Educating youth about human impact on freshwater ecosystems using an online serious game

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***Abstract*—Freshwater ecosystems are among the most biodiverse ecosystems on the planet and constitute key natural resources for human economies. These ecosystems, however, are endangered due to persistent human activities, ranging from temperature changes to water pollution. Here, we develop an online serious game to educate youth regarding human impact on freshwater ecosystems. In particular, we focus on how environmental variables can affect the behavior and well-being of freshwater fish, which are critical to the food web and the function of the whole ecosystem. In the game, players aim to maximize fish fitness by foraging and reproducing, despite adversarial environmental conditions. We leverage dynamical systems theory to create mathematical models for all the game characters and components, including animal locomotion and hydrodynamic interactions with the flow physics of a virtual river. We test the educational value and usability of the game on a group of middle-school students from New York City. Our results suggest that games like the proposed serious game could be a viable tool to engage youth in environmental education about freshwater ecosystems.**

***Index Terms*—dynamical systems, education, freshwater ecosystems, human-computer interaction, serious game**

I. Introduction

Freshwater ecosystems are among the most biodiverse on the planet, hosting one-third of vertebrate species [1], [2]. While freshwater ecosystems only cover 2% of the planet surface, they host at least 9% of all documented species [3]. Together with their riparian habitats, these ecosystems are essential for the sustenance of human and non-human life. Humans heavily rely on bodies of fresh water for food and energy production, transportation, and waste disposal; approximately 30% of freshwater flow is currently diverted for agriculture, industry, and domestic use [4].

In spite of the high interdependence between our economies and freshwater ecosystems, human activities are a major threat to their biodiversity and productivity [4]. Within a time span of merely 42 years, from 1970 to 2012, the population of freshwater vertebrates declined by 88% [5], at a rate faster than the decline of vertebrates in terrestrial or marine ecosystems [6]. Recent studies have documented several direct and indirect causes of these losses, ranging from temperature changes and flow modification to the introduction of invasive species and pollution by nutrients and toxicants [3].

Despite an increasing interest in environmental issues [7], threats to freshwater ecosystems are constantly emerging and/or being exacerbated by human activities [3]. Toward the mitigation of current environmental issues and the prevention of new ones on the horizon, it is paramount to promote awareness of environmental issues. In fact, public awareness is critical to enhance conservation efforts at local and global scales, as informed societies can help adopt sustainable behavior within their communities and drive governments' agendas toward more stringent laws that protect ecosystems [8]–[10]. For instance, Hasan [11], discussed the importance of public awareness for waste management and provides concrete examples of four case studies where the implementation of awareness programs led to successful clean-up campaigns of highly contaminated regions across the U.S. In similar studies, Arrifin and Sulaiman emphasized the importance of public awareness about sewage pollution in Malaysian rivers [12] and Gelcich et al. highlighted the role of awareness of marine issues in orchestrating efforts by scientists and policymakers [8].

One powerful means to raise awareness of pressing issues is the use of serious games [13], [14]. Serious games are designed to meet a specific learning aim that extends beyond pure entertainment [15], [16], capitalizing on the engaging nature of video games. More specifically, serious games have the potential to connect cognition with the psychological reward system, thereby improving learning and the motivation to learn [17]. Not only do serious games foster motivation, but also they may also induce cognitive flow [18]. According to the theory established by Csikszentmilhalyi, flow is a state of deep concentration and absorption that is reached during intrinsically interesting activities [19]. Flow is maximized when the skills of the user and difficulty of their task are balanced [20]. A few studies have shown that flow is highly conducive to learning [21], [22].

Given the consensus regarding the activation of the reward system during play and the benefits of flow in learning, incorporating serious games into education has been on the rise [17]. For instance, Montes et al. developed a serious game to enhance learning of computer programming, where players organized sequential instructions on a board while avoiding obstacles [23]. The authors compared learning in two groups, one that interacted with the game and one that did not, on tests

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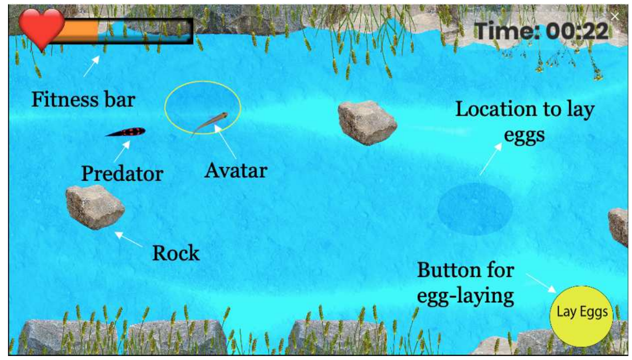
This work was supported in part by the National Science Foundation under grant CMMI-1901697 and in part by the Mitsui USA Foundation. (Corresponding author: Maurizio Porfiri.) D. A. Burbano Lombana, and R. Barak Ventura, and Y. Tian Chen are with the Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, NY 11201 USA (e-mail: daburbanol@gmail.com; rbv215@nyu.edu; ytc344@nyu.edu). M. Porfiri is with the Center for Urban Science and Progress, Department of Biomedical Engineering, and Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, NY 11201 USA (e-mail: mporfiri@nyu.edu). Color versions of one or more of the figures in this paper are available online at [DIR] and showed that the former group performed better on tests. Similarly, Moosa et al. developed a serious game to inform diabetic children about their condition [24]. In the game, players monitored the blood glucose of a character that suffers from diabetes and differentiated between healthy and unhealthy foods affecting the character's health. The authors showed that interaction with the game improved the children's knowledge about diabetes and helped them adopt a healthier lifestyle. Another example of serious games in medicine focused on pediatric patients [25], in an effort to teach them about their medical condition. In addition to reaching learning objectives, the authors demonstrated the value of serious games in coping with negative emotions, such as loneliness, sadness, and fear, which were exacerbated due to long periods of hospitalization.

Within the context of social and environmental sustainability, different serious games have been proposed [26]. For instance, Marsh et al. developed a serious game to raise awareness of issues and threats affecting ecosystems in Australia's Great Barrier Reef [27]. In the game, players can explore three different scenes corresponding to a healthy reef, a transition from a healthy to an unhealthy reef, and to a dead reef. In similar efforts, [28] and [29], developed serious games to teach primary school students about the impact of marine litter on marine life and promote sustainable behavior among players.

In the context of freshwater ecosystems, few existing serious games are designed to promote sustainable management [30]–[32]. Other games are majorly implemented as board games [33], [34]. For example, Khelifa and Mahdjoub [33] developed a board game called "EcoDragons" to teach players about basic ecological thinking related to environmental issues and biodiversity conservation. In the game, players could use dragonflies to colonize, establish, and maintain biodiversity in an empty landscape that is negatively affected by human activities. Similarly Gitgeatpong and Ketpichainarong [34] designed a board game with the intent of educating students about the mangrove ecosystem and its conservation. In the game, each person could play with a different character representing different mollusk species living in a mangrove. The main goal of the game is to survive by following rules similar to those of Monopoly.

Although freshwater ecosystems are essential for the survival of many species and the function of other ecosystems, presently there are no computer serious games in the literature to educate about how human activity can harm such ecosystems. Fish, in particular, constitute a key element in the freshwater food web; not only are fish essential to maintain freshwater environments healthy, but also they provide stability to other ecosystems [35].

In this paper, we propose a novel online serious game to support the education of middle school students regarding human impact on freshwater ecosystems, and in particular its impact on fish behavior and well-being. Our game consists of a fish avatar swimming in a river. The goal of the game is to maintain the fish fitness by foraging, reproducing, and avoiding predation, despite human impact. Specifically, players can explore the effects of three environmental variables, namely, pollution, temperature, and flow speed. These variables represent typical changes in the environment that affect freshwater ecosystems because of human activities, such as water contamination, changes in the river's landscape, and temperature changes.



(a)

Fig. 1. Main game interface featuring the fish avatar and predator swimming in a virtual river.

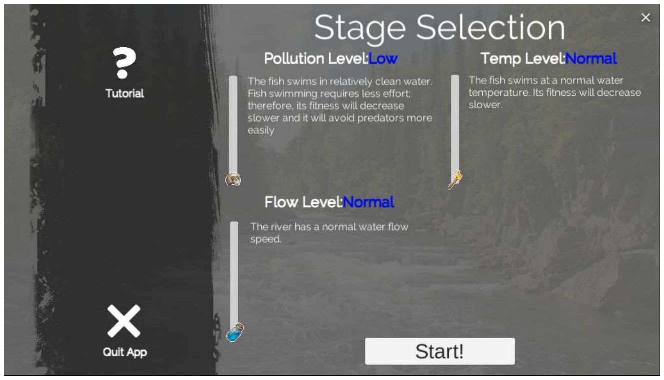
A significant novelty of our game is the realistic simulation of fish behavior. Within the literature on game design, it has been shown that high-quality graphics and realistic replication of motion can enhance the learning experience [13], [36], [37]. This notion is motivated by the theory of Situated Cognition, formulated by Brown, Collins, and Duguid [38]. According to this theory, knowledge is best gained when performing a task in a real-world situation that is tied to social, cultural, and physical contexts, compared to an unrealistic situation [39], [40]. Considering that realism is an important factor in the design of serious games, we use dynamical systems theory to develop simple, yet realistic, mathematical models to animate all characters and components of the game.

The contribution of this paper is twofold. First, we developed novel mathematical models of fish swimming in a virtual river. The models are presented as sets of ordinary differential equations (ODEs) with adjustable parameter values, modulated by environmental conditions and user commands. The proposed models encompass hydrodynamic interactions with the background flow and obstacles, as well as predatory interactions. Second, we conducted a usability study with middle-school students from New York City to assess the effectiveness of our serious game. We hypothesized that, by interacting with our serious game, students would improve their knowledge about human impact on freshwater ecosystems and fish behavior. In addition, we hypothesized that students' ability to learn from the game would be modulated by their passion for sustainability, their desire to pursue a scientific career, and their interest in topics of biology and mathematics.

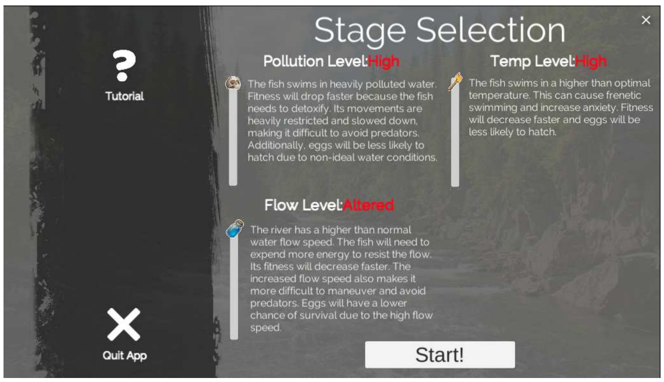
II. Materials and Methods

A. Game overview

We programmed a game in Unity 3-D real-time engine (Unity Technologies, San Francisco, CA, USA). In the game, the player was presented with a top view of a fish avatar swimming in a virtual river (see Fig. 2(a)). The virtual river



(a)



(b)

Fig. 2. A screen shot of stage selection prior to starting the game. The player can set the levels of pollution, temperature, and flow as: (a) low, by drawing the respective bar to the bottom, or (b) high (or altered in the case of flow), by drawing the respective bar to the top. Each of these settings would instigate a different effect on fish behavior and fitness, as described in the text on the right of the bar.

featured streamside plants, rocks, and water flowing from the right to the left of the screen. The player could navigate the fish along the river using the direction keys on their keyboard. To move the fish forward, the player would press the up arrow key [↑], and to turn it left or right, the player would press the left arrow key [←] or right arrow key [→], respectively. The user-controlled fish could not swim backwards.

The objective of the game was to maintain the fish fitness, represented by a health bar, for as long as possible. Fitness is the ability of an animal to survive in the environment so to pass on its genetic material to the next generation [41]. It depends on various aspects of the animal's life, including its ability to forage, reproduce, and avoid predation.

B. Game mechanics

The user-controlled fish's fitness was continuously reduced at a constant rate, commensurate with the energy it "used" to maintain its position in a moving current. At the same time, a predator fish was persistently following the user-controlled fish and performing random attacks. Every time the predator made contact with the user-controlled fish, its avatar flickered to represent it was eaten. The fitness bar subsequently decreased in an instant.

To regain fitness, the player could either forage or lay eggs. To perform the former action, the player drove the user-controlled fish to intercept food particles that are floating downstream. This action resulted in an instantaneous increase in fitness. To perform the latter action, the player positioned the user-controlled fish above a potential nest (depicted as a shaded elliptical region in the river) and clicked the "Lay Eggs" button with the [Enter] key. The nest might consequently turn green to indicate that the eggs had hatched, leading to an instantaneous increase in fitness. Alternatively, the nest might turn red to indicate the eggs failed to hatch, causing no change to the fish fitness.

To intuitively expose players to human activities that impact the river ecosystem, we introduced three salient environmental factors affecting fish fitness and behavior: pollution ($\mathcal{P}$), temperature ($\mathcal{T}$), and flow speed ($\mathcal{F}$). For the sake of simplicity, we considered these variables as boolean, taking values in $\{0, 1\}$, where 0 denotes low and 1 high pollution, high temperature, or altered flow. The user could explore the effects of each of these factors by setting them as low or high on a Stage Selection screen, before starting the game (see Fig. 2(b)). The effect of each selection on the avatar movement and fitness was explained to the player through text.

Heavy metal-polluted sites (namely, lead and cadmium), crude-oil aluminum contamination, and pesticides can impair spatial memory and learning in fish [42]. Also, fish exposed to pollutants have higher metabolic rates and greater energetic needs, because detoxification and repair processes are costly [43]. Therefore, in high levels of pollution ($\mathcal{P} = 1$), fish movements were dampened and the probability of eggs hatching was reduced, relative to low levels of pollution ($\mathcal{P} = 0$).

Temperature has a critical effect on fish since most species do not have physiological means to regulate their body temperature which is then determined by environmental temperatures [44], [45]. In fact, fish growth, reproduction, and locomotion varies according to temperature in a non-linear fashion similar to a reversed U-shape. That is, there is an optimal temperature where fish exhibit their optimal performance which decreases for either very low or high temperatures [46]. Regarding locomotion, high temperatures are associated with frantic and intense swimming activity [45], [47]. Therefore, in high temperatures ($\mathcal{T} = 1$), the user-controlled fish's movements were programmed to display more intense swimming and its fitness bar reduced at a faster rate, relative to when temperatures were low ($\mathcal{T} = 0$).

Finally, human activities such as building dams or alteration of watersheds can change river flows [48]. Flow controls the supply rate of food resources and nutrients and fish metabolic needs [49], and it can also promote the establishment of invasive species [50], [51]. Altered flows, either low or high, can compromise fish behavior and fitness. For instance, for lower flow regimes fine sediments might tend to accumulate, thus, negatively impacting the survival of fish eggs and larvae [48]. In higher flow regimes, however, fish presence decreases, whereby eggs and larvae suffer higher mortality rates and fewer fish thrive in those environments [52]. Therefore, for altered flow ($\mathcal{F} = 1$), the likelihood of eggs hatching was compromised and the fitness bar reduced at a faster rate, relative to normal flow regimes ($\mathcal{F} = 0$).

C. Mathematical models to animate game components

Here, we present the mathematical models used to generate the motion of the game components and create a realistic animation. In particular, we employed the models to animate two characters (the fish avatar and predator fish) and four components (fluid flow, food pallets, rocks, and fish fitness).

1) Virtual river model: We considered a virtual two-dimensional river of dimensions $[-y_{\max}, y_{\max}]$ in width and infinite longitude $[0, \infty)$, as depicted in Fig. 3(b). We assumed the flow velocity profile to be uniaxial and inviscid and given by

$$U(\mathcal{Y}) = \eta(a_u \mathcal{Y}^2 + b_u), \tag{1}$$

where a_u [cm^{-1}s^{-1}] and b_u [cm s^{-1}] were two constant parameters. Parameter η was a unitless scaling constant greater than zero, used to manipulate the strength of the flow velocity.

2) Flow around rocks: To model hydrodynamic interactions, we utilized potential flow theory, which is typically used to approximate the flow around a solid body in many applications [53], [54]. We employed a doublet function [54] to describe the flow past a cylinder of radius r, which approximate the flow around a rock located at $(x_{\rm r}, y_{\rm r})$ (see Fig. 3(b)). Specifically, we adopted the velocity functions

$$R_x(\mathcal{X}, \mathcal{Y}, x_{\rm r}, y_{\rm r}) = -r^2 U(\mathcal{Y}) \frac{(\mathcal{X} - x_{\rm r})^2 - (\mathcal{Y} - y_{\rm r})^2}{[(\mathcal{X} - x_{\rm r})^2 + (\mathcal{Y} - y_{\rm r})^2]^2}, \tag{2a}$$

$$R_y(\mathcal{X}, \mathcal{Y}, x_{\rm r}, y_{\rm r}) = r^2 U(\mathcal{Y}) \frac{2(\mathcal{X} - x_{\rm r})(\mathcal{Y} - y_{\rm r})}{[(\mathcal{X} - x_{\rm r})^2 + (\mathcal{Y} - y_{\rm r})^2]^2}. \tag{2b}$$

3) Model of the user-controlled fish: To capture the motion of a fish in a current, we split the model into two main components: fish swimming and fish tail beating. Fish swimming pertained to the motion of the fish centroid on the $\mathcal{X} - \mathcal{Y}$ plane and comprised both translational and rotational movements. We approximated the flow around a fish by a pair of point vortices [55], [56], as shown in Fig. 3(c), yielding a system of ODEs [57],

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = v(t)\cos(\theta(t)) + U(y(t)), \tag{3a}$$

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = v(t)\sin(\theta(t)), \tag{3b}$$

$$\frac{\mathrm{d}\theta(t)}{\mathrm{d}t} = -U'(y(t))\cos^2(\theta(t)) + \omega(t). \tag{3c}$$

Here, $(x(t), y(t))$ represented the position of the fish centroid on the $\mathcal{X} - \mathcal{Y}$ plane; t was the time variable; $\theta(t) \in [-\pi, \pi)$ was the fish heading; $U'(\mathcal{Y})$ was the flow gradient along the width of the virtual river; and variables $v(t)$ and $\omega(t)$ were the fish speed relative to the background flow and its turn rate, both taken as inputs.

We did not consider hydrodynamic interactions between the fish and rocks to facilitate the maneuverability of the avatar when navigating close to rocks. We imposed, however, a hard boundary condition around the perimeter of a rock, defined by a circle of radius r, where the fish could not enter.

4) Predator behavior: Similar to the user-controlled fish, we implemented a set of ODEs to describe the swimming behavior of the predator. However, different from the avatar fish, we considered hydrodynamic interaction with a rock through the velocity functions in equation set (2) to allow the predator for automatically avoiding obstacles along the river. The resulting set of coupled ODEs capturing fish motion in a river were given by

$$\frac{\mathrm{d}x_{\rm p}(t)}{\mathrm{d}t} = v(t)\cos(\theta_{\rm p}(t)) + U(y_{\rm p}(t)) + I(t)\zeta_x(t) + \mathrm{sign}\{\cos(\theta_{\rm p}(t))\} R_x(x_{\rm p}(t), y_{\rm p}(t), x_{\rm r}, y_{\rm r}) \tag{4a}$$

$$\frac{\mathrm{d}y_{\rm p}(t)}{\mathrm{d}t} = v(t)\sin(\theta(t)) + I(t)\zeta_y(t) - \mathrm{sign}\{\cos(\theta_{\rm p}(t))\} R_y(x_{\rm p}(t), y_{\rm p}(t), x_{\rm r}, y_{\rm r}) \tag{4b}$$

$$\frac{\mathrm{d}\theta_{\rm p}(t)}{\mathrm{d}t} = -U'(y_{\rm p}(t))\cos^2(\theta_{\rm p}(t)) + \zeta_\theta(t) \tag{4c}$$

where $(x_{\rm p}(t),\ y_{\rm p}(t))$ and $\theta_{\rm p}(t)$ were the position of the centroid and the heading angle of the predator, respectively. To ensure repulsion from rocks along the river, we utilized the sign functions above together with the following constraints when reaching the circle enclosing a rock:

$$\frac{\mathrm{d}x_{\rm p}(t)}{\mathrm{d}t} = c_{\rm r}\,\mathrm{sign}\{x_{\rm p}(t) - x_{\rm r}\}, \tag{5a}$$

$$\frac{\mathrm{d}y_{\rm p}(t)}{\mathrm{d}t} = c_{\rm r}\,\mathrm{sign}\{y_{\rm p}(t) - y_{\rm r}\}, \tag{5b}$$

where $c_{\rm r}$ [cm s^{-1}] was a positive constant denoting the speed of repulsion from a rock.

The additional terms, $\zeta_x(t)$, $\zeta_y(t)$, and $\zeta_\theta(t)$, encapsulated a hot-pursuit strategy toward the fish avatar. Such a strategy was implemented when the predator was swimming away from a rock through the indicator function $I(t)$ taking values in $\{0, 1\}$: $I(t)$ was 0 if the fish was approaching the rock, and $I(t) = 1$ otherwise. The hot-pursuit strategy was formulated as a feedback control problem, where the predator fish aimed to track the movements of the prey and eventually attack it. Towards this aim, we implemented a full-state proportional feedback controller

$$\zeta_x(t) = k_{px}\ (x^*(t) - x_{\rm p}(t)) \tag{6}$$

$$\zeta_y(t) = k_{py}\ (y^*(t) - y_{\rm p}(t)) \tag{7}$$

$$\zeta_\theta(t) = k_{p\theta}\,(\theta^*(t) - \theta_{\rm p}(t)) \tag{8}$$

where k_{px}, k_{py}, and $k_{p\theta}$ were positive control strengths, and $x^*(t)$, $y^*(t)$, and $\theta^*(t)$ were the target states of the predator, which are given by

$$x^*(t) = x(t) - d_x(t), \tag{9}$$

$$y^*(t) = y(t) + d_y(t), \tag{10}$$

$$\theta^*(t) = \mathrm{atan2}\left(y(t) - y_{\rm p}(t), x(t) - x_{\rm p}(t)\right). \tag{11}$$

Here, $d_x(t)$ and $d_y(t)$ denoted the distances on each coordinate from the predator to the user-controlled fish.

To simulate an attack, the distance $d_x(t)$ should gradually become zero until the predator has reached the target fish.

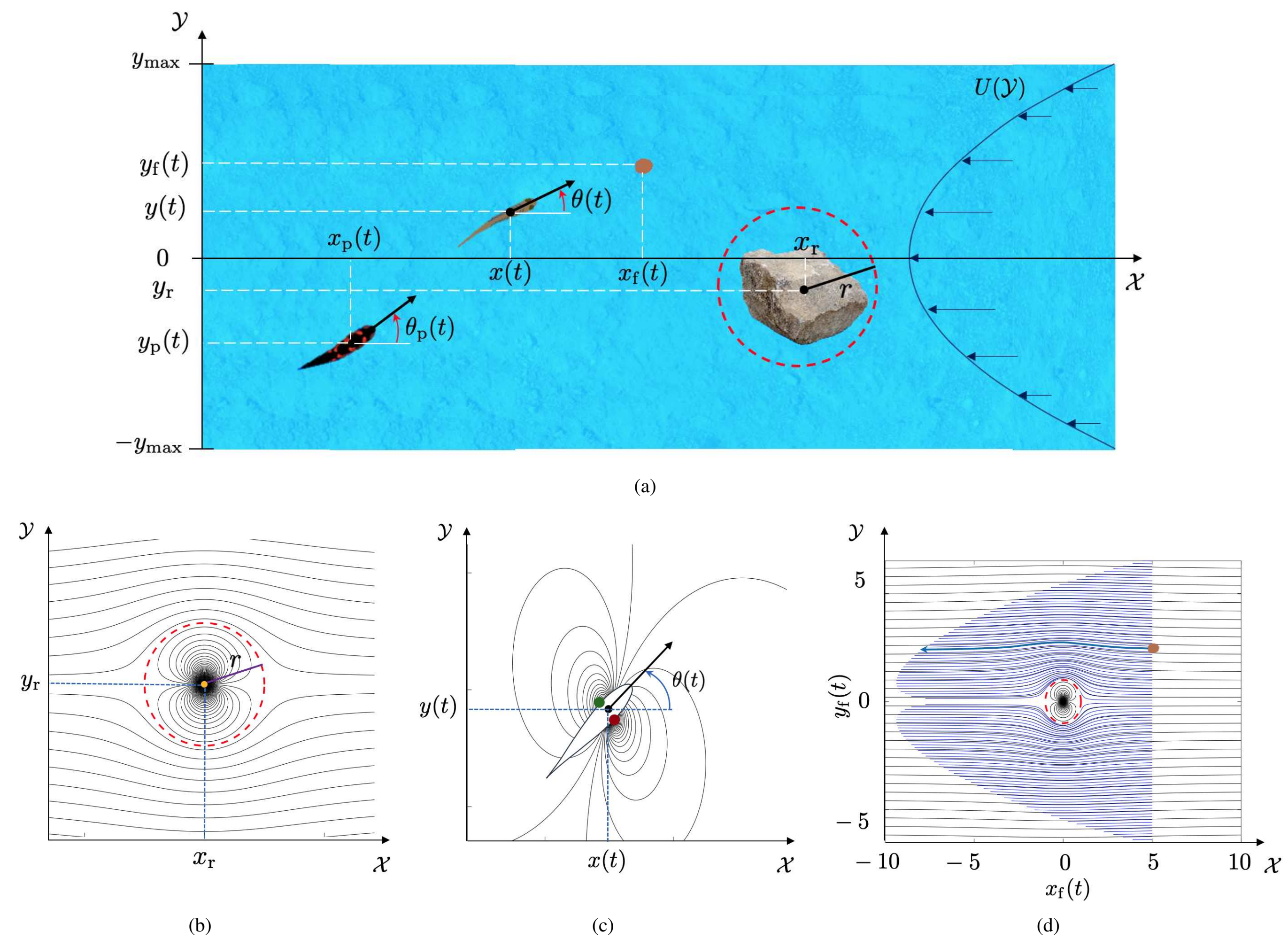


Fig. 3. Mathematical models that capture the motion of fish swimming in a virtual river. (a) Fish kinematics describing interaction with rocks and background flow on the plane $\mathcal{X}-\mathcal{Y}$. The function $U(\mathcal{Y})$ is a parabolic function used to describe the background flow. Coordinates $(x(t), y(t))$ and angle $\theta(t)$ represent the instantaneous centroid and the heading angle of the user-controlled fish, respectively. Similarly, coordinates $(x_{\mathrm{p}}(t), y_{\mathrm{p}}(t))$ and angle $\theta_{\mathrm{p}}(t)$ represent the instantaneous centroid and heading angle of the predator. $(x_{\mathrm{r}}, y_{\mathrm{r}})$ is the centroid of the rock and the dashed-red line denotes the rock approximation by a circle of radius r. $(x_{\mathrm{f}}(t), y_{\mathrm{f}}(t))$ is the instantaneous position of a food particle along the virtual river. (b) Example of flow around a rock approximated as a flow past a cylinder of radius r. The black lines are the streamline function calculated for a constant background flow. (c) Flow around a fish is approximated using a pair of point vortices (represented by the green and red dots) whose strength can change over time. The black lines are the streamline function obtained from the potential function of the dipole model. (d) Illustration of the motion followed by the food particles. Streamlines are identified by black color while blue color represents the food particle trajectory. Initial conditions are set at the same position along the river $x_{\mathrm{f}}(0) = 5$, but at different position across it. Equations are integrated for 4 s. The ticker blue line is one single trajectory followed by a food particle.

Hence, we utilized a first order linear system describing the behavior of $d_x(t)$, that is,

$$\frac{\mathrm{d}d_x(t)}{\mathrm{d}t} = \left(d^* - \alpha_d d_x(t)\right) Z(t) - \alpha_d d_x(t)(1 - Z(t)) \quad (12)$$

where $Z(t)$ was a boolean input in $\{0, 1\}$. Note that if $Z(t) = 0$ for all $t > 0$, $d_x(t)$ would asymptotically converge to d^* at a rate of α_d, while if $Z(t) = 1$ for all $t > 0$, $d_x(t)$ would asymptotically vanish. In fact, α_d defined how fast the predator approaches or retracts from the target.

The input $Z(t)$ was generated based on the diagram shown in Fig. 4(a), where the predator behavior transitioned between three different modes: (i) chasing (C, blue circle, the predator would not attack), (ii) attack (A, orange circle, the predator would start an attack in a time-window of fixed length T_1), and (iii) retracting (R, green circle, the predator would retract without attacking for a fixed time T_2).

The random event initiating the predator attack was identified by another binary random variable $J(k\Delta)$ with $k = \{1, 2, \cdots\}$ and Δ being a constant time period. We chose the realizations of $J(k\Delta)$ to be drawn from a Bernoulli distribution with probability of attacking $\Pr(J(k\Delta) = 1) = p_a$. We set $Z(t) = 1$ during chasing, and once an attack was initiated at time $t^* = k^*\Delta$, the variable would transition as follows:

$$Z(t) = \begin{cases} 0, & t \in [t^*, t^* + T_1) \\ 1, & t \in [t^* + T_1, t^* + T_1 + T_2) \end{cases}. \quad (13)$$

An example of the time-series of $Z(t)$ is shown in Fig. 4(b).

Likewise, we assumed that the distance between the predator and user-controlled fish along the y coordinate, $d_y(t)$, was

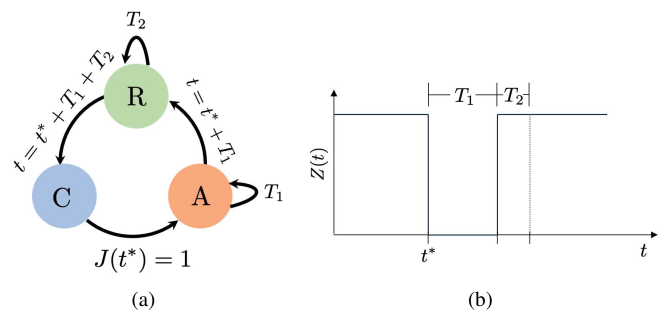


Fig. 4. Description of predator behavior. (a) Transition diagram: normally the predator is in chasing mode (blue circle), once $J(t^*) = 1$ at time t^*, the predator enters the attacking mode (orange circle) and remains there for a time T_1. Then, the predator enters the retracting mode (green circle), where a new attack is not allowed, for an additional time T_2. Finally, the predator resumes the state of chasing where a new attack can be initiated. (b) Representative time-series $Z(t)$ based on the transition diagram of an attack.

zero during chasing. Upon entering the attack mode, we set

$$d_y(t) = \begin{cases} d_0, & t \in [t^*, t^* + T_1) \\ 0, & t \in [t^* + T_1, t^* + T_1 + T_2) \end{cases}, \quad (14)$$

where d_0 was drawn from a Gaussian distribution with mean $\mu_{\rm d}$ and variance $\sigma_{\rm d}$.

5) Food particles model: To capture the motion of food particles $(x_{\rm f}(t), y_{\rm f}(t))$ passively floating downstream the virtual river, we used a similar equation as the one in equation set (4) with no input variables and with no rotation term. Namely, we set $v(t) = \omega(t) = 0$ in equations (4a)-(4b) and we neglected the rotation in equation (4c), yielding

$$\frac{{\rm d}x_{\rm f}(t)}{{\rm d}t} = U(y_{\rm f}(t)) + R_x(x_{\rm f}(t), y_{\rm f}(t), x_{\rm r}, y_{\rm r}) \quad (15a)$$

$$\frac{{\rm d}y_{\rm f}(t)}{{\rm d}t} = -R_y(x_{\rm f}(t), y_{\rm f}(t), x_{\rm r}, y_{\rm r}). \quad (15b)$$

To illustrate the motion of the food particles suspended on the virtual river, we integrated (15) for different initial conditions across the width of the river. The time interval of integration was $[0, 4]$ s for all simulations. The resulting particle trajectories ($x_{\rm f}(t)$,$y_{\rm f}(t)$) are shown in blue color in Fig. 3. We note that particles avoided the rock (red-dashed circle) and traveled faster when they were closer to the center.

6) Tail beating animation: To animate the motion of tail beating for both the user-controlled fish and the predator, we adapted the tail undulation scheme presented in [58], which was inspired by carangiform models of fish swimming. Within this scheme, we set the tail frequency, $F_{\rm t}(t)$, to be proportional to the fish speed $v(t)$ through the relation

$$F_{\rm t}(t) = \frac{c_v}{L} v(t) + \frac{c_l}{L^{1/3}} \quad (16)$$

where c_v was a nondimensional scaling constant, and c_l [cm$^{1/3}$ s^{-1}] and L [cm] were constant parameters – the latter being the length of the avatar or the predator.

7) Fertility: Fertility was implemented in the game as the ability to successfully lay eggs in the designated locations as described in Section II-B. We denoted by p_s the probability of eggs to successfully hatching after laying them on the designated nest locations. High values of p_s would indicate that egg hatching was very likely to succeed, while for low values of p_s it was more likely that hatching fails.

8) Fitness bar: The increase/decrease of the fitness bar over time, $B(t)$, depended on the energy that the fish used to swim and was also modulated by environmental variables. For simplicity, we assumed that the rate of change of the fitness bar was inversely proportional to the fish speed $v(t)$, that is,

$$\frac{{\rm d}B(t)}{{\rm d}t} = -\alpha_B(\beta_B v(t) + \gamma_B) + u_B(t) \quad (17)$$

where α_B, β_B, and γ_B were constant parameters denoting the rate of decrease of the fitness bar, weighting factor for the speed, and nominal constant value of fitness decrease, respectively. u_B was an external input capturing rewards or penalties to fitness. These contributions were positive, when successfully releasing eggs and picking food, and negative when being hit by a predator. The fitness bar variable, $B(t)$, was constrained to the set $[0, 100]$, that is, (17) was only defined on this interval. For values outside the interval, $B(t)$ saturated to the limit values of the set: $B(t) = 0$ for $B(t) > 0$ and $B(t) = 100$ for $B(t) > 100$. The input $u_B(t)$ was set to

$$u_B(t) = s(t)(\alpha_B(\beta_B v(t) + \gamma_B) + \lambda_B \delta(t)). \quad (18)$$

Here, λ_B was a constant parameter scaling the input $\delta(t)$ that represented the number of points that were added or subtracted from $B(t)$. The variable $s(t)$ was also a boolean variable, taking values in $\{0, 1\}$. Specifically, $s(t)$ was 1 if at least one of the following three events occurred: (i) foraging, the user-controlled fish intercepted a food particle, (ii) predator attack, the predator fish intercepted the user-controlled fish, and (3) reproduction, eggs hatched. Otherwise, $s(t)$ was 0.

For each of these three events, the variable $\delta(t)$ took values $\delta(t) = \delta_1$, $\delta(t) = -\delta_2$, and $\delta(t) = \delta_3$, respectively, where δ_1, δ_2, and δ_3 were positive constants. The negative sign indicated that δ_2 points were subtracted from fitness while positive signs indicated an addition of δ_1 or δ_3 points to fitness.

9) User input functions: The variables $v(t)$ and $\omega(t)$ in (3) were controlled by user commands. We indicated with $u_v(t)$ and $u_\omega(t)$ the time-varying signals generated by [↑] and [←],[→] keys, respectively. We used a first-order linear filter to simulate inertia in changing the fish speed through the speed input $u_v(t)$, that is,

$$\frac{{\rm d}v(t)}{{\rm d}t} = -\alpha_v\, v(t) + u_v(t) \text{ if } 0 \leq v(t) \leq v_{\rm max}. \quad (19)$$

where $\alpha_v > 0$ was a damping coefficient and $u_v(t)$ was

$$u_v(t) = \begin{cases} v_0, & \text{if user press [↑]} \\ 0, & \text{Otherwise} \end{cases} \quad (20)$$

with v_0 being a positive constant. We constrained the fish speed to $v(t) \in [0, v_{\rm max}]$ where $v_{\rm max}$ was the maximum attainable speed. The turn rate input, $\omega(t)$, was defined as

$$\omega(t) = \alpha_\omega u_\omega(t), \quad (21)$$

with α_ω being a positive constant capturing the sensitivity (or rate of response) of turning to the user commands. The user input $u_\omega(t)$ in equation (21) was defined as $u_\omega(t) = u_{\omega 0}$ when the user presses [←], $u_\omega(t) = -u_{\omega 0}$ when pressing [→] key, and $u_\omega(t) = 0$ otherwise.

D. Effect of environmental variables

Here, we summarize the effect of the environmental variables $\mathcal{P}$, $\mathcal{T}$, and $\mathcal{F}$ on the game components:

1) Flow rate: During the stage selection, the flow rate was selected to be normal ($\mathcal{F} = 0$) or altered ($\mathcal{F} = 1$). We defined η in (1) as $\eta = \eta_0$ for $\mathcal{F} = 0$, while $\eta = \eta_1$ for $\mathcal{F} = 1$, where η_0 and η_1 were both constant parameters associated with normal or altered flow rate.

2) Fish speed: The speed of the user-controlled fish was modulated by the constant v_0 in equation (20). We set the speed to take four different values corresponding to the entries of the vector $\tilde{v} = [\tilde{v}_0, \tilde{v}_1, \tilde{v}_2, \tilde{v}_3]$. The entries of $\tilde{v}$ represented High (H), Normal (N), Low (L), and Very Low (L-) speeds, respectively.

3) Turn rate sensitivity: Sensitivity of turning was encapsulated by the parameter α_ω in equation (21). We assumed this parameter to take four different values represented by the entries of a vector $\Omega = [\omega_0, \omega_1, \omega_2, \omega_3]$. These values represented High (H), Normal (N), Low (L), and Very Low (L-) sensitivities, respectively.

4) Fitness bar: The rate at which fitness changed was described by the parameter α_B in equation (17). We considered α_B to take five different values corresponding to the entries of the vector $\Lambda = [l_0, l_1, l_2, l_3, l_4]$, where the entries represented Normal (N), Moderate (H-), High (H), Very High (H+), and Extreme High (H++) rates, respectively.

5) Fertility: The probability of successful egg hatching was modulated by the probability p_s. We considered four different values of p_s corresponding to the four entries of the vector $\rho = [f_0, f_1, f_2, f_3]$. Respectively, the entries of this vector denoted Normal (N), Low (L), Very Low (L-), and Extreme Low (L--) likelihood of successful hatching.

6) Predator attacks: The frequency of predator attacks was modulated by the parameter p_a in (12). For larger values of p_a, the fish avatar was more prone to be attacked by the predator, while lower values indicated a lower chance of attacks. Three different probabilities of attack were given by the entries of the vector $P_a = [p_0, p_1, p_2]$, corresponding to Normal, High, and Very High likelihood of an attack, respectively.

Finally, we defined a set of parameter values for fish speed, turn rate sensitivity, fitness bar rate, fertility, and predatory avoidance (see Table I) so that each of those functions would vary with the environmental conditions set by the player.

7) Discrete time implementation and parameter selection: The motion of the game characters and objects was obtained by numerically solving the set of differential equations presented above using Euler's method with a time step of $1/30$ s. Parameters of the mathematical models and control inputs are shown in Table II. These parameters were selected heuristically and they were calibrated by conducting a test with the members of the Dynamical Systems Laboratory at NYU.

TABLE I
PARAMETER VALUES AS A FUNCTION OF THE ENVIRONMENTAL VARIABLES $\mathcal{P}$, $\mathcal{T}$, AND $\mathcal{F}$.

($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (0,0,0)		(F1,F2,F3) = (0,1,0)	
Speed = N,	$v_0 = \tilde{v}_1$	Speed = H,	$v_0 = \tilde{v}_0$
Sensitivity = N,	$\alpha_\omega = \omega_1$	Sensitivity = H,	$\alpha_\omega = \omega_0$
Fitness = N,	$\alpha_B = l_0$	Fitness = H+,	$\alpha_B = l_3$
Fertility = N,	$p_s = f_0$	Fertility = N,	$p_s = f_0$
Predator =N,	$p_a = p_0$	Predator = N,	$p_a = p_0$
($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (0,0,1)		($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (0,1,1)	
Speed = N,	$v_0 = \tilde{v}_1$	Speed = H,	$v_0 = \tilde{v}_0$
Sensitivity = N,	$\alpha_\omega = \omega_1$	Sensitivity = H,	$\alpha_\omega = \omega_0$
Fitness = H-,	$\alpha_B = l_2$	Fitness = H+,	$\alpha_B = l_3$
Fertility = L,	$p_s = f_1$	Fertility = L-,	$p_s = f_2$
Predator = H,	$p_a = p_1$	Predator = H,	$p_a = p_1$
($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (1,0,0)		($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (1,0,1)	
Speed = L-,	$v_0 = \tilde{v}_3$	Speed = L-,	$v_0 = \tilde{v}_3$
Sensitivity = L-,	$\alpha_\omega = \omega_3$	Sensitivity = L-,	$\alpha_\omega = \omega_3$
Fitness = H-,	$\alpha_B = l_1$	Fitness = H,	$\alpha_B = l_2$
Fertility = L,	$p_s = f_1$	Fertility = L-,	$p_s = f_2$
Predator = H,	$p_a = p_0$	Predator = H+,	$p_a = p_2$
($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (1,1,1)		($\mathcal{P}$,$\mathcal{T}$,$\mathcal{F}$) = (1,1,0)	
Speed = L,	$v_0 = \tilde{v}_2$	Speed = L,	$v_0 = \tilde{v}_2$
Sensitivity = L,	$\alpha_\omega = \omega_2$	Sensitivity = L,	$\alpha_\omega = \omega_2$
Fitness = H++,	$\alpha_B = l_4$	Fitness = H,	$\alpha_B = l_2$
Fertility = L--,	$p_s = f_3$	Fertility = L-,	$p_s = f_2$
Predator = H+,	$p_a = p_2$	Predator = H,	$p_a = p_1$

TABLE II
PARAMETER VALUES OF THE MATHEMATICAL MODELS DESCRIBING THE MOTION OF THE GAME COMPONENTS AND CHARACTERS.

Model	Prameter	Value	Unit
	a_u	0.013	cm
	b_u	2	cm s^{-1}
Flow	η_0	1	-
	η_1	2	-
	$y_{\max}$	12	cm
	r	1	cm
Rock	α_v	0.5	cm^{-1}
Speed	$v_{\max}$	$[10, 9, 8, 7]$	cm s^{-1}
	$\tilde{v}$	$[10, 9, 8, 7]$	cm s^{-1}
Turn rate	$u_{\omega 0}$	20	rad
	Ω	$[0.5, 0.3, 0.2, 0.1]$	s^{-1}
	c_{r}	9	cm s^{-1}
	k_{px}	3	s^{-1}
	k_{py}	1	s^{-1}
Predator	$k_{p\theta}$	3	s^{-1}
	T_1	3.5	s
	T_2	0.5	s
	Δ	0.03	s
	$(\mu_{\mathrm{d}}, \sigma_{\mathrm{d}})$	$(1, 0.5)$	-
	d^*	9	cm
	α_d	1	s^{-1}
	P_a	$[0.008, 0.01, 0.02]$	-
Tail beat	$L(\text{avatar})$	2	cm
	$L(\text{predator})$	2	cm
	c_l	1.41	cm$^{1/3}$s^{-1}
	c_v	0.24	-
Fertility	ρ	$[0.8, 0.6, 0.5, 0.4]$	-
	Λ	$[0.2, 0.25, 0.3, 0.35, 0.4]$	s
	β_B	1/2	s^{-1}
Fitness bar	Γ_B	3	s^{-1}
	λ_B	1/30	-
	δ	$[7, 15, 10]$	-

III. GAME USABILITY STUDY

To test the usability of the game and its educational potential in teaching users about fish behavior and ecology, we conducted a usability study. According to the guidelines developed by the New York State Education Department [59], the topics of ecosystems and biodiversity, and humans' impact on them are taught in middle school. Since our game was designed to support the learning of these topics, we focused on this

TABLE III
A LIST OF QUESTIONS ADMINISTERED IN THE STUDY. M1-M4 ASSESSED THE PARTICIPANT'S INTEREST IN PURSUING A SCIENTIFIC CAREER, BIOLOGY, MATHEMATICS, OR CONSERVING THE ENVIRONMENT. Q1-Q8 TESTED THE PARTICIPANT'S KNOWLEDGE OF FISH BEHAVIOR AND ECOLOGY. THE CORRECT ANSWERS TO THESE QUESTIONS ARE MARKED WITH A ∗. E1-E5, WHICH WERE ONLY PRESENTED TO PARTICIPANTS IN THE GQ CONDITION, EVALUATED THE PARTICIPANT'S ENGAGEMENT AND ENJOYMENT WHILE PLAYING THE GAME.

Question	Response
M1. I am interested in pursuing a career as a scientist and/or engineer	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
M2. I am concerned about preserving ecosystems	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
M3. I am interested in Biology	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
M4. I am interested in Mathematics	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
Q1. How does pollution affect fish?	a) It impairs their ability to escape from predators ∗ b) It impairs their memory so they can't distinguish their food c) It makes them more curious so they explore their environment more
Q2. How is pollution affecting fish eggs?	a) They hatch prematurely b) They are more likely to be eaten by predators c) They are less likely to hatch ∗
Q3. How is global warming affecting fish reproduction?	a) Fish become anxious in higher temperatures and do not mate ∗ b) Fish increases metabolism and produce more eggs c) Fish become confused and cannot identify their mates
Q4. In high temperatures, fish's metabolism:	a) Increases ∗ b) Pauses c) Decreases
Q5. Under which conditions are fish more likely to catch food?	a) High flow during the day b) Moderate flow during the day ∗ c) Moderate flow during the night
Q6. Fish will fatigue faster when:	a) The flow is stronger ∗ b) The flow is weaker c) The flow strength keeps changing
Q7. Fish prefer to spawn in areas with a moderate flow because:	a) There is less predation b) Their eggs are less likely to be carried away by the water ∗ c) The water is cooler and it changes the color of the eggs to camouflage
Q8. When water flow is strong:	a) Nutrients are replaced more frequently so fish get more food ∗ b) Fish become tired and do not absorb nutrients c) Fish become less hungry
E1. I enjoyed the game	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
E2. I was trying my best in the game	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
E3. It was easy to play the game	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
E4. I liked the game graphics	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree
E5. I would like to play the game again	☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree

age group (10-14 years old adolescents). We hypothesized that students who play the game would gain a better understanding of fish behavior and ecology and would be better prepared to answer questions about those topics. Further, we hypothesized that the extent to which students would learn about these topics from playing the game, reflected through their success in answering questions, will be moderated by their level of interest in conservation ecology, biology, and mathematics.

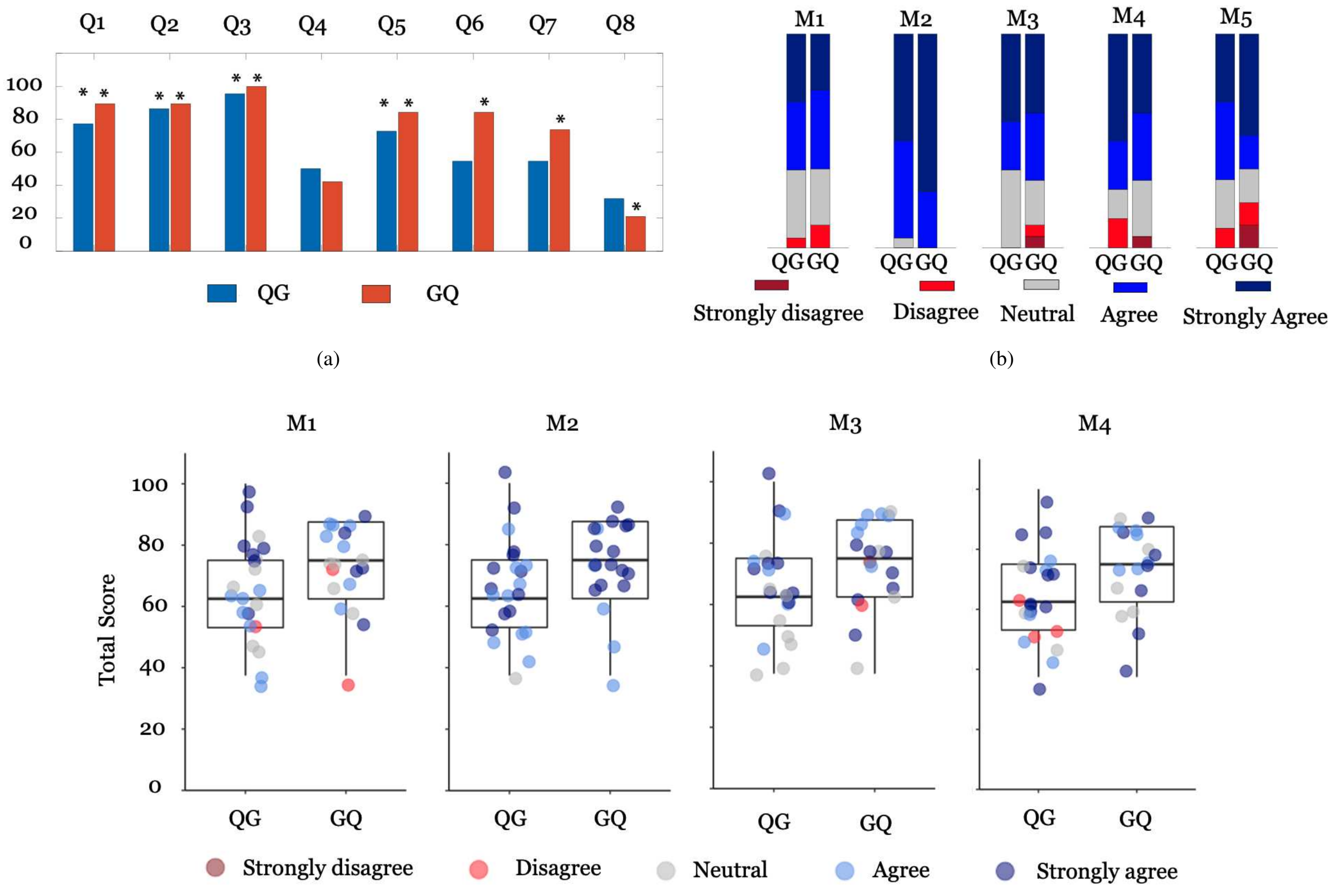
To test these hypotheses, we performed two conditions. In the experimental condition, denoted as GQ, students would first interact with the game and then complete a questionnaire to assess their knowledge about fish ecology and behavior. In the control condition instead, denoted as QG, students would complete first the questionnaire and then play the game.

1) Data collection: An E-mail inviting potential participants to the study was sent to students enrolled in programs by New York University K12 STEM Education Department during the Summer of 2021 and Spring of 2022. Since these programs aim to create a diverse student body, the students who received the E-mail attended middle schools across New York City, and came from socioeconomically diverse backgrounds. Students who were interested in participating signed up for an online Zoom session at a time that fit their schedule.

To establish a baseline of knowledge among students, a 30-minutes lecture was delivered to participants prior to introducing the game or questionnaire. Specifically, the students engaged in an active discussion about human activity and its impact on marine environments, fish fitness, and fish behavior. The slides that were used to lead the discussion (see Data and Game Availability Section) followed the appropriate topics and terminology in the curriculum adopted by New York State Education Department [59].

Upon completion of the lesson, students were randomly divided into two groups of equal size using the "breakout rooms" feature on Zoom. One group was subjected to the GQ condition whereas the other to the QG condition. Participants in the former group were promptly provided with a link to the game through the chat box. They were instructed to interact with the game for as long as they wished, and to explore the different levels offered by the game. Once they were done playing the game, GQ participants were provided with a link to the questionnaire. Participants in the latter group first received a link to the questionnaire. Once they have completed it, they were offered the opportunity to interact with the game.

The questionnaire included 17 items. Eight multiple-answer questions assessed knowledge about fish behavior and ecology (Q1-Q8 in Table 2). In addition, students' interest in pursuing a career as a scientist or develop expertise in biology, mathemat-



(a) (b) (c)

Fig. 5. Summary of students' answers to (a) all knowledge questions Q1-Q8 and (b) general interest questions M1-M5. Bars represent proportions with respect to the number of individuals in each condition QG and GQ, respectively. (c) Student's total score for condition QG and GQ and for different moderator variables M1-M5. Symbol $*$ indicates difference from chance at $p < 0.05$.

ics, or sustainability was assessed by scoring four statements on a 5-point Likert scale (M1-M4 in Table 2). Finally, GQ students were inquired about their enjoyment and engagement while playing the game (E1-E5 in Table 2). Once students submitted their responses, the experiment was concluded.

This protocol was carried out in compliance with the guidelines and regulations set by the institutional review board (IRB) at New York University's Committee on Activities Involving Human Subjects (UCAIHS; IRB-FY2021-4928).

2) Data analysis: The influence of the game on students' scores of knowledge was investigated by fitting the experimental condition and total score into a generalized linear mixed-effects model (R lme4 package, Version 1.0.136; [60], [61]). Students' scores of knowledge of fish behavior and ecology was computed as the percent of questions Q1-Q8 they responded correctly to. The score was specified as the dependent variable, condition (2 levels: GQ and QG) as an independent variable and discussion group ID as a random effect. The significance of the influence of condition on score was tested using a likelihood ratio test by comparing the model against a null model, in the absence of condition as the independent variable. To test whether incorrect or correct answers were equally chosen by students for each one of questions Q1-Q8, we utilized Cochran's Q tests [62], using a custom-build function in Matlab.

To test the moderating effect of interest in pursuing a scientific career, biology, mathematics, or sustainability, we constructed four separate generalized linear mixed-effects models. In all models, the students' total score was specified as the dependent variable and discussion group ID was specified as a random effect. Each individual model contained an interaction between condition and participants' response to one of the statements M1-M4 (see Table 2) as an independent variable. To test the significance of those interactions, the models was compared against a model specifying the condition and the level of respective interest as non-interacting independent variables, through a likelihood ratio test.

Finally, we evaluated students' engagement and enjoyment from their responses to E1-E5. Likert scale scores for each statement were converted from responses "Strongly disagree", "Disagree", "Neutral", "Agree", and "Strongly agree" to corresponding integer values increasing from -2 to 2, respectively. The scores were averaged across students, and compared against zero through a one-sample t-test. In all statistical tests, the significance level was set to $\alpha = 0.05$.

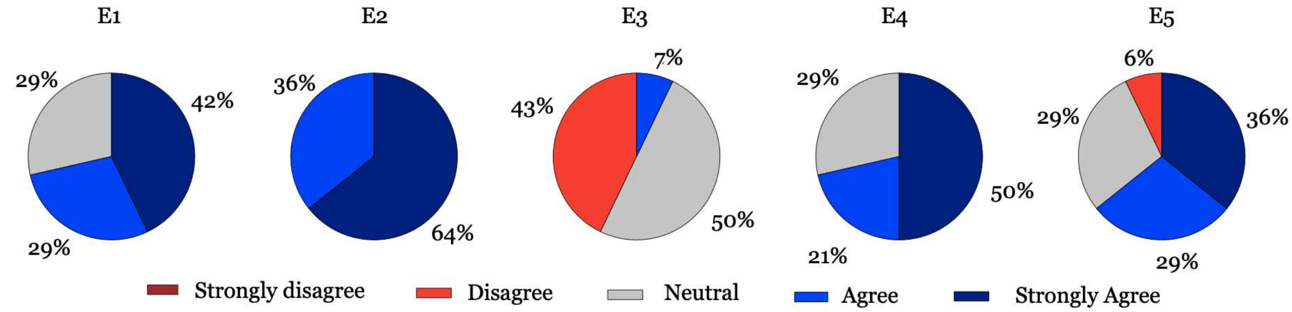


Fig. 6. Summary of the student answers to questions regarding engagement E1-E5.

3) Results: Overall 47 students signed up for the study, however, only 41 students completed the questionnaires. Among those students, 20 self-identified as female, 20 self-identified as male , and 1 preferred to not disclose their gender. Of the 41 participants, 22 were in condition QG whereas 19 were in condition GQ.

A summary of answers to questions Q1-Q8 are shown in Fig. 5(a). The total average score of all students was 68.902 ± 2.395 (mean ± standard error). The average score for condition QG and GQ were 65.340 ± 3.384 and 73.026 ± 3.208, respectively. The generalized linear mixed-effects models indicated that the condition to which participants were subjected did not affect their total score ($\chi_1^2 = 2.348$, $p = 0.125$).

Next, we analyzed whether correct or incorrect answers were equally chosen by the participant for each one of the questions Q1-Q8 in condition QG and GQ, respectively. For condition QG, we found that participants did not equally choose incorrect and correct answers for questions Q1 ($\chi_1^2 = 6.545, p = 0.010$), Q2 ($\chi_1^2 = 11.636, p < 0.001$), Q3 ($\chi_1^2 = 18.181, p < 0.001$), and Q5 ($\chi_1^2 = 18.181, p < 0.001$), whereby 77% (17 participants out of 22) selected the correct answer for Q1 while for Q2, Q3, and Q5, the results of correct answers were 82% (19 participants), 86% (19 participants), 95% (21 participants), and 72% (16 participants), respectively. Instead, for questions Q4 and Q6-Q8, we did not register a significant difference between correct and incorrect answers; that is, Q4 ($\chi_1^2 = 0.181, p = 0.669$), Q6 ($\chi_1^2 = 0.181, p = 0.669$), Q7 ($\chi_1^2 = 0.181, p = 0.669$), and Q8 ($\chi_1^2 = 2.909, p = 0.088$).

For condition GQ, we found that participants had more correct answers in six out of the eight questions. Specifically, we registered that incorrect and correct answered were not equally selected for questions Q1 ($\chi_1^2 = 11.842, p < 0.001$), Q2 ($\chi_1^2 = 11.842, p < 0.001$), Q3 ($\chi_1^2 = 19.000, p < 0.001$), Q5 ($\chi_1^2 = 8.894, p = 0.002$), Q6 ($\chi_1^2 = 8.894, p = 0.002$), Q7 ($\chi_1^2 = 4.263, p = 0.038$), and Q8 ($\chi_1^2 = 6.368, p = 0.011$). For question Q4, we did not detect a significant difference between correct and incorrect answers ($\chi_1^2 = 0.473, p = 0.491$).

In addition, we found that students' overall score was moderated by their interest in pursuing a scientific career ($\chi_3^2 = 9.461$, $p = 0.023$) and their interest in biology ($\chi_2^2 = 6.248$, $p = 0.043$), while for their interest in mathematics we registered a trend ($\chi_2^2 = 5.376$, $p = 0.068$). We did not find, however, that the students' score was moderated by their concerns about the environment ($\chi_1^2 = 0.119$, $p = 0.729$).

Finally, we analyzed the students engagement by assessing the answers to questions E1-E5 shown in Fig. 6. The t-tests revealed that students enjoyed the game ($t_{18} = 6.050$, $p < 0.001$) and would like to play it again ($t_{17} = 4.013$, $p < 0.001$). The students reported that they tried their best at the game ($t_{17} = 13.626$, $p < 0.001$), and they confirmed that the graphics were likeable ($t_{16} = 4.968$, $p < 0.001$). At the same time, the game was not too easy nor too difficult to play ($t_{16} = -1.767$, $p = 0.096$).

IV. Discussion

For millennia, freshwater ecosystems have provided us with crucial resources for survival, culture, and education [63]. Freshwater ecosystems are among the most bio-diverse on Earth [1], [2], [64], but also among the most affected by human activities [3], [5]. The decline in freshwater systems results from several factors, including, but not limited, to changes in temperature, introduction of invasive species, pollution, and flow modifications. These factors compromise fresh water quality and quantity that, in turn, disrupt biogeochemical and ecological processes determining the overall well-being of the system [3], [4]. Several studies recognize the importance of capitalizing on public awareness about pressing environmental issues in order to promote future conservation efforts [8]–[10].

In an effort to promote education and awareness about the human impact on freshwater ecosystems among younger generations, we developed a serious game that teaches players about human impact on fish ecology and behavior. Serious games are carefully designed to achieve a specific learning objective using play as the primary instructional strategy which is conducive to learning [13], [16]. Our game featured a fish avatar that swims along a virtual river. The aim of the game was to maintain the fish's fitness by foraging and reproducing, despite of harsh environmental conditions and predatory threats. To control the difficulty of the game, the player could set the environmental conditions to which the fish was exposed based on three variables: pollution, temperature, and flow speed.

We implemented the animation of all game components using a dynamical system approach in which a set of ODEs describes the motion of each one of them. Specifically, our models considered flow physics by utilizing potential flow theory to describe hydrodynamic interactions with the background flow and rocks. Also, our models incorporated users commands, the effect of environmental variables, and interactions with a predator. Adding realism to the games has been identified as an important factor for engagement and learning [36]. This stems from the theory of situated cognition, in which learners maximize knowledge acquisition by performing activities in a relevant and meaningful context [40]. In line with this theory, Dale's Cone of Experience model stipulates that students would remember only 10% after reading, while they will remember 90% after performing a task [65].

To test the effectiveness of the game, we conducted a game usability study on a group of middle-school students from across New York City. Although the GLME (generalized linear mixed-effects) model did not register a difference in the total students scores between the control and experimental group, the results of the individual analysis on each of the questions indicated a higher performance of the experimental group. In particular, we found that the experimental group had a higher number of correct answers in six out of eight questions. In contrast, with the control group in which students had a high number of correct answers, only in four out of eight questions. In addition, we found that the students' performance, quantified in terms of total score, is modulated by the students' general interest in pursuing a career in science or engineering, and also by their interest in biology or mathematics.

These results offer partial support to the notion that targeted computer games could complement traditional teaching methods and enhance learning, especially when an underlying interest in the topic exists. The role of interest in learning has been widely documented [66], [67]. Interest is defined as a psychological state that is characterized by increased attention, cognitive and effective functioning, and persistent effort. This behavior, along with motivational concepts such as task value and achievements goals, strongly influences the learning process [66]. Therefore, we can argue that within the serious game context interest is a key driver in enhancing student learning. With respect to motivational concepts, situated cognition and engagement constitute an important component to maximize learning within the serious game context [13], [36]. In fact, engagement is crucial to maintain a state of flow – which is a mental state of full immersion on the activity [68]– bring focus and enjoyment and ultimately enhance the learning experience [13], [69].

Our engagement results indicate that the vast majority of students enjoyed the game and would like to play it again. Most importantly, students found our game not too easy, yet not too difficult to play. This finding suggests that students experienced the right balance between their gaming abilities and game challenges, which is crucial to maximizing engagement [13], [70]. It is tenable that the game maintained user's flow experience, thereby guaranteeing engagement and enhancing the learning process.

Our work is not free of limitations that call for future research endeavors. For example, our student population consisted of middle-school students with an age range between 11-14 years old. It would be important to conduct the study in a larger population of students of different ages to explore possible cultural and age factors. In addition, the game currently does not allow to register and store information regarding the real-time performance of the players, such as time series of the user commands and fitness bar. In a future version of the game, we plan to incorporate such functionalities that could allow us to delve into users' engagement and performance beyond classical questionnaires. Additionally, we might consider a multi-player version of the game, where social interactions that enhance engagement and learning are included [71].

Finally, we wish to emphasize that the set of questions Q1-Q8 do not fully encompass the complexity of how environmental variables affect fish behavior and fitness. In addition, answers to those questions might vary according to the fish species. For instance, temperature has a different effect on endothermic fish than ecothermic fish, which comprise most of the fish species [45]. In a future version of the game, we plan to add different characters (fish species) with additional behavioral rules along with more realistic features, such as limited egg supply, distinction between polluted and clean egg-laying sites, among many others.

Although there are several directions to extend our study, the present work provides important insights into how serious games can help to address contemporary environmental issues by promoting education and raising awareness among youth generations. Our results uniquely complement the literature on serious games related to freshwater ecosystems [30]–[34] by affording a novel, interactive tool to educate youth regarding pressing issues that affect freshwater ecosystems in general, and the behavior and well-being of fish in particular.

Data and Game Availability

The datasets and game unity codes presented in this study can be found in the online repository https://github.com/Dynamical-Systems-Laboratory/UnityFishApp along with the links to the online game and slides used in the lecture.

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