
Supplementary Materials

Fish adapt and dynamically avoid an approaching robotic fish across repeated exposures

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S1 SIZE OF DATASET AFTER PREPROCESSING

Table S1 shows the remaining number of frames at each step of the the data preprocessing pipeline. Frames were systematically removed based on several criteria to ensure the integrity of the analysis. First, frames corresponding to the initialization phase (milling process) and the post-experiment period were excluded, followed by the removal of frames where 25 or more consecutive frames lacked tracking data. By applying this exclusion criterion, we kept the number of frames requiring interpolation—referred to as corrections—relatively low. Corrections were applied to less than 2% of the remaining frames after exclusion. This was an important consideration, as interpolation, while necessary for handling small gaps in data, could alter key distributions (e.g. speed) if applied too extensively.

S2 FIXED-EFFECTS MODELS OF VARIOUS RESPONSE LATENCIES

The fixed-effects (FE) models investigate how robot behavior affected the fish's avoidance speed v_{avoid}^F . The predictor variables included the distance d_{FR} between the robot and the fish, the robot's approach speed v_{app}^R , and the distance d_{FW} between the fish and the nearest tank wall. In the manuscript, we shifted the avoidance speed forward by $\Delta = 0.32s$ (8 frames), to take response latency into account. Table S2 shows that other values of $\Delta \in 4, 12, 16$ yield results consistent with the 8-frame shift.

subject	original	selection	exclusion	corrections
0	16040	14500 (-1540)	12605 (-1895)	231 (1.83%)
1	19668	17530 (-2138)	16575 (-955)	307 (1.85%)
2	18629	16700 (-1929)	15455 (-1245)	256 (1.66%)
3	23045	20500 (-2545)	18961 (-1539)	149 (0.79%)
4	24547	20300 (-4247)	18406 (-1894)	351 (1.91%)
total	101929	89530 (-12399)	82002 (-7528)	1294 (1.57%)

Table S1: The number of frames per subject and in total, after each step of data processing. Original: the initial frame count for each video. Selection: the removal of frames associated with the initialization phase (milling process) and the post-experiment period (the delay between the end of the experiment and video termination). Exclusion: the number of frames discarded when 25 or more consecutive frames have no tracking data. Corrections: the number of frames where positions were interpolated, expressed as a percentage of the remaining frames after exclusion.

response at $t + \Delta$	predictor at t	coeff.	signif. code	statistics
v_{avoid}^F ($\Delta = 4$)	fish-robot distance d_{RF}	-0.0235	**	$R^2 = 0.0252$
	robot approach speed v_{app}^R	0.0521	***	$Re = 0.1985$
	fish-wall distance d_{WF}	-0.0195		$F_{(3,81974)} = 705.48$ $p < 0.001$
v_{avoid}^F ($\Delta = 8$)	fish-robot distance d_{RF}	-0.0294	***	$R^2 = 0.0386$
	robot approach v_{app}^R	0.0657	***	$Re = 0.1986$
	fish-wall distance d_{WF}	-0.0185		$F_{(3,81954)} = 1095.45$ $p < 0.001$
v_{avoid}^F ($\Delta = 12$)	fish-robot distance d_{RF}	-0.0330	***	$R^2 = 0.0502$
	robot approach v_{app}^R	0.0762	***	$Re = 0.1988$
	fish-wall distance d_{WF}	-0.0177		$F_{(3,81934)} = 1442.04$ $p < 0.001$
v_{avoid}^F ($\Delta = 16$)	fish-robot distance d_{RF}	-0.0351	***	$R^2 = 0.0591$
	robot approach v_{app}^R	0.0837	***	$Re = 0.1990$
	fish-wall distance d_{WF}	-0.0170		$F_{(3,81914)} = 1714.43$ $p < 0.001$

Table S2: Results from 4 fixed effects models, each examining the relationship between fish avoidance speed (v_{avoid}^F) at future time points ($t + \Delta$) and predictor variables at time t , including fish-robot distance (d_{RF}), robot approach speed (v_{app}^R), and fish-wall distance (d_{WF}). Each model uses a different shift Δ to model the response latency of the fish to the robot's behavior. All models are significant ($p < 0.001$) and yield consistent results. Significance codes of the predictor terms: $p < 0.001$ (** *); $p < 0.01$ (**); $p < 0.05$ (*); $p < 0.1$ (.); $p \geq 0.01$ ()

predictor at \bar{t}	coeff.	CI (95%)	p-value	test statistics
robot-fish distance d_{FR}	-0.032	[-0.0419, -0.0222]	$p < 0.001$	$R^2 = 0.0625$
robot approach speed v_{app}^R	0.081	[0.0662, 0.0962]	$p < 0.001$	$F_{(4,12316)} = 205.10$
wall-fish distance d_{FW}	-0.015	[-0.0321, 0.0012]	$p > 0.05$	$p < 0.001$
distance \times speed ($d_{FR} \cdot v_{app}^R$)	0.001	[0.00005, 0.00189]	$p < 0.05$	

Table S3: Results from the two-way fixed-effects model analyzing predictors of fish avoidance speed (v_{avoid}^F) at aggregated time $\bar{t} + \Delta$ with $\Delta = 2$. The model includes individual- and time-specific fixed effects. Coefficients, 95% confidence intervals, and significance levels are reported. The model is significant with $p < 0.001$.

predictor at t	coeff.	p-value	test statistics
robot-fish distance d_{FR}	-0.029	$p < 0.001$	$R^2 = 0.0386$
robot approach speed v_{app}^R	0.066	$p < 0.001$	$Re = 0.199$
wall-fish distance d_{FW}	-0.019	$p > 0.05$	$F_{(3,81954)} = 1095.45$ $p < 0.001$

Table S4: Baseline one-way individual fixed-effects model (without coupling term) predicting fish avoidance speed (v_{avoid}^F) at $t + \Delta$ with $\Delta = 8$ from predictors at time t : robot-fish distance (d_{FR}), robot approach speed (v_{app}^R), and wall-fish distance (d_{FW}). Cluster-robust (Arellano HC1) standard errors are used, and the model is estimated on $N = 82,002$ observations.

S3 TWO-WAY FIXED-EFFECTS MODEL ON AGGREGATED DATASET

To include the time-specific fixed effect, the dataset was aggregated by subject and time. The frame number was first converted to seconds using a sampling rate of 25 Hz. Afterwards, the data was averaged within 5-second time windows. This process resulted in a dataset with one observation per interval per subject, allowing us to estimate a two-way fixed-effects model with both individual- and time-specific effects. To ensure robustness of the inference, we additionally applied a Driscoll–Kraay correction, which accounts for potential heteroskedasticity, serial correlation, and cross-sectional dependence in the panel structure. The results presented in Table S3 align with the findings from the one-way (individual) fixed-effects model reported in the manuscript, demonstrating consistency across modeling approaches and confirming the stability of the estimated effects.

S4 COUPLING EFFECTS

Table S4 reports the baseline one-way individual fixed-effects model predicting fish avoidance speed (v_{avoid}^F) at time $t + \Delta$ (with $\Delta = 8$) from predictors measured at time t , including robot-fish distance (d_{FR}), robot approach speed (v_{app}^R), and wall-fish distance (d_{FW}). As shown in Table S4, distance and approach speed exhibit robust associations with the avoidance response, whereas the wall-distance control does not reach statistical significance in this

predictor	coeff.	SE	p-value	test statistics
trial number (fixed)	0.204	0.054	$p < 0.001$	pseudo $R^2 = 0.234$
subject identity (random)	0.527	0.211	$p < 0.05$	$Re = 0.785$ $\chi^2(2) = 24.09$ $p < 0.001$

Table S5: Results from the generalized linear mixed model (GLMM) with a logit link function, analyzing avoidance behavior as the binary response variable during the pre-encounter phase. The fixed effect is trial number, and subject identity is included as a random effect. Coefficients, standard errors (SE), and p-values are reported for the predictors. Test statistics of the model are also reported (right column). The model is statistically significant ($p < 0.001$) based on the likelihood ratio test $\chi^2(2) = 24.09$. The repeatability estimate ($Re = 0.785$) indicates that 78.5% of the total variance in avoidance behavior is explained by individual-level differences between subjects.

baseline specification.

To investigate potential coupling effects between predictors, the main manuscript extends this model by including an interaction term between robot–fish distance and robot approach speed ($d_{FR} \times v_{app}^R$). We formally compared the baseline model (Table S4) with the extended interaction model using a robust Wald test of the nested specifications. The test rejects the null hypothesis that the interaction coefficient equals zero ($\chi^2(1) = 5.25$, $p = 0.0219$), indicating a modest but statistically significant coupling effect.

S5 LOGISTIC REGRESSION ANALYSIS OF AVOIDANCE BEHAVIOR DURING THE PRE-ENCOUNTER PHASE

To assess whether avoidance behavior during the pre-encounter phase changes with repeated trials and whether there is variability across subjects, a Generalized Linear Mixed Model (GLMM) with a logit link function was fitted. The binary outcome variable, avoidance, indicated whether avoidance behavior occurred (1) or not (0) during each trial. As predictor variables, we included the trial number, which represents the progression of trials to examine changes over time, and the subject identity, which accounts for individual variability across subjects.

Table S5 revealed a significant positive effect of trial number on avoidance behavior. This finding indicates that avoidance behavior during the pre-encounter phase increases significantly with the number of trials. As subjects are exposed to more trials, the likelihood of exhibiting avoidance behavior becomes progressively higher, demonstrating that repeated exposure amplifies the tendency for avoidance during this phase of the experiment. Additionally, there was significant variability across subjects, highlighting the individual differences in avoidance patterns.

predictor	coeff.	SE	p-value	test statistics
relative angle θ_{RF} (fixed)	-0.2624	0.168	$p > 0.05$	pseudo $R^2 = 0.146$
speed ratio $\frac{v^F}{v^R}$ (fixed)	-5.3713	1.076	$p < 0.001$	$Re = 0.6879$
distance d_{RF} (fixed)	-0.1025	0.014	$p < 0.001$	$\chi^2(4) = 99.42$
subject identity (random)	-0.0642	0.095	$p > 0.05$	$p < 0.001$

Table S6: Results from the generalized linear mixed model (GLMM) with a logit link function, analyzing the occurrence of an extreme turn as the binary response variable. The fixed effects are the relative angle θ_{RF} , the fish-robot speed ratio $\frac{v^F}{v^R}$, and the fish-robot distance d_{RF} . The subject identity is included as a random effect. Coefficients, standard errors (SE), and p-values are reported for the predictors. Test statistics of the model are also reported (right column). The model is statistically significant ($p < 0.001$) based on the likelihood ratio test $\chi^2(2) = 99.42$. The repeatability estimate ($Re = 0.688$) indicates that 68.8% of the total variance in turning behavior is explained by individual-level differences between subjects.

S6 LOGISTIC REGRESSION ANALYSIS OF EXTREME TURNS

To investigate the factors influencing the likelihood of a fish executing an extreme turn (defined as a turn exceeding its individual baseline), a Generalized Linear Mixed Model (GLMM) with a logit link function was applied. The binary response variable indicated whether an extreme turn occurred (1) or not (0) within each distance bin during the pre-encounter phase. Predictor variables included the relative angle between the fish and the robot (θ_{RF}), the fish-robot speed ratio ($\frac{v^F}{v^R}$), the distance between the fish and the robot (d_{RF}), and the subject identity as a random effect to account for inter-individual variability.

Table S6 presents the model results, showing statistical significance ($p < 0.001$) based on the likelihood ratio test ($\chi^2(2) = 99.42$). Among the predictors, the fish-robot speed ratio ($\frac{v^F}{v^R}$) exhibits a significant negative effect ($\beta = -5.371$, $SE = 1.076$, $p < 0.001$). This suggests that as the speed ratio increases, the likelihood of an extreme turn decreases, likely because a faster-moving fish is already distancing itself from the robot, making turning unnecessary. Similarly, the distance between the fish and the robot (d_{RF}) shows a significant negative effect ($\beta = -0.102$, $SE = 0.014$, $p < 0.001$), indicating that the likelihood of turning increases as the robot approaches closer proximity. This behavior aligns with the expectation that closer encounters with the robot heighten the need for evasive maneuvers. In contrast, the relative angle (θ_{RF}) does not have a statistically significant effect ($\beta = -0.262$, $SE = 0.168$, $p > 0.05$). This may be due to the limited variability in θ_{RF} across conditions, with most observations concentrated between $\frac{3}{4}\pi$ and π (Fig S1). Alternatively, it is possible that when fish are nearly immobile, turning behavior is less dependent on the relative angle since any directional movement suffices for evasion. Lastly, the subject identity random effect does not indicate significant differences in the likelihood of turning across individuals ($\beta = -0.064$, $SE = 0.095$, $p > 0.05$). The high repeatability ($Re = 0.688$) suggests that the variability appears to be more influenced by within-subject dynamics rather than subject-specific characteristics.

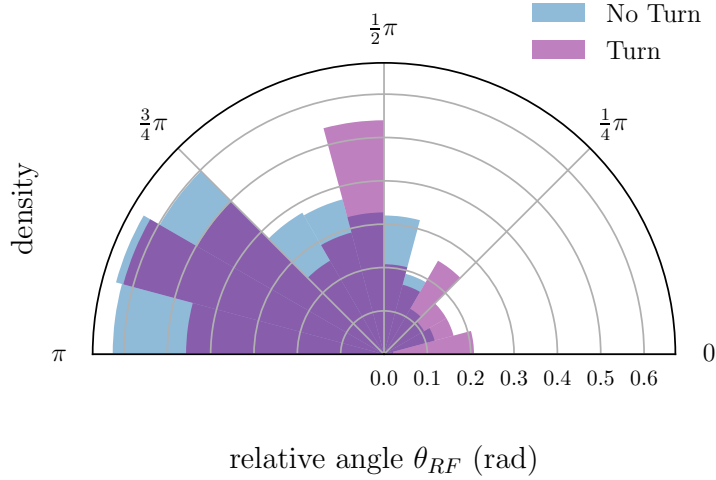


Figure S1: Density distribution of the relative angle θ_{RF} for the instances of extreme turn (purple) and no turn (blue), sampled from all trials and subjects.

S7 FISH MOVEMENT PATTERNS IN THE POST-ENCOUNTER PHASE

Figure S2 illustrates the movement patterns of the fish during the post-encounter phase, after the robot finished approaching. The fish predominantly moved in the opposite direction of the robot, with a slight preference for veering to the left from the robot's perspective (highest density of θ_{RF} observed at between $\frac{10}{12}\pi$ and π , Fig S2A). The highest density of maximum speeds lies in the range of 10 to 15 cm/s. Analysis using a FE model showed that post-encounter speeds were significantly higher compared to the early pre-encounter phase (Estimate = 3.80, SE = 0.75, $t = -5.06$, $p < 0.001$), supporting the claim that fish exhibit high-speed avoidance behavior. Figure S2B shows the density distribution of fish speeds one second after the robot ceases its approach, fitted with a two-component Gaussian model. The first component represents relative slow movements, with speeds around 3-4 cm/s, while the second component reflects higher-speed movements, centered around 11-12 cm/s. This suggests that while the majority of movements occur at a slow pace, a significant proportion of instances involve higher-speed motion. A linear mixed model (LMM) of these speeds, incorporating subject identifier as a random effect ($\beta = 7.019$, $SE = 1.345$, $p < 0.001$), indicates substantial variability both between subjects ($\sigma^2 = 8.547$) and within subjects ($\sigma^2 = 8.491$). The inset depicts fish displacement ($\mu = 7.62$, $\sigma = 4.14$), calculated as the change in robot-fish distance after 1 second.

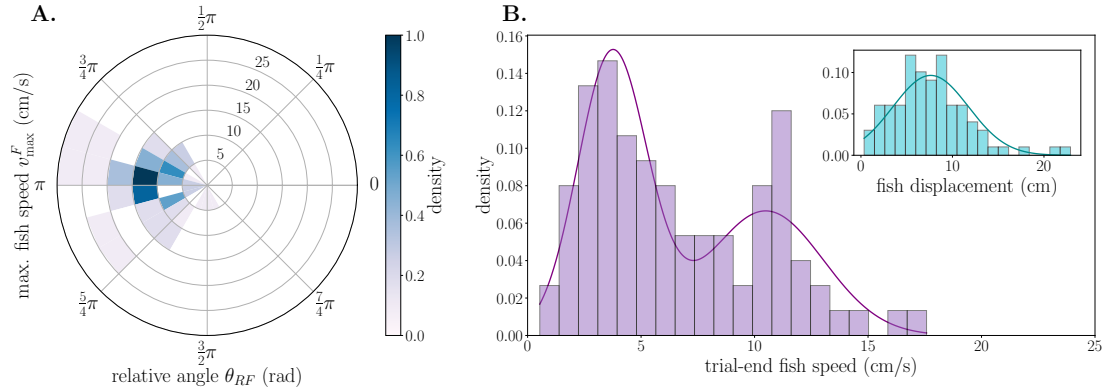


Figure S2: **(A)** Density of the fish's maximum speed (v_{\max}^F) and the relative angle (θ_{RF}) in the initial period of the post-encounter phase (0.4s). The radial gridlines represent relative angles in radians, with π indicating movement directly away from the robot. The concentric circles indicate levels of maximum speed with values increasing outward from the origin. Color intensity represents density, with darker colors (blue) indicating higher densities and lighter colors (purple, white) indicating lower densities. **(B)** Density distribution of the of the fish's speed 1 s into the post-encounter phase. The inset shows the density distribution of fish's straight-line displacement from its position at the start of the post-encounter phase to its position 1 s later. The solid lines represent Gaussian fits, with two components in the main plot and one component in the inset.

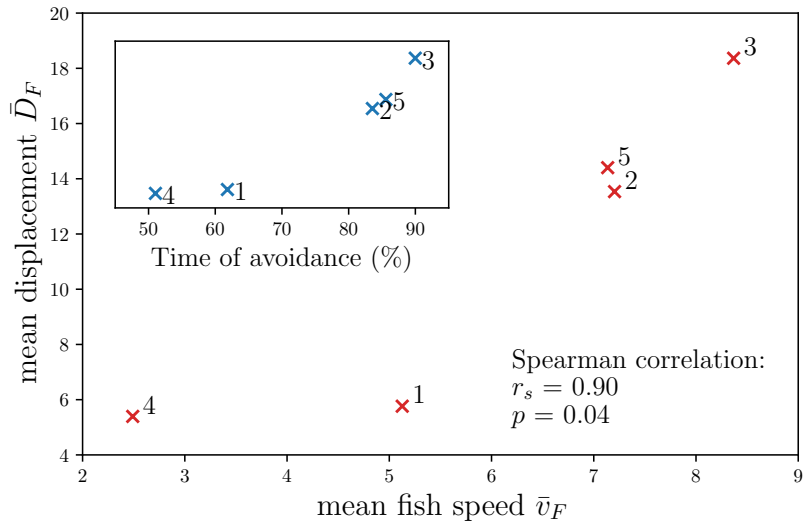


Figure S3: For each individual fish, the mean displacement \bar{D}_F in the first 2 seconds of the post-encounter phase is plotted against the mean speed \bar{v}_F . Each data is labeled with its respective subject identifier. The Spearman correlation coefficient is $r_s = 0.90$ with significance of $p = 0.04$ and a 95% confidence interval of $[0.11, 1]$. The inset shows the relationship between mean displacement and the time of avoidance.

S8 PER-SUBJECT ANALYSIS OF FISH DISPLACEMENT IN THE POST-ENCOUNTER PHASE

Figure S3 illustrates the relationship between mean fish speed and post-encounter displacement across individual fish. Notably, individuals with lower fish speeds also show lower displacements during the post-encounter phase. The displacement is calculated as the difference between the fish-robot distance at the start of the post-encounter phase and the distance 2 seconds afterwards. The Spearman test reveals a positive correlation ($r_s = 0.90$, $p < 0.05$, 95% CI = $[0.11, 1]$), indicating that less active fish tend to move shorter distances away from the robot. As the inset illustrates, the relationship between mean speed and displacement mirrors the trend observed between the time of avoidance behavior and displacement. Subjects exhibiting less avoidance behavior during the experiment also tend to show shorter displacements.

S9 RELATIVE ANGLE BETWEEN THE ROBOT'S POSITION AND THE FISH'S HEADING DIRECTION

Figure S4 shows the density distribution of the relative angle θ_{RF} using data collected across the entire experiment for all subjects, restricted to instances where the fish was moving at a speed greater than 2 cm/s. The results show that the vast majority of the density lies between

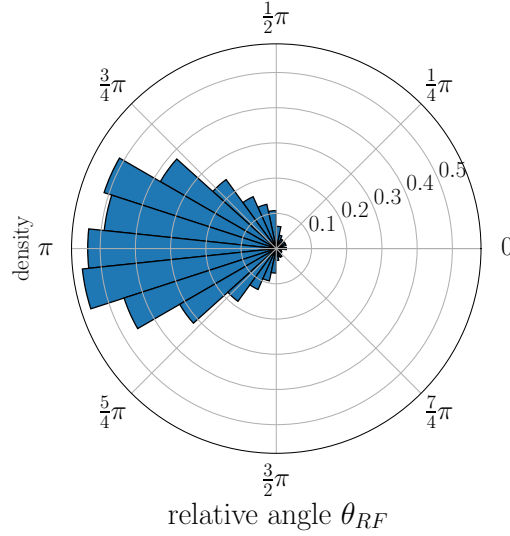


Figure S4: Density distribution of the relative angle θ_{RF} , derived from data collected across the entire experiment for all subjects, where the fish is moving at a speed greater than 2cm/s.

$\frac{1}{2}\pi$ and $\frac{3}{2}\pi$, indicating that the robot was positioned behind the fish for most of the experiment. Notably, the regions with the highest density (0.4) are centered around π .

S10 FISH AVOIDANCE ACCELERATION IN FUNCTION OF THE ROBOT'S RELATIVE POSITION

Figure S5A and B show, respectively, the smoothed (Gaussian filter with $\sigma = 2$) and unsmoothed heatmaps of the guppies' avoidance acceleration (a_{avoid}^F) as a function of the relative position of the robot. The color scale visually represents areas of high (yellow) and low (blue) values, with missing data shown in white. Contour lines in Figure A are provided for visual clarity.

The fish show the highest avoidance accelerations when the robot is located close the fish, particularly when positioned beside them (as indicated by the contour lines). Thus, the fish is not merely avoiding the robot upon encounter, rather, this suggests the fish is performing an escape maneuver. The fish perceives the robot as most threatening when it is present at these directions, prompting a rapid acceleration away from the robot. Additionally, there appears to be a clear pattern of reduced acceleration at greater distances, indicating that the fish only exhibit significant bursts of movement when the robot is in close proximity.

Escape movements, characterized by rapid, high-acceleration avoidance behavior, were most prominent when the robot was in close proximity. The distinct acceleration patterns observed laterally suggest heightened sensitivity in these regions, likely due to enhanced sensory detection and threat perception. This observation is consistent with previous studies [1, 2] showing that fish rely heavily on lateral-line systems to detect nearby objects or potential

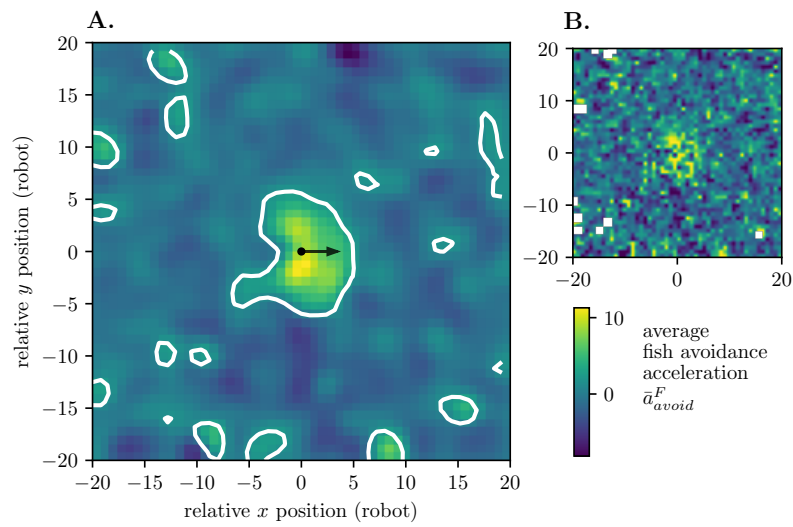


Figure S5: Smoothed **(A)** and unsmoothed **(B)** heatmaps showing the guppies' avoidance acceleration \bar{a}_{avoid}^F as a function of the robot's relative position, with the fish positioned at the origin, facing east (indicated by a black arrow). To smooth the heatmap, missing data is first replaced with neighborhood averages, followed by Gaussian smoothing with $\sigma = 1$. The color scale indicates areas of high (yellow) and low (blue) acceleration. Contour lines, with 3 levels, are added for visual clarity in (A). Missing data is represented in white in (B).

threats. Our findings suggest that fish are more likely to prioritize escape movements over freezing behaviors, especially when the robot approaches from the side at close range.

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