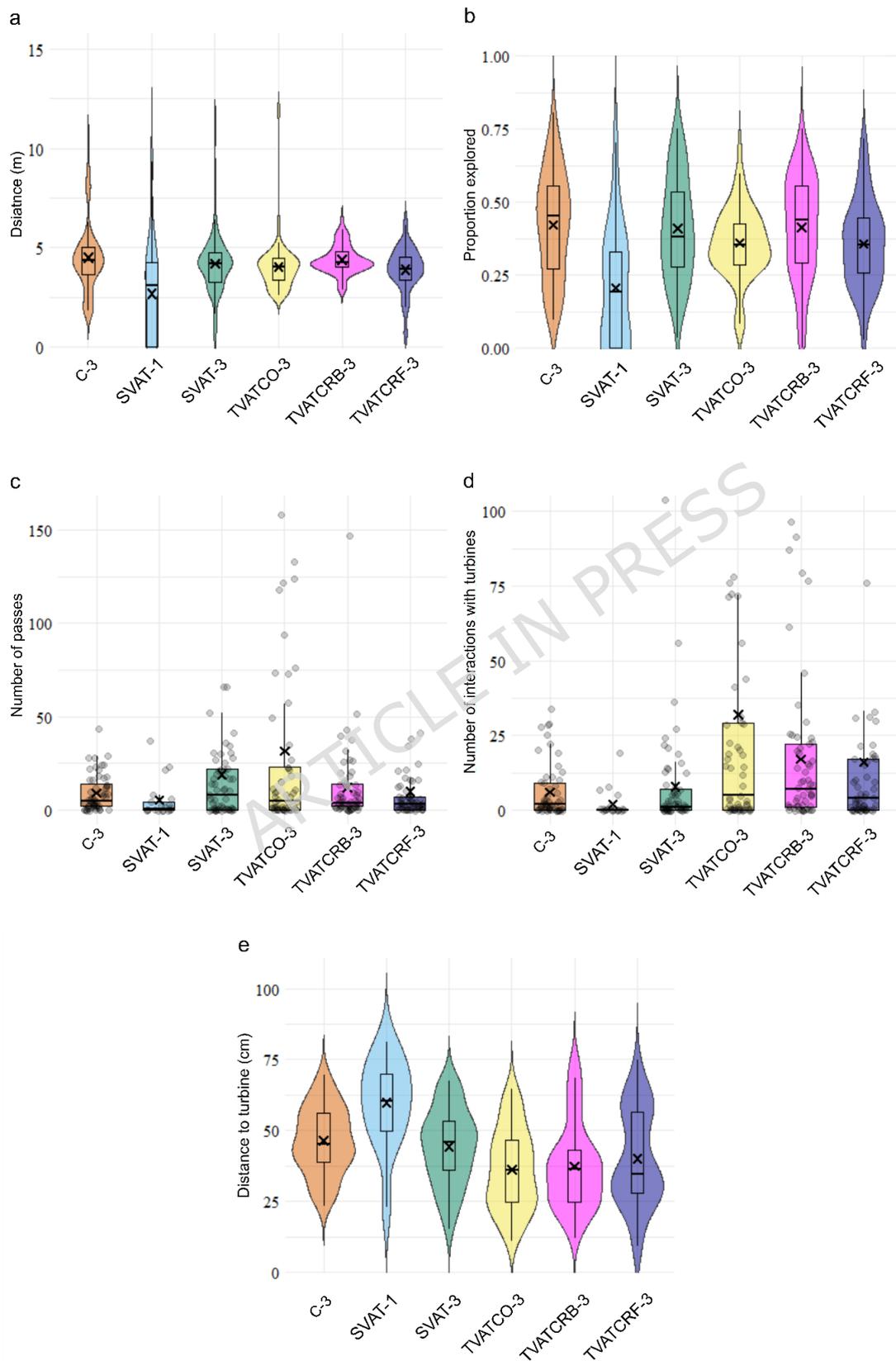
137 There is still a knowledge gap concerning hydrokinetic turbine configuration and
138 shoaling in the context of hydrokinetic turbines that needs to be filled before these
139 devices are implemented in sensitive ecosystems. This study examines the behaviour
140 of juvenile rainbow trout (*Oncorhynchus mykiss*) in the presence of five different
141 configurations of single or twin laboratory scale VATs, and compares scenarios for a
142 single fish and for a shoal of three fish. This species' native range covers North
143 American countries and their introduced range includes almost all other continents
144 where this technology may be useful, moreover rainbow trout are an established
145 model species for fish behaviour and shoaling^{44,48,52,62} and are closely related to
146 migratory salmonids like steelhead (*Oncorhynchus mykiss*). The aim is to provide a
147 new understanding of how twin-turbines and their combined hydrodynamics affect fish
148 behaviour alone or while shoaling, and whether shoaling affects fish ability to navigate
149 complex flow fields generated by laboratory scale turbines.

150 **Results**

151 *Distance, exploration and passage*

152 Fish swam the largest distance in the control conditions (C-3, non-rotating turbine with
153 fish shoal) with a mean of 4.5 m (C-3, Figure 1a), and significantly less in treatments
154 SVAT-1 (single turbine and single fish), TVATCO-3 (co-rotating twin turbines with fish
155 shoal), and TVATCRF-3 (counter-rotating twin turbines with fish shoal) within the
156 working section of the flume in comparison with C-3 (GLMM, $p < 0.02$). This is reflected
157 in the proportion of the total working area explored by each fish (Figure 1b), where the
158 fish in C-3 on average explored significantly more of the working area (average of
159 40%) than the fish in SVAT-1 (20% on average), and TVATCO-3 and TVATCRF-3 (26%
160 on average), which was significantly lower than all other treatments too (GLMM,
161 $p < 0.017$). The decreased distance and exploration did not, however, affect passage
162 success past the turbines (Figure 1c), all treatments statistically having the same
163 passage as control C-3, except for TVATCO-3 that had significantly more (GLMM,
164 $p = 0.001$). Figure 1d shows fish entering the turbine area ($52 < x < 68$ cm, $52 < y < 66$
165 cm in Figure 5) compared to C-3, with SVAT-1 having significantly fewer interactions
166 with the turbine (GLMM, $p = 0.002$) whereas SVAT-3 had more than C-3 (GLMM, $p = 5e-6$),
167 TVATCRB-3 and TVATCRF-3 had significantly more than C-3, SVAT-1 and SVAT-
168 3 (GLMM, $p = 2e-16$). Notably, TVATCO-3 had the most fish entering the turbine area
169 out of all treatments (GLMM, $p = 2e-26$). This finding correlates with the amount of time
170 spent very close to the turbines (blue rectangle in Figure 5), with fish in TVATCO-3
171 and TVATCRF-3 spending significantly more time there (GLMM, $p < 0.03$). Figure 1e
172 shows the same trend in the results from the relationship between treatment and
173 distance to the turbines, where fish in SVAT-1 stayed significantly further away from

174 the turbine than all other treatments (Figure 2; GLMM, $p < 0.005$), and the three
 175 treatments with twin turbines staying significantly closer than control (GLMM,
 176 $p < 0.008$).



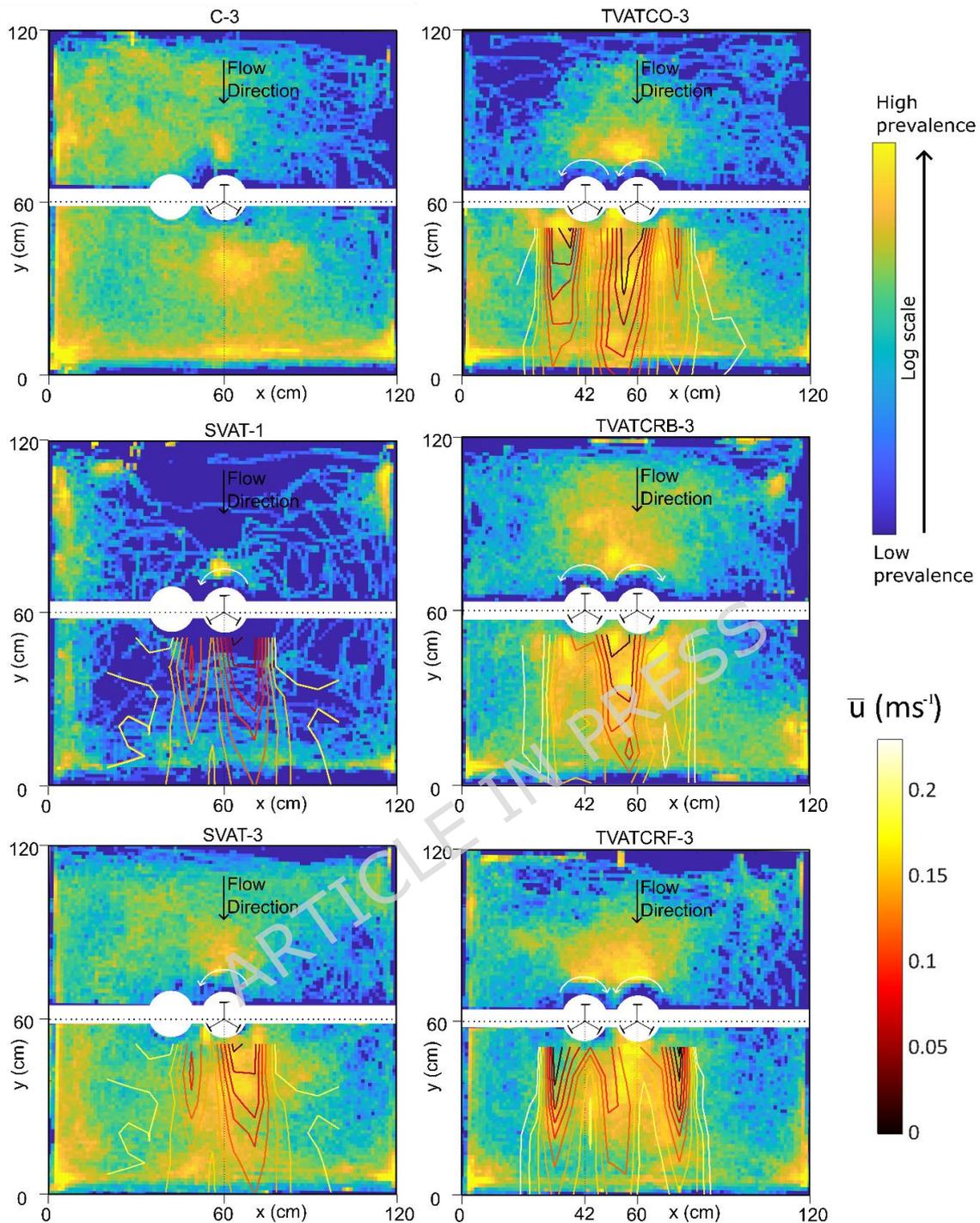
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178 Figure 1. Violin and Boxplots describing, for each treatment: a) Distance swam by fish;
179 b) The proportion of the working area explored by fish; c) The number of times each
180 fish passes from downstream to upstream or from upstream to downstream of the
181 turbines; d) Number of times fish entered the turbine area; e) The average distance
182 between fish and the nearest turbine throughout the trial. In all cases, the box and
183 violin plots show median, interquartile range, and 95th percentile and the cross marks
184 the mean.

185 *Time in the working area*

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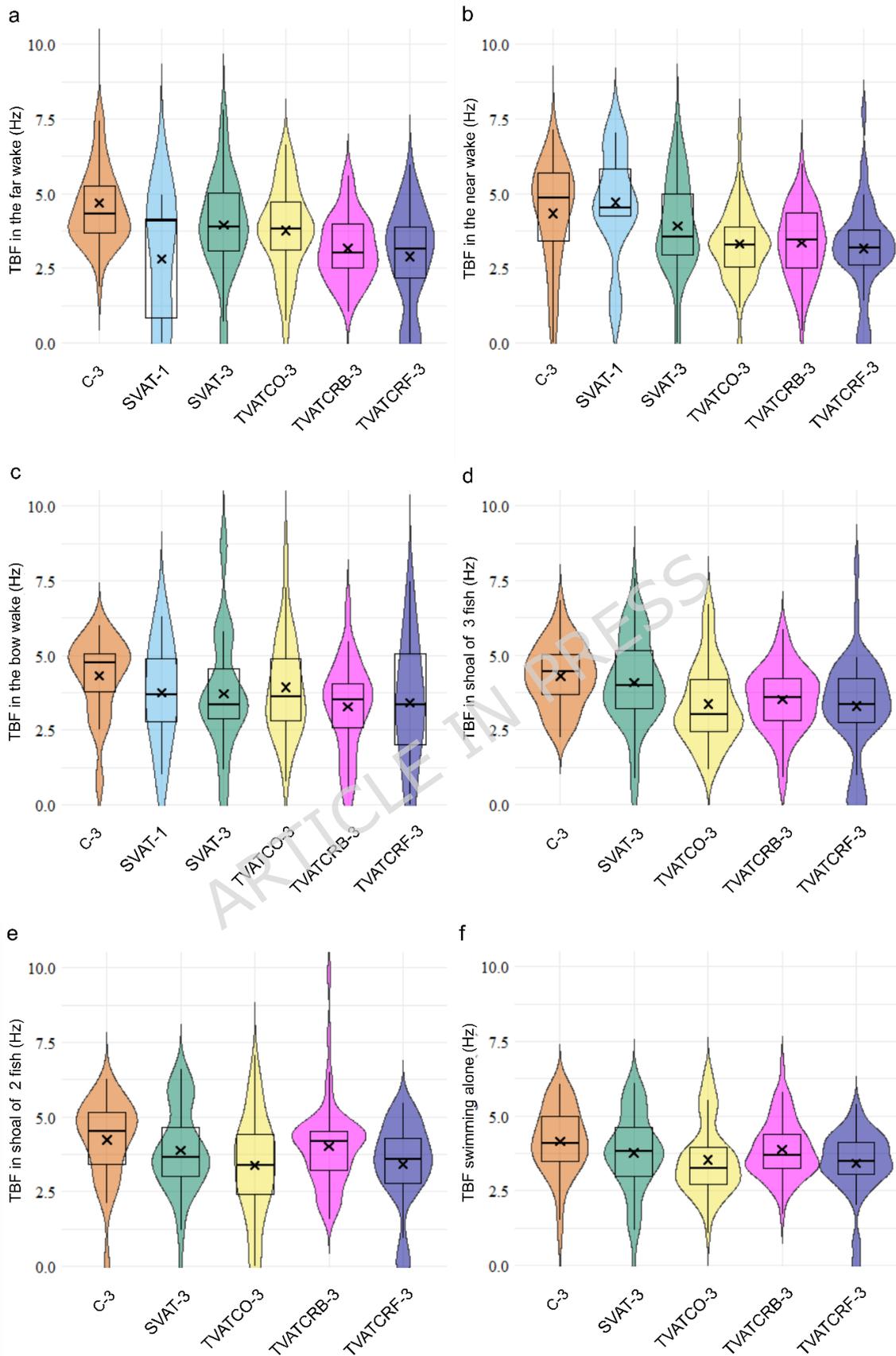
188 Figure 2. Heatmaps showing the prevalence in spatial occupation of the experimental
 189 area by the fish and the turbine wake overlaid to show the streamwise velocity borders
 190 downstream of the turbines. Colour scales for both the density plot and the streamwise
 191 velocity are given to the right of the plot. For each treatment, data from all fish is
 192 combined, thus treatments with single fish have less data. The white arrows indicate
 193 turbine rotational direction.

194 In all treatments, fish spent approximately 25% of time upstream and 75% downstream
 195 of the turbines (GLMM, $p > 0.12$). Part of the downstream time was spent resting on the
 196 flow straightener, where fish in SVAT-1 spent significantly more time resting (GLMM,

197 p=0.007) and fish in TVATCRB-3 spent significantly less time resting (GLMM, p=0.003)
198 compared to the control (C-3). Time spent in the near wake was highest in the three
199 treatments with twin turbines (GLMM, p<0.005) with a mean value of 123 s which is
200 20.5% of the experiment's duration, while the rest of the shoaling treatments were
201 statistically the same as the control (Figure 2). Time in the far wake, however, did not
202 vary across treatments, except for TVATCRF-3 where it was 45.8% lower than control
203 (GLMM, p=0.044). Time in the bow wake (Figure 2) was the statistically the same for
204 all treatments except for TVATCO-3 in which the fish spent more time there, 20 s on
205 average (GLMM, p=0.0015). Areas of low velocity in the wake of the turbines shown
206 in Figure 2 is generally associated with high prevalence, this can be seen to extend to
207 the flume's lateral walls, indicating that the fish were seeking low velocity areas.

208 *Tailbeat frequency*

209 Overall tailbeat frequency (TBF) was 14.6% higher in C-3 than SVAT-1, SVAT-3,
210 TVATCO-3 and TVATCRF-3 (GLMM, p<0.02) throughout all swimming areas. In the
211 far wake (Figure 3a), a lower TBF than control with a mean of 4.9 Hz is present for
212 treatments with rotating turbines (GLMM, p<0.012). In the near wake, TBF was
213 significantly lower than control only in treatments with twin turbines as these generated
214 the largest low-velocity region (Figure 3b; GLMM, p<0.002). In the bow wake, there
215 was no difference among any treatment in TBF with mean values ranging between 3.0
216 Hz and 4.5 Hz (Figure 3c; GLMM, p>0.08). When in a shoal of three fish (Figure 3d),
217 the combined TBF values for all shoaling fish in all three treatments with twin turbines
218 were lower on average by 21% (GLMM, p<0.005) than the TBF of 4.1 Hz found in the
219 control (C-3) and single turbine cases (SVAT-1 and SVAT-3). When shoaling as a pair
220 (Figure 3e), fish swimming together had a lower TBF only in TVATCO-3 and TVATCRF-
221 3, all other treatments being the same as control. When swimming alone, however, all
222 treatments except TVATCRB-3 had a lower TBF than the control (GLMM, p<0.02), as
223 shown in Figure 3f.



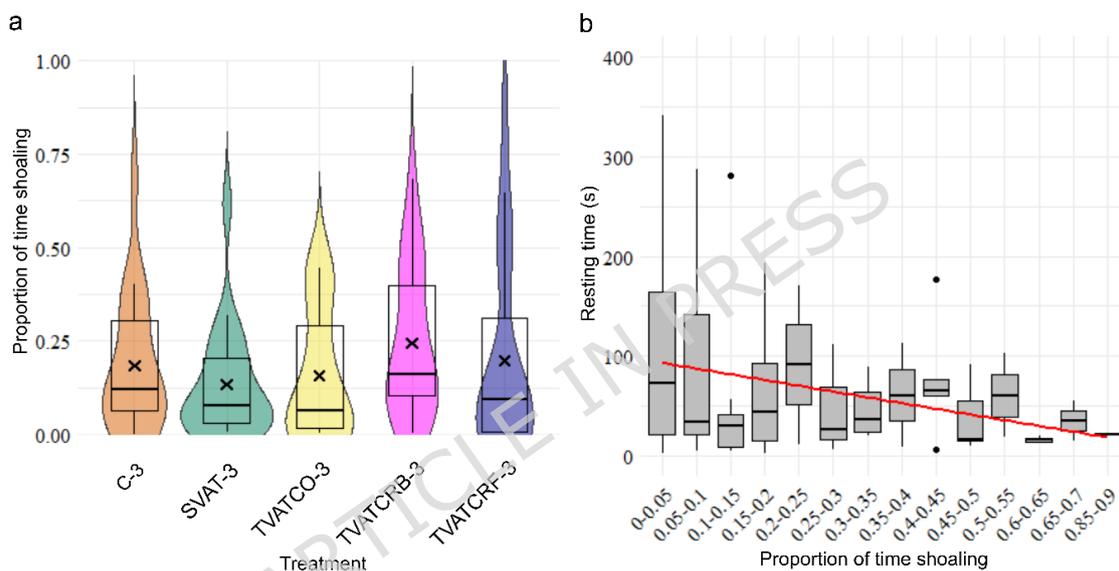
224

225 Figure 3. Results of average tailbeat frequency (TBF) for each fish for several
 226 swimming areas and shoal configurations for each treatment. a) Far wake (yellow box
 227 in Figure 5). b) Near wake (green box in Figure 5). c) Bow wake (red box in Figure 5).

228 d) When swimming in a shoal of three fish. e) For the fish swimming in a shoal of 2
 229 fish (disregarding the fish swimming alone). f) When swimming alone. Boxplots show
 230 median, interquartile range, and 95th percentile and the cross marks the mean.

231 Shoaling behaviour

232 While shoaling, the proportion of time that an individual led was split equally between
 233 the three fish the longer they shoaled, with an individual only appearing dominant if
 234 the shoaling duration was short (GLMM, $p=0.005$) and there was no difference in
 235 dominance of an individual between treatments (Figure 4a; GLMM, $p>0.11$). Shoaling,
 236 however, was associated with a reduced TBF in the bow wake (GLMM, $p=0.007$) but
 237 not in the near and far wake (GLMM, $p>0.62$). Shoaling fish also spent less time
 238 resting, (Figure 4b; GLMM, $p=0.004$), and were more likely to interact with the turbine
 239 (GLMM, $p=2.4e-14$).



240

241 Figure 4. a) The proportion of time spent shoaling (combined data for a shoal of three
 242 and a shoal of two) per treatment with treatment SVAT-1 excluded. b) Negative
 243 correlation between the time spent resting on the downstream flow straightener and
 244 the proportion of time spent shoaling.

245 Individual and shoal behaviour comparison

246 Individual fish swam significantly shorter distances than shoaling fish for the same
 247 single turbine configuration (Figure 1a; GLMM, $p=0.02$) and explored less of the
 248 working area (GLMM, $p=5.6e-6$) but this did not translate to a reduced passage rate.
 249 Resting time (shown in Figure 4b) was increased by an average of 181 s in SVAT-1
 250 compared to SVAT-3 (GLMM, $p=0.003$), with very few turbine interactions (GLMM,
 251 $p=0.002$) and less time spent near the turbine (GLMM, $p<0.04$). Despite the presence
 252 of shoalmates in SVAT-3, fish in SVAT-1 had the same TBF values in all areas (GLMM,
 253 $p>0.12$).

254 Discussion

255 For all tested configurations, the hydrokinetic turbines did not limit fish passage in a
256 flume where the turbines blocked 25% of the cross-section. This is consistent with
257 findings from laboratory and field studies evaluating hydrokinetic turbine passage^{20,30–}
258 ³³. Narrow channels, however, can constrict movement^{31,40} but in the relatively wide
259 channel where neither turbine nor their wakes span across the entire cross-section,
260 fish were able to use the wide undisturbed corridors without turbine influence to pass
261 up and downstream. The passage data is further supported by the lack of differences
262 in time spent upstream and downstream of the turbines across treatments. This is
263 despite the decrease in distance covered and proportion of the area explored caused
264 by presence of rotating rather than stationary turbines, but this may be explained by
265 fish choosing to spend more time holding station in the turbine wake. The treatments
266 for which distance covered was lower than the control (single fish, and shoals with co-
267 rotating turbines and forward counter-rotating turbines) were the same in which either
268 the amount of time spent resting was higher (SVAT-1) or the amount of time entraining
269 in the near- and bow-wake was higher (TVATCO-3 and TVATCRF-3). TVATCO-3 was
270 also the only treatment to have significantly higher passage rates than C-3 but still had
271 lower distance and exploration, this may be explained by the increased time spent in
272 the bow wake in which fish may have crossed the passage line briefly. This is apart
273 from TVATCRB-3 in which fish spent time in the near wake on a similar level as
274 TVATCRF-3 but did not swim significantly shorter distances compared to C-3. The
275 proportion of the area explored was highest with a stationary turbine downstream of
276 the turbine and may be explained similarly by the fish finding hydrodynamic benefit
277 generated by the turbine wake, which is absent when the turbine is stationary²².
278 Finding favourable hydrodynamic conditions may then lead to a reduced need to
279 explore areas with higher flow velocity. This can be supported by lower TBF for
280 treatments with paired turbines that produce a larger wake region and from previous
281 studies where rainbow trout entrained behind moving foils and cylinders^{56,57,66}.

282 The current findings also agree with existing literature^{29–31,33,37,41} regarding 100%
283 survival and no visible injuries after the trials. Although the turbine used in our study
284 was a scaled version of a VAT and is therefore not representative of a full-scale turbine
285 in terms of injury and mortality, the findings remain encouraging and support findings
286 from a field study with similar rpm ranges⁴⁰.

287 The most widely observed response to turbines is avoidance^{29,31,32}, and this was also
288 seen in our single fish treatment (SVAT-1), where the distance to the turbine was
289 significantly higher and turbine interactions significantly lower than control (three fish
290 with a stationary turbine). When shoaling, however, the trout had increased turbine
291 interactions, spent more time closer to the turbines, and made wider use of the near
292 wake and bow wake, particularly for co-rotating turbines. Despite a higher count of
293 interactions with turbines for all shoaling treatments, only fish in TVATCO-3 and
294 TVATCRF-3 spent more time in the area very close to the turbines, suggesting either
295 that the flow within and between the turbines was more turbulent in other treatments,
296 or that the turbine was still perceived as dangerous by the fish and that it may not have
297 been visible to them until very close³⁷. Another explanation is that more time spent in
298 the bow wake led to fish crossing the boundary with the turbine region leading to a
299 higher apparent amount of time spent in the turbine area. The single fish in SVAT-1

300 spent more time resting than all shoaling treatments, a behaviour also noted in
301 previous studies^{31,37} but which is not entirely explained by the hydrodynamics as the
302 shoals did not seem to create a hydrodynamic advantage in terms of TBF. This
303 suggests that increased resting time may be socially driven by the absence of shoal
304 mates as revealed by the analysis of the resting time compared to the proportion of
305 time spent shoaling.

306 Fish did not make use of the far wake of the rotating turbines. The velocity in the wake
307 of a single VAT is 95% recovered by 5D (five turbine diameters) downstream of the
308 turbine²¹ and with the TVATCRF turbine configuration, momentum recovery occurred
309 by 5D²⁷. This indicates that the potential benefits of a turbine wake, like lower
310 velocities, have diminished by the downstream end of the working area, especially for
311 TVATCRF-3. In the upstream end of the far wake region, however, there were reduced
312 TBF values for treatments with twin turbines, showing that velocity reductions could
313 still be exploited in what Müller et al. (2021) termed the transition zone.

314 Time spent in the bow wake was very consistent across treatments except for
315 TVATCO-3 in which significantly more time was spent there. With the TVATCO-3
316 setup, there is a velocity reduction in the induction region upstream of the two turbines,
317 potentially providing a more stable swimming environment for the fish than the
318 TVATCRF, TVATCRB, and SVAT layouts²⁶. The SVAT setup has reduced velocities
319 upstream of the turbine but to a lesser magnitude and spatial extent than twin turbines,
320 TVATCRF has a stronger velocity reduction but the velocity gradient is larger and the
321 reduction more localised whereas TVATCRB has a lower velocity reduction and flow
322 accelerating between the two turbines driven by the turbine rotation²⁶, potentially
323 explaining why bow waking was more common with the TVATCO setup. The TBF in
324 the bow wake was only reduced while the trout were shoaling, potentially indicating
325 that it is still an unstable area to swim in for single fish whose TBF was not overall
326 lowered in the bow wake. A probability density function analysis of the midline fish
327 body data did not, however, reveal any obvious destabilisations of the fish swimming
328 in the bow wake. Some shoaling studies suggest that one mechanism of information
329 transfer and hydrodynamic benefit of shoaling is the reduced pressure difference and
330 lower velocity directly in front of fish behind the leader⁵⁸. These hydrodynamic
331 conditions are partially replicated by the turbine's upstream induction region, so there
332 is a possibility that fish were in effect 'shoaling' with the turbines as these had
333 diameters in the same order of magnitude as the fish (the ratio of mean fish size to
334 turbine diameter is 0.56) and turbine rotors were spaced relatively close to each other.
335 Similarly, time spent in the near wake was higher for all treatments with paired turbines
336 as they produced a larger velocity reduction in the near wake compared to a single
337 turbine²⁷. Tailbeat frequency data is lower with more time spent in the near wake with
338 TBF in the near wake being significantly lower in treatments with paired turbines. This
339 is most likely due to the reduced velocities but could also be due to the vortices shed
340 by the turbine blades which match the TBF of the fish (59 rpm with three blades leads
341 to 2.95 Hz and the TBF was around 3.4 Hz) and fish have been shown to use vortex
342 streets to reduce energy consumption^{57,67}. The vortices behind the turbines, however,
343 are likely unsuitably placed for fish to draw a hydrodynamic gain from them so velocity
344 reduction is the most likely explanation for the lower TBF values.

345 Overall, TBF was not affected by shoaling alone. Most reductions in TBF were
346 associated with the turbine wake region indicating that shoaling in this study did not
347 bring direct energetic advantages to the fish. This is contrary to previous findings
348 reporting shoaling reducing swimming effort ^{51,53,54,59} but in line with a previous study
349 where no metabolic benefit was found in rainbow trout shoaling ⁵². An analysis of TBF
350 by treatment filtered by shoal size also did not find differences. It is possible that a
351 shoal of three fish was not of sufficient size to bring energetic benefits but there is
352 evidence to show that it did affect behaviour by increasing turbine interactions and
353 decreasing resting time. Hence, shoaling does not have an exclusively hydrodynamic
354 role but that there are social benefits to being close to other fish.

355 The longer a fish shoaled, the more equally distributed the role of leader was among
356 the shoalmates. This offers insight into the shoaling dynamics of the trout, in very short
357 durations of shoaling there was insufficient time for fish to take their turn as leader but
358 for longer durations, the fish were able to share this role equally, independent of
359 treatment or location within the working area. These results also highlight the
360 difference between the behaviour of a shoal and an individual fish. Shoaling is often
361 overlooked in flume studies assessing fish movement and behaviour but this study
362 has shown marked differences in behaviour when shoaling thus studies with a single
363 fish only reveal part of the picture. Shoaling is common in many species of fresh and
364 saltwater fish and should therefore be considered more widely in future studies of fish
365 behaviour at turbines.

366 The ecological considerations arising from this study are overall positive. Passage
367 remains unaffected with one or two laboratory scale turbines in a relatively wide
368 channel and the probability of strike are very low. There is also evidence to suggest
369 that turbine wakes may reduce energy expenditure as fish were more likely to hold
370 station in these areas but this may potentially lead to increased predation hotspots ³⁶.
371 With passage and survival rates far exceeding those of most hydropower plants,
372 hydrokinetic turbines could score better in environmental evaluations, ⁶ which can be
373 used as management tools by regulators in appraising different schemes. It must be
374 noted, however, that this laboratory study cannot replicate the real operation of a full
375 scale turbine which would produce a comparatively more energetic wake and operate
376 in a more turbulent environment. Another limitation of the study is that the relative
377 swimming performance of the fish used in this study is too high.

378 **Conclusion**

379 An experimental study of single and twin hydrokinetic turbines show that these devices
380 neither limit upstream or downstream passage of rainbow trout. Paired turbines led to
381 increased engagement by shoals of trout that used the bow- and near-wake low
382 velocity regions to potentially reduce energy consumption over a single turbine
383 because of the larger extension and lower velocities in the wake regions. Areas of low
384 velocity were generally preferred by the fish. Tailbeat frequency was reduced by low
385 velocity areas in the turbine's downstream wakes while remaining unaffected by
386 shoaling alone. Single fish swimming alone displayed increased resting times and
387 fewer approaches to the turbine whilst shoals were bolder and more likely to exploit
388 the potential hydrodynamic benefits of the turbine wakes. Our findings have the

389 potential to inform environmental impact assessments involving hydrokinetic turbines
390 being a suitable technological solution to generate energy from rivers and tidal-
391 streams while reducing disruptions to fish populations in the aquatic environment.

392 **Methods**

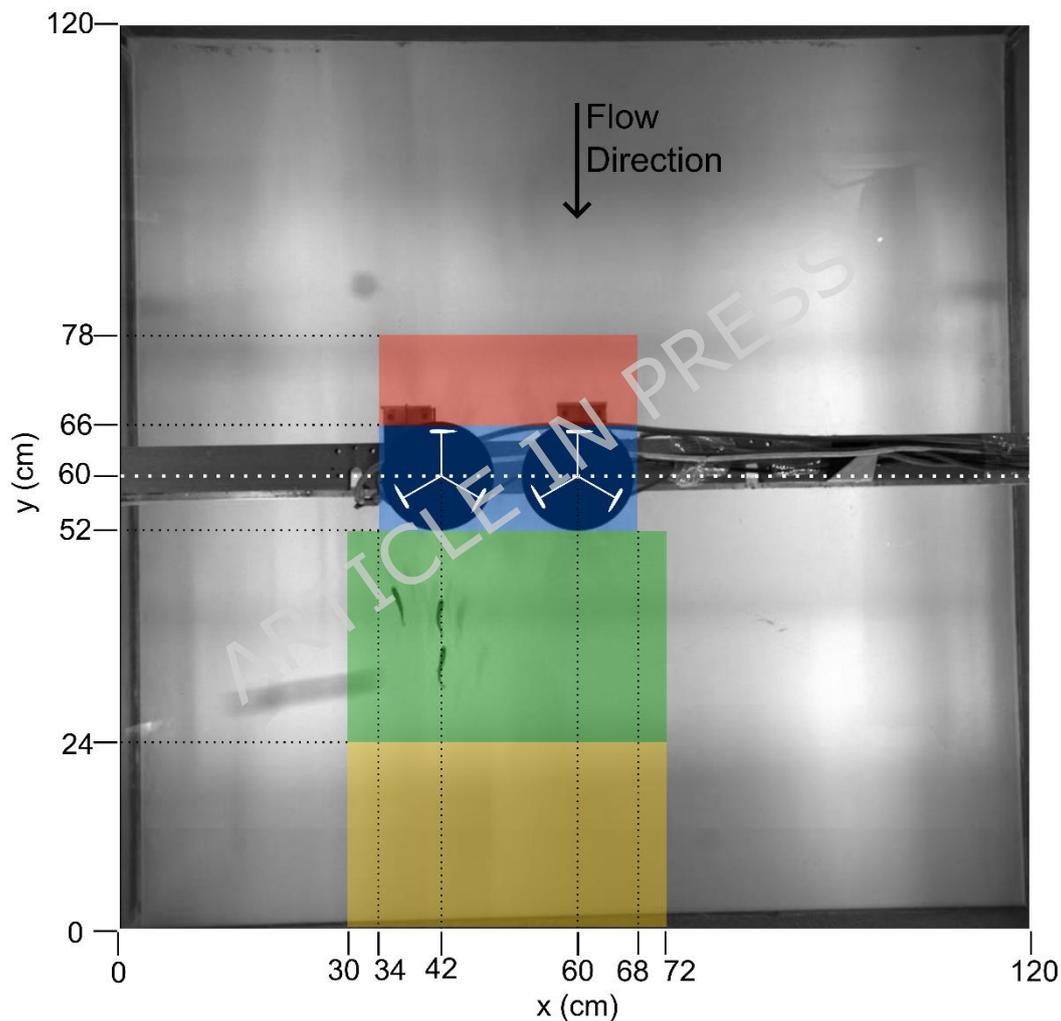
393 *Fish origin and maintenance*

394 Fish trials were performed between 29th March and 7th April 2021 from 8:00 to 17:00
395 for individual fish and between 22nd March and 30th April 2021 from 8:00 to 17:00 for
396 shoaling fish. The fish used in these trials were female triploid Rainbow trout
397 (*Oncorhynchus mykiss*, N = 80) purchased from Bibury Trout Farm, UK. Trout total
398 length was 67.5 ± 10.7 mm. Before the experiment, they were housed in a Recirculating
399 Aquaculture System (RAS) in tanks of 60-80 L at 40 fish per tank in Cardiff School of
400 Biosciences on a 12h:12h light:dark cycle at $15 \pm 1^\circ\text{C}$ in water being constantly filtered
401 by the RAS. They were fed daily with trout pellets in the morning. Shortly before the
402 start of the flume trials, the trout were transported to a holding tank in Cardiff School
403 of Engineering where they were separated into size-matched shoals, isolated in plastic
404 mesh cylinders within a larger holding tank of 500 L. The trout were maintained in
405 dechlorinated water (Tetra AquaSafe Seachem Prime Concentrated Conditioner),
406 aerated with multiple air pumps, cooled to $13 \pm 1^\circ\text{C}$ by a D-D Aquarium Solution DC
407 750 chiller, and filtered by an external canister filter (Aquamanta EXF 600). Water
408 quality was checked weekly with a water quality test kit (Nutrafin). The trout were kept
409 on a 14h:10h light:dark cycle and fed trout pellets every morning. The tank was
410 provided with plastic tubes and other refugia. The shoals were acclimated for two
411 weeks in this setup before any testing occurred to allow fish to familiarise with their
412 shoal. The shoaling trials were carried out in three batches over the course of two
413 months. After the end of the trials, the fish were transferred back to the RAS at Cardiff
414 School of Biosciences. In the case of the single fish treatment, the 20 trout were
415 housed in the 500 L tank with no plastic mesh sub-dividers but otherwise kept in the
416 same way as the shoals. When the single trout had completed the experiment, they
417 were transferred directly back to the School of Biosciences.

418 *Experimental setup*

419 A recirculating open channel flume (10 m long, 1.2 m wide, and 0.3 m high with a
420 1/1000 bed slope) at Cardiff School of Engineering was used in this study. The working
421 section of the flume was bounded up and downstream by honeycomb flow
422 straighteners and on the flume walls by glass. The flume bed in the working section
423 was a white PVC sheet and the water surface was covered by a transparent acrylic
424 sheet. The upstream end of the working section was located 4.4 m from the upstream
425 end of the flume and measured 1.2 m long and 1.2 m wide with a flow depth of 0.23
426 m. Laboratory scale Vertical Axis Turbines (VATs) were constructed with a diameter
427 and height of 0.12 m, with three blades of 0.03 m chord length and a NACA0015
428 profile. The turbine diameter was scaled geometrically to fish length. Full details of
429 scaling are given in Supplementary materials 1. With a single VAT, it was positioned
430 at the centre of the working area, at (x = 60 cm, y = 60 cm) in Figure 5, whereas when
431 a second turbine was present it was inserted at (x = 42 cm, y = 60 cm) in Figure 5, a
432 spacing of 1.5 turbine diameters. Each blade was mounted to a central shaft by two 3

433 mm diameter struts and was laser sintered from white PA2200. The central shaft was
 434 mounted in a bearing embedded in the flume bed and held the bottom of the blades
 435 20 mm from the bed. The upper end of the shaft was connected to an encoder and a
 436 DC motor (Kübler, 5-30VDC, 100 mA and Nider DMN37K50G18A, DC 12 V
 437 respectively) which was held by a beam resting on the sides of the flume. The turbine
 438 operated at a fixed rotational speed of 59 rpm, combined with a bulk velocity of 0.19
 439 ms^{-1} ($Q = 53 \text{ Ls}^{-1}$), this gave the optimum tip speed ratio of 1.9^{21,27}. The working area
 440 was illuminated from both sides by a total of four spotlights (Neewer Bi-Colour LED)
 441 and recorded at 55 frames per second (fps) from an overhead camera (Baumer VLXT-
 442 50M.I). The water in the flume was dechlorinated using Prime Dechlorinator and
 443 cooled to $14 \pm 1^\circ\text{C}$ by a D-D Aquarium Solution, DC2200.



444

445 Figure 5. Schematic of the working area with all measurements in cm and the water
 446 flowing from top to bottom with the lateral direction defined as the x axis and the
 447 streamwise direction as the y axis. The two turbines are both depicted as rotating
 448 counter-clockwise (TVATCO-3 treatment, see Table 1). The single turbine tests were
 449 conducted with a turbine positioned on the flume centreline and the turbine centred at
 450 ($y = 42 \text{ cm}$, $x = 60 \text{ cm}$) was removed. The coloured areas represent the areas defined
 451 in Table 2, where yellow = far wake, green = near wake, blue = turbine, and red = bow
 452 wake.

453 *Experimental procedure*

454 For shoaling treatments, $n = 19$ groups of three fish and for the single fish treatment n
 455 $= 16$ individual fish were included in the analysis. Each shoal (or single fish) was
 456 transferred from the holding tank to the flume in a bucket of water and released at the
 457 downstream end of the experimental area. The fish were then allowed to acclimate for
 458 a total of 20 minutes - the first 5 minutes at a reduced flowrate of 24.5 Ls^{-1} and
 459 corresponding turbine rotation of 7 rpm, the following 5 minutes at 37 Ls^{-1} and 30 rpm,
 460 and the final 10 minutes at the nominal flowrate of 53 Ls^{-1} and 59 rpm. At the end of
 461 the acclimation period, the fish were removed from the working area into a bucket
 462 whilst the perspex sheet was placed above the area. The recording was started with
 463 a 10 minute 30 second timer, with the first 30 seconds used to place the trout at the
 464 downstream end of the experimental area and to start the experiment (these initial 30
 465 seconds were discarded from the analysis). After the 10-minute experiment, the trout
 466 were removed from the flume and transferred back to their holding tank. In the case
 467 of single fish, the fish length and weight were measured with a calliper and a scale
 468 and then immediately transferred to a tank. The single fish only took part in one
 469 treatment, namely a single fish with a single turbine (SVAT-1, Table 1), with more
 470 information on the single fish treatment (SVAT-1) featured in a previous study²⁴ where
 471 the results of this treatment were used to investigate the impact of flume width on fish
 472 swimming behaviour. In contrast, the shoals of three fish took part in all treatments
 473 (Table 1), with each shoal only taking part in one treatment per day, completing all five
 474 different treatments over five consecutive days. The treatment order was randomised
 475 for the shoals to remove any temporal, learned behaviour, or tiredness bias.

476 Table 1. Details of the treatments investigated in the study, where in the treatment
 477 names C = Control, SVAT = Single VAT, TVAT = Twin VAT, CO = Co-Rotating, CRB =
 478 Counter-Rotating Backwards, CRF = Counter-Rotating Forwards, and the number
 479 denotes the number of fish. In the rotation direction column, where two turbines are
 480 present, their relative rotational directions are described from left to right looking
 481 upstream (Figure 5). For shoaling treatments $n = 19$ shoals and for the single fish
 482 treatment $n = 16$.

Treatment	No of Fish	No of Turbines	Rotation direction	Turbine Rotational speed (rpm)	Flowrate (Ls^{-1})	Bulk Velocity (ms^{-1})	Flow Depth (m)
C-3	3	1	Stationary	0	53	0.19	0.23
SVAT-1	1	1	Counter-Clockwise	59	53	0.19	0.23
SVAT-3	3	1	Counter-Clockwise	59	53	0.19	0.23
TVATCO-3	3	2	Counter-Clockwise	59	53	0.19	0.23
TVATCRB-3	3	2	Clockwise and Counter-Clockwise Backwards	59	53	0.19	0.23

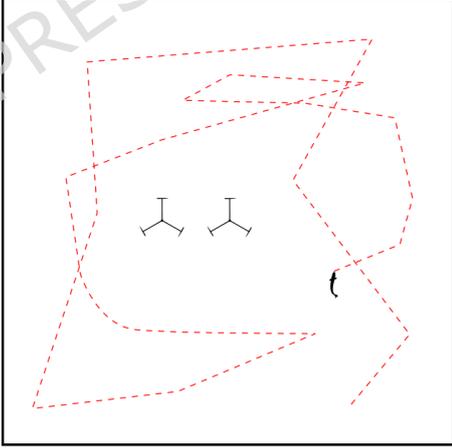
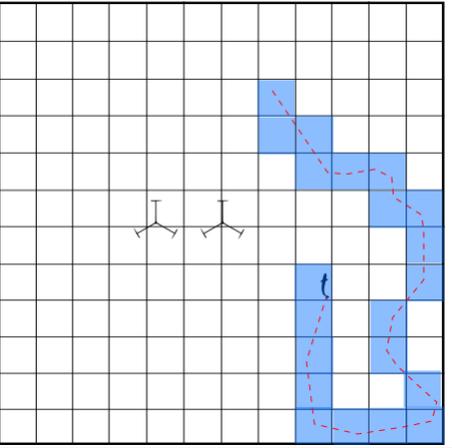
TVATCRF-3	3	2	Counter-Clockwise Forwards and Clockwise	59	53	0.19	0.23
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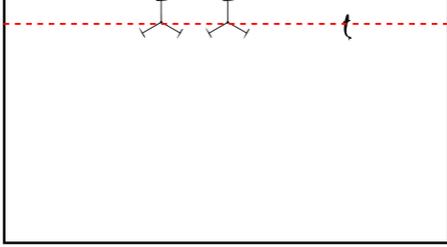
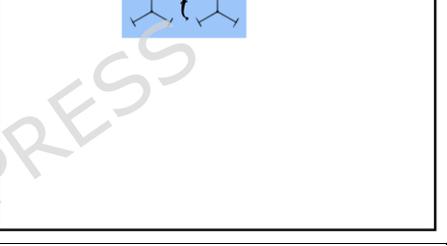
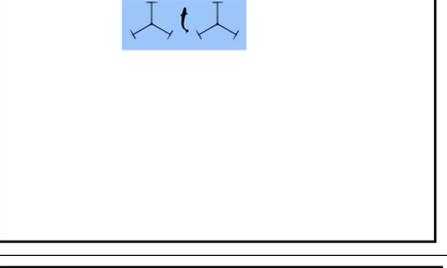
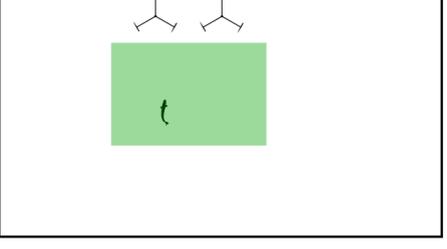
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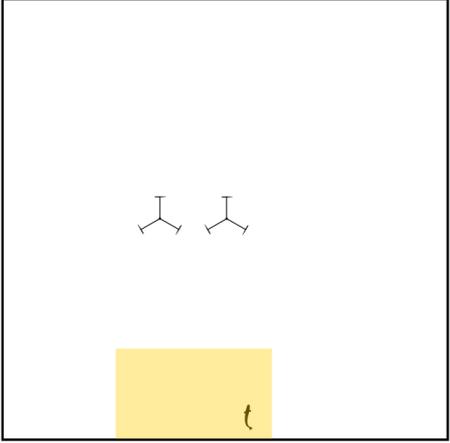
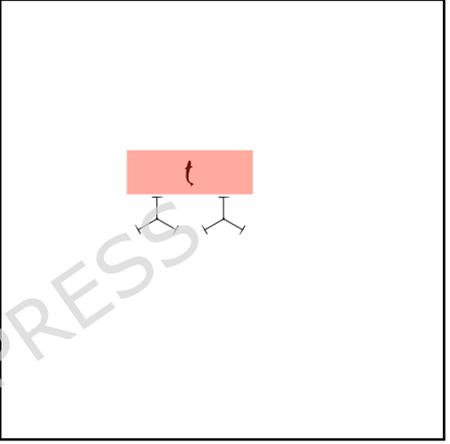
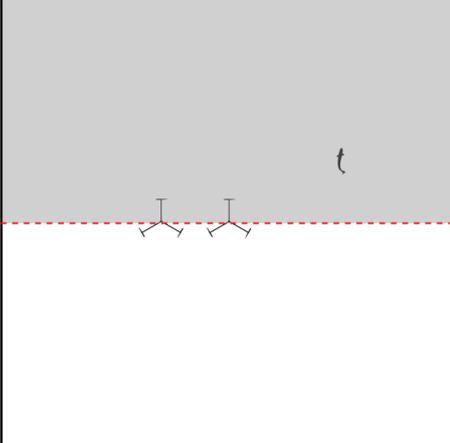
484 *Data Analysis*

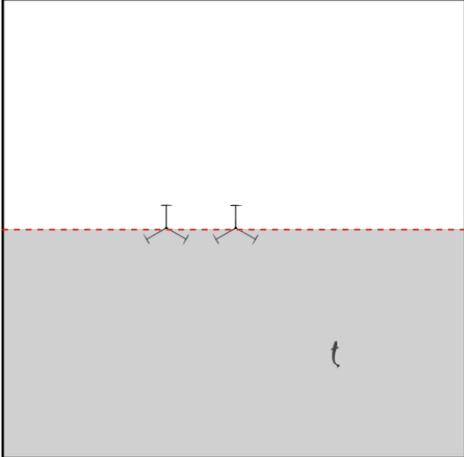
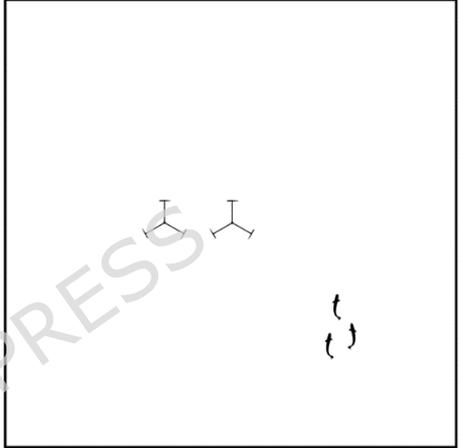
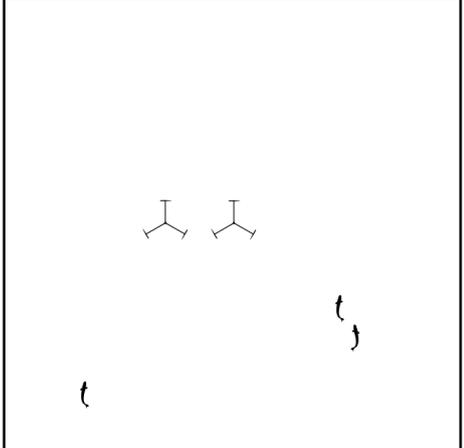
485 The video recordings of the fish were processed removing the initial 30 s using Matlab
 486 R2024a ⁶⁸, and then they were then analysed in TRex ⁶⁹ with which the positions and
 487 midline points of all fish for each frame were inspected, corrected where necessary,
 488 and exported as Matlab files. The data for each fish were then analysed in Matlab to
 489 obtain the parameters shown in Table 2, some of which are based on a grid defined
 490 with the origin at the left corner of the downstream end of the working area, also shown
 491 in Figure 5.

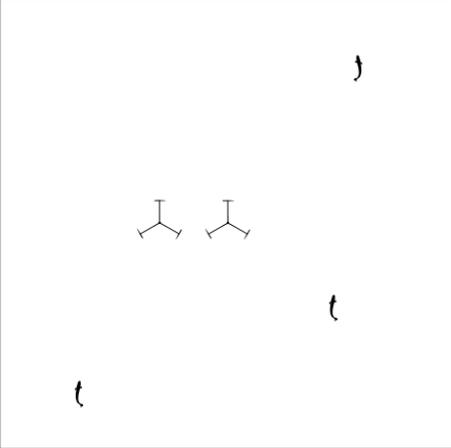
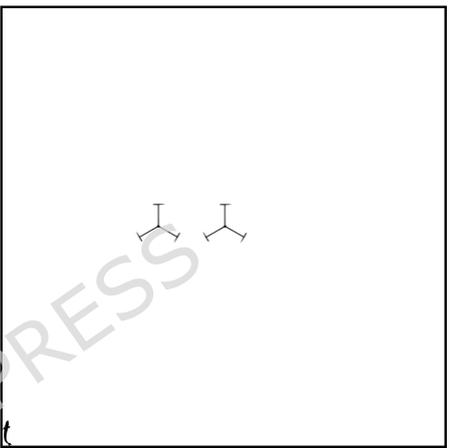
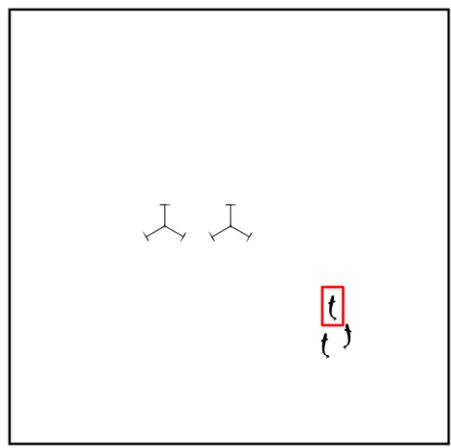
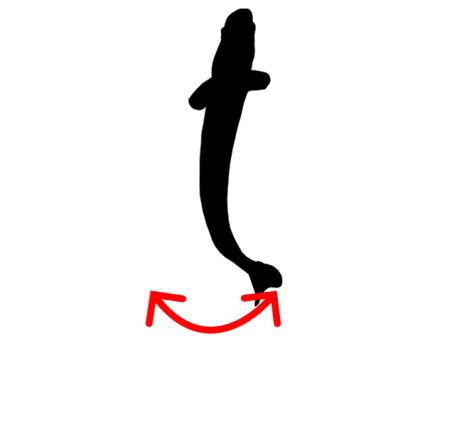
492 Table 2. The variables calculated from the tracking and posture data of rainbow trout
 493 in the current study. The x and y values (given in cm) in the description are in reference
 494 to the coordinates shown in Figure 5. Areas are also defined in Figure 5.

Variable	Description	Diagram
Distance (m)	Total distance travelled by each fish, calculated by summing the distance between each frame over the 10 minutes of the trial.	
Proportion explored (-)	The 14,400 cm ² working area was split into 100 cm ² squares and the number of squares entered by each fish counted and expressed as a proportion of the total number of squares.	

Cross count (-)	Number of times each fish passed upstream or downstream of the turbines ($y = 60$ cm).	
Turbine count (-)	Number of times each fish entered the turbine rotor region, defined as ($52 < x < 68$ cm, $52 < y < 66$ cm) when one turbine was present and as ($34 < x < 68$ cm, $52 < y < 66$ cm) for two turbine configurations.	
Turbine time (s)	Time spent in the turbine area (defined above).	
Near wake time (s)	Time spent by each fish in the near wake ($30 < x < 72$ cm, $24 < y < 52$ cm).	

Far wake time (s)	Time spent by each fish in the far wake ($30 < x < 72$ cm, $0 < y < 24$ cm).	
Bow wake time (s)	Time spent by each fish in the bow wake (directly in front of the turbine) ($34 < x < 68$ cm, $66 < y < 78$ cm).	
Time upstream (s)	Time spent by each fish upstream of the turbine ($60 < y < 120$ cm).	

<p>Time downstream (s)</p>	<p>Time spent by each fish downstream of the turbine ($0 < y < 60$ cm).</p>	
<p>Time in 3 fish (-)</p>	<p>The amount of time for which all three fish were within three fish lengths of each other (based on the average total fish length of that shoal) expressed as a proportion of the total time. This analysis was also repeated for each of the areas defined above by only considering time in that area.</p>	
<p>Time in 2 fish (-)</p>	<p>The amount of time for which two fish were within three fish lengths of each other (based on the average total fish length of that shoal) expressed as a proportion of the total time. This analysis was also repeated for each of the areas defined above by only considering time in that area.</p>	

Time alone (-)	The amount of time for which all fish were more than three fish lengths away from one another (based on the average total fish length of that shoal) expressed as a proportion of the total time. This analysis was also repeated for each of the areas defined above by only considering time in that area.	
Time resting (s)	Number of frames during which the swimming speed and tailbeat frequency of the fish was approximately zero.	
Dominance (-)	The proportion of time during shoaling for which each fish was upstream of its shoalmates was calculated for each fish and the second highest proportion was subtracted from the highest proportion.	
Tailbeat frequency (TBF) (Hz)	The tail movement was extracted from the posture tracking and a fast Fourier transform performed on the signal. The dominant frequency was extracted for every second of data. This method was validated against human analysed swimming clips. This analysis was also repeated for each of the areas defined above by only	

	considering frames in that area.	
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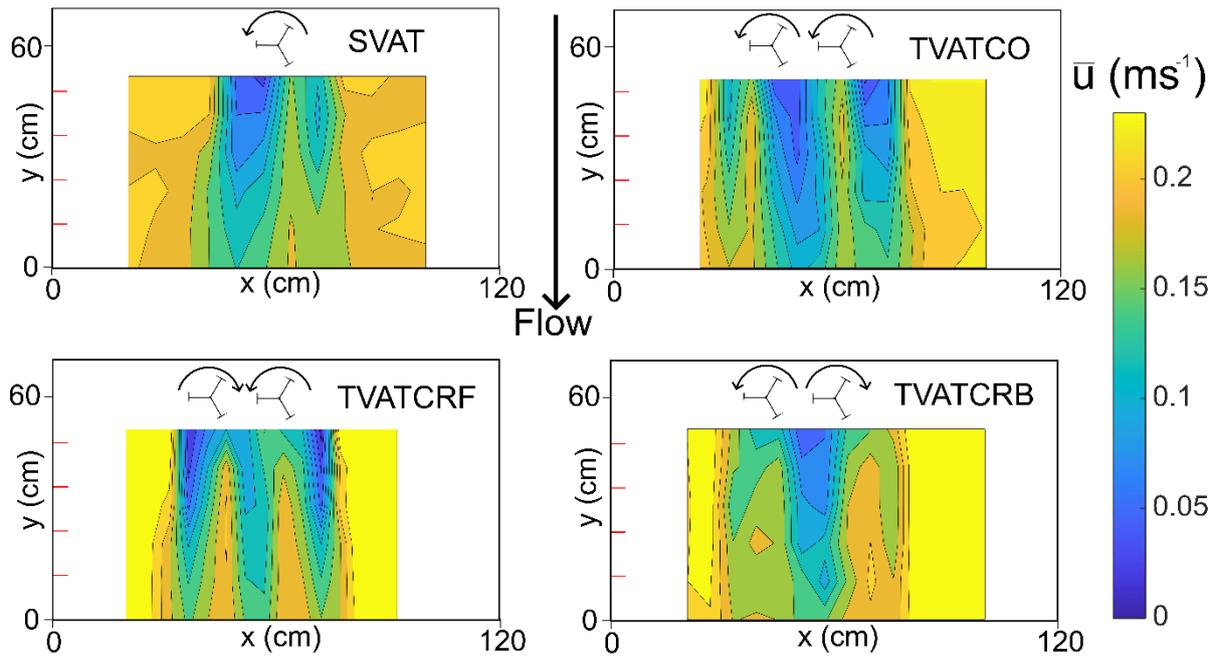
495

496 *Statistical Analysis*

497 The statistical analysis for this study was performed in RStudio (R Version 4.2.2) ⁷⁰.
498 The data was imported into R and checked for normality. Due to the repeated use of
499 the same shoals, Generalised Linear Mixed Models (GLMM) were utilised to account
500 for pseudo-replication by including shoal ID as a random effect. To perform the GLMMs
501 the lme4, nlme, and lmerTest packages were used ^{71–73}. The study was performed in
502 batches, so batch effects were first inspected to verify that there were no statistical
503 differences between batches for all response variables (GLMM, $p > 0.44$). The data
504 was normally distributed so a Gaussian GLMM produced the best residual distributions
505 compared to other GLMMs tested. Count data was analysed using a Poisson GLMM
506 which outperformed negative binomial and other GLMMs. To further analyse TBF,
507 Matlab was used to perform a Probability Density Function (PDF) for TBF in different
508 areas of the working section. In all cases the p value use to determine significance
509 was 0.05, where multiple relationships are reported on (for instance the relationship of
510 all treatments compared to control), the upper bound of the p value for significant
511 results is given.

512 *Hydrodynamics*

513 A previous experimental study ²¹ fully characterised the three dimensional wake shape
514 from Acoustic Doppler Velocimetry data for the turbine configurations tested. Data was
515 available for the following distances downstream of the turbines: 1D, 1.5D, 2D, 3D,
516 4D, and 5D where D is the turbine diameter equal to 12 cm. Figure 6 provides contours
517 of time-averaged streamwise velocity for flow depth $z = 100$ mm. The slowest
518 velocities in the wake are generated in the downstream region corresponding to the
519 upstream motion of the blades. The TVATCRB setup generated the wake with the
520 smallest horizontal footprint while the velocity deficit is largest for the TVATCO ²⁷. The
521 highest turbulence intensity across the wake is from the TVATCRB ²⁷.



522

523 Figure 6. Contour plots of time-averaged streamwise velocity taken at mid turbine
 524 depth for all turbine configurations. The coordinate system on each plot aligns with
 525 that of Figure 5. Red marks on the y axis represent diameters downstream of the
 526 turbines. Acoustic Doppler Velocimetry was used to collect this data by Müller et al.
 527 (2021). The turbine spacing was 1.5 turbine diameters and longitudinal extent of the
 528 wake is shown downstream of the turbines up to the flow straightener at $y = 0$ cm (5
 529 turbine diameters, Figure 5).

530 *Animal ethics statement*

531 All work was performed under the relevant guidelines and regulations and approved
 532 by Cardiff University Animal Ethics Committee and linked to UK Home Office
 533 PP816714 and followed ARRIVE guidelines.

534 **Data availability**

535 Data from this study is freely available at DOI: 10.17632/xmrptb6mjw.1

536 **Acknowledgements**

537 This study was carried out with financial support from the Natural Environment
 538 Research Council (NERC) FRESH CDT grant NE/R011524/1 and the Engineering and
 539 Physical Science Research Council WISE CDT grant EP/L016214/1. The authors
 540 thank Paul Leech for his technical support and Drs Rhi Hunt and Scott MacAulay for
 541 fish care.

542 **Contributions**

543 C.W., J.C. and P.O. obtained the funding and supervised all the work. All authors
 544 planned the experimental work. G.S.S. and S.M performed the experimental work and
 545 G.S.S performed the data analysis. G.S.S prepared the original manuscript. All authors
 546 reviewed the manuscript.

547

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