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Raising public awareness on anthropogenic underwater noise by means of playful activities and serious games

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Anthropogenic underwater noise can seriously affect the marine environment and species. Although great progress has been made both from a normative and scientific point of view, public perception of this hazard is very limited. The Noixe project addresses precisely this gap and aims to raise collective awareness of this problem and the role each of us can play in reducing the impact on the environment. This paper describes what we have developed to raise knowledge and awareness of this issue through playful activities and serious games both in live situations and online. The Noixe events are divided into two sections: First, all the concepts needed to understand anthropogenic noise are explained using experiences that anyone can have in their lives. For example, it is possible to explain how noise can make a message contained in an acoustic signal unrecognizable, staging the case of a teacher explaining something to a noisy class. The second moment of a Noixe event is the serious game. Here, in a quiz-like environment, two teams compete against each other to guess a set of sounds that are initially masked by noise. The system we developed makes it possible to gradually reduce the volume of the noise and increase the volume of the sound until it becomes intelligible. The team that identifies more sounds wins. The online version of Noixe is built on a similar workflow but cannot offer all the features of the live events. In particular, it is very difficult to recreate collective experiences such as team games due to possible connectivity issues. This is why we opted for a single user mode. We have found that our approach is very effective in raising awareness on the topic of anthropogenic noise in both live and online settings. This is demonstrated by the fact that practically all Noixe participants decided to join citizen science activities on noise monitoring we later offered them. In this paper we present the technical details of the activities we have developed so that anyone can replicate and improve our work.

KEYWORDS

underwater anthropogenic noise, masking, serious games, playful activities, scientific literacy

1 Introduction

Light does not penetrate deep at sea due to turbidity. Other senses such as smell or taste may also be limited due to the loss of information in marine ecosystems (Popper and Hastings, 2009). Conversely, sound in water travels faster than in air and it is also less attenuated, which, in general enables it to reach long distances. In this, high frequencies are filtered out faster than low frequencies meaning that these latter can reach longer distance than the former. Sound is therefore an important sensory modality for marine species that rely heavily on it to make contact with their environment (Codarin and Picciulin, 2015) for communication, predation,

and orientation. If sound propagates well at sea, the noise generated by human activity can also travel great distances and affect the lives of marine life (Slabbekoorn et al., 2010).

The Marine Strategy Framework Directive (MSFD; Van der Graaf et al., 2012) of the European Parliament and of the Council states that noise at sea can have a negative impact on marine life (Commission Decision (EU) 2017/848, 2017) and requires Member States to take measures to prevent adverse effects on marine species. Following Popper and Hastings (2009), underwater noise is defined as sound that has a deleterious effect on the marine environment having long-term consequences for the different marine species. Effects of marine noise on marine life include behavioral responses (Thomsen et al., 2009), masking (Codarin et al., 2009; Hawkins, 2014; Vasconcelos et al., 2007), hearing loss (Popper and Hastings, 2009), and physical and physiological effects including death (Robinson et al., 2020).

A variety of sources can generate underwater noise. These sources can be natural, such as for example sea waves, rain, or earthquakes; or anthropogenic, such as ships, seismic surveys, and sonar. Recently, offshore wind farms (Mooney et al., 2020) and tidal turbines (Haxel et al., 2022) have also been considered, while merchant ships are still considered the most ubiquitous and widespread source of anthropogenic noise in the oceans (Erbe et al., 2019). Several studies relate shipping noise mainly with propeller cavitation and ship speed (Sezen et al., 2021). The International Maritime Organization (IMO) and the European Union identified strategies to reduce underwater noise. In the context of the Marine Strategy Framework Directive (MSFD), the EU adopted indicators and recommendations for a Good Environment Status (GES) in the case of underwater noise. The IMO Correspondence Group focused on ship design and construction and developed technical guidance on how to reduce noise pollution. In particular, following Leaper and Renilson (2012) changing ship design and lowering speed can reduce considerably the overall contribution of ship noise to the global ocean noise budget.

Masking is a situation that occurs when a loud sound interferes with the intelligibility of a quieter one. This can be particularly serious if the frequency spectrum of the masking sound overlaps with that of the masked sound, and in the case of marine species when the noise has a similar frequency to biologically important signals, such as for example mating calls (Erbe et al., 2019). In addition, not only communication can be at stake due to masking, but also echo-location and the detection of environmental and predator–prey sounds. Masking is a very common feature of natural communication systems, while it is not simple to model because it is defined by several factors that generally are not simple to estimate and that are related to the sender, the environment and the receiver. The sender emits a signal with a specific spectral characteristic at a given source level. The signal propagates through the environment where it is subject to physical phenomena such as attenuation, scattering and absorption that modify the signal. During the travel, the signal adds to other sounds from natural sources and to anthropogenic noises that distort the original signal. Eventually, the resultant signal is sensed as a function of the listener's auditory system.

Hearing sensitivity describes how marine species react to acoustic stimuli. This can change from species to species. Marine invertebrates, for example, lacking gas-filled cavities, respond mostly to particle motion, while other receptor systems can also be present. Cephalopods, for example, have superficial receptor systems sensitive to local water movements (Hanlon and Budelmann, 1987) and the statocyst (Solé et al., 2023) which is similar to the vertebrate inner ear (otolith). In bony fishes hearing is realized by the close relationship of the swim bladder and ear region (Tavolga et al., 2012). Marine mammals have a hearing apparatus like all other mammals. The human ear has a potential maximum frequency range of 20 Hz to 20 kHz with the best sensitivity between 500 Hz and 4 kHz, which is also the range where most of the speech occurs. We know that many animals hear sounds that are inaudible to humans such as elephants, that communicate with infrasound signals at frequencies lower than 20 Hz. Different species perceive sounds differently and in different frequency ranges (Fay, 1994). This means that a noise disturbs the single marine species or not, depending on the fact that it falls or not within their hearing frequency ranges and is compatible or not with their physiology.

1.1 Public awareness of underwater anthropogenic noise

The negative impact of anthropogenic noise is rarely borne by the actors that generate it, while it is very often a burden on society. This is mostly due to a lack of awareness of the topic by the general public. In the cases where this issue emerges, it is focused mainly on the impact it has on marine mammals, while there is less concern about fishes and invertebrates. At the same time, the public perceives underwater noise originating in maritime and inland waterway traffic as less significant in comparison to other types of pollution (Vukić et al., 2021). In fact, if in urban areas, noise pollution, such as that originating from traffic or industries, has been recognized as not only an environmental nuisance but as a threat that can damage health and reduce the nearby property value, the Maritime sector has been traditionally considered less relevant (CE Delft et al., 2019). On the contrary ship noise can endanger seafarers and passengers, affect port areas, coastal residents and, as mentioned earlier, marine fauna (Badino et al., 2012). Following Nastasi et al. (2020) noise has only recently been considered in port sustainability assessments. As a matter of fact, the impact of noise on citizens in port areas has also been underestimated; for example, in the port of Livorno, noise from arriving and departing ships has been measured to increases by 6–10 dB above existing background noise levels (Fredianelli et al., 2020). In this perspective, several international initiatives to monitor underwater noise have rapidly appeared such as, to name only a few, Jomopans (Kinneging, 2023), Soundscape (Petrizzo et al., 2023) or CORMA (Diviacco et al., 2021). These, using hydrophones, have the ambition to reconstruct a model of the sound pressure at sea in the designated area, and using sound propagation modelling, to cover large marine areas where measurements have not been carried out, to identify anomalies and hotspots and communicate this information to policy makers and the public.

The relationship between economic development and pollution has been interpreted within several paradigms (Mensah, 2019; Perman and Stern, 2003; Stern, 2004). From the Environmental Kuznets Curve (EKC; Grossman and Krueger, 1991) through the Brundtland Report (Brundtland, 1987) to the 2030 Agenda for Sustainable Development with Sustainable Development Goals (SDGs; Transforming Our World, 2015). These interpretations integrated progressively the dependance of sustainable development on income-independent, time-related factors such as for example the different behaviors of different pollutants

(John and Pecchenino, 1994; Lopez, 1994; McConnell, 1997; Selden and Song, 1995; Dasgupta et al., 2002) for example, claims that while some traditional pollutants might have an inverted U-shape EKZ curve, after an initial increase in pollution, there should be a decrease, which some scientists associate with economic growth, the new pollutants that are replacing them do not. In this perspective, noise pollution is unique in comparison with other forms of pollution since it is the only one that disappears completely and immediately when the source of pollution is shut down. From this perspective, public engagement plays a crucial role in the development of measures to reduce noise pollution in general (Khatibi et al., 2021; Ernst and van Riemsdijk, 2013; Lassen et al., 2011) and in the case of noise pollution in particular.

1.2 Learning and social participation through play

The importance of play in learning was already recognized at the times of John Locke (Androne, 2014). Following Rieber (1996) play is a very important activity in psychological, social and intellectual development, it is strongly motivating and grants learners to find participating in the activity to be rewardful without the need of external incentives. Parker and Thomsen (2019) examined a large literature on the topic highlighting that all considered papers report that playful experiences lead to deeper learning. Problems have been also identified, but they mostly lie in the social acceptance of learning through play. The importance of playing in learning can be traced back to the observation that when players first start to play a new game, they learn how it 'works' (Wagner, 2015), acquiring knowledge and awareness on the context of the game and of players previous experiences and beliefs (Friedenberg and Meier, 2017). These latter, in particular, could have been shaped previously by external factors such as for example the social media and the web, which can have a detrimental effect on public environmental awareness. Information technologies, and social media in particular, can alter people's mental attitudes from a very young age (Chen and Madni, 2023) vehiculating wrong messages. Distrust in science can be problematic for society as a whole. For example, people who do not believe in anthropogenic climate change will see no need to take political action to slow its progress (Huber et al., 2019). The relationship between learning and social engagement is therefore extremely relevant. Following Galston (2001) knowledge and education are the most important aspects to consider in this perspective. In the absence of formal education or individual life experience (Rothstein, 2003), 'incidental learning' (Tewksbury et al., 2001) can also influence one's level of social engagement.

Serious games are games that incorporate elements of serious applications, that aim to teach, to exercise and to change behaviors (Göbel et al., 2010). Serious games are known to be a powerful tool for engagement and education. They can generate collective intelligence and environmental practices faster than other existing means (Flood et al., 2018).

1.3 Objectives

The 2030 Agenda resolution extends its scope to social, economic (Transforming Our World, 2015) and environmental development in five areas of critical importance: People, Planet, Prosperity, Peace and Partnership. Within this framework, Target 4.7 promotes sustainability education, in order to "Empower people to take responsibility for present and future generations" and "actively contribute to societal transformation." With this in mind, while participating in many activities related to anthropogenic underwater noise we realized that the general public suffered from a knowledge-action gap, probably due to a lack of understanding of the topic we are addressing, and that people could be much more engaged and supportive if they were better informed about this issue. With this in mind, we decided to launch a specific outreach initiative (the Noixe Project) to raise awareness of anthropogenic underwater noise.

Since the beginning of the initiative, we were faced with the problem of understanding how this can be put into practice and answering research questions such as:

Are top-down science outreach initiatives appropriate to enable people to participate in building new knowledge and raise awareness of anthropogenic underwater noise, or would it be better to consider other means to reach the general public? And in the second case, can playful activities and serious games be more effective, especially among the new generations? (RQ1).

Are there differences that need to be taken into account when addressing different age groups or motivation levels of participants, or can we develop a one-size-fits-all tool? (RQ2) Can such initiative be hosted on the internet? And how? And what do we potentially risk losing? (RQ3).

2 Methods

Within the Noixe project, we tested different approaches, from simple playful activities to more complex serious games with the aim of explaining the following sequence of concepts: (i) *communication*, (ii) *noise*, and (iii) *masking*, which are necessary to understand anthropogenic underwater noise. In doing so, we strived to give participants the opportunity to experience physical phenomena, mechanisms, and effects and to recognize their own role and relationship to them.

After a variety of trials and experiences, the final design of the project's public events was based on selecting the most effective, but also the simplest activity that would allow participants to understand each concept.

2.1 Playful activities to understand the concept of communication

The first and fundamental concept to explain is: what the term *communication* actually means. The Shannon–Weaver model (Shannon, 1948) describes how communication takes place in terms of five basic components: a source, a transmitter, a channel/medium, a receiver, and a destination.

To translate these concepts into something that participants of any age can understand we tested the popular children's game *Chinese whispers*. Its name in other languages such as French (*téléphone sans fil*) or Italian (*telefono senza fili*), besides the fact of being naively anachronistic (meaning wireless telephone) connotates better what we want to convey.

Before the game begins, all the terminology (e.g., what a source is) is briefly introduced. The participants are then divided into two teams and placed one behind the other in two rows. The first participant in each team's row is given a message to whisper in the ear of the next participant in the row. Each team receives a different message. When all participants have passed on the message, the last team member in the row finally tells the audience what he/she has received. The comparison with the original message inevitably leads to amusement for everyone. At the end of each experience, the concepts are summarized again and the participants are randomly asked a few questions to check whether they have understood them correctly.

2.2 Playful activities to understand the concept of noise

Once all the terminology has been grasped, it is possible to introduce the concept of noise as a disturbance in communication that renders the message unintelligible. In this we tested a role play where a message must be dispatched in a classroom from the teacher (source) to a couple of volunteers (receivers) while the rest of the participants, positioned in between, are encouraged to produce as much noise as possible. This set up is very familiar to most school classes and teachers, but we must say that, so far, we have never encountered any group of people (of any age) that was not enthusiastic about being free to shout, clap and/or stomp. When the playful activity is offered to primary schools, once the concept of how much a disturbance can obliterate the message is acknowledged, we noted also a general realization by students of how hard the work of teachers can be; something that can be a goal in itself. Also in this case we found very useful, at the end of the activity, to summarize what noise is and check with the audience that the concept was fully understood.

In our experience, these games are very effective in explaining the mechanisms of communication and noise. There has never been a need to resort to more complex methods, so they have been adopted as an introductory part of the Noixe events, following the principle of being as simple as possible.

2.3 Masking and perception

While the playful activities explained above are very effective in explaining what communication and noise are, in our experience it proved more difficult to explain a more complex concept such as masking using only this approach. As mentioned above the phenomenon of masking consists in the difficulty to hear a sound where a noise overlays it. From a perception point of view this can be a very complex phenomenon. Human beings have specific psychoacoustic mechanisms that allow them to 'unmask' hidden sounds. An example of this is the so called "cocktail-party effect" (Cherry, 1953), which is the ability of listeners to select the target speech while ignoring other ambient sounds. Recent research discovered that this ability is mostly due to binaural hearing (Bronkhorst, 2015). In fact, the 'shadow' effect that the head exerts allows the brain to calculate the difference between what arrives at the different ears providing a clue on what the actual message could be (Lingner et al., 2016). At sea this is very difficult to take place since the speed of sound is five times faster than in the air and that the shadow effect is minimal considering that the density of marine species bodies is similar to that of water. These factors reduce binaural detection (McFadden and Pasanen, 1978). Directionality is perceived by those few marine species that are equipped with specific sensory organs.

2.4 Experiencing masking in a serious game

To let participants experience the phenomenon of masking we decided to develop and test a serious game where the phenomenon is replicated in a controlled environment and where it is possible to interactively hear and combine sounds and noises. Cagiltay et al. (2015) maintain that, leveraging on competition, participants can be highly concentrated and motivated to take part in the learning activities. Considering this and the fact that the experiences with the above-described introductory playful activities were very positive, we decided to focus on a quiz-like set up, where participants are gathered in two teams: in our implementation the 'blue team' and the 'red team'.

The aim of the game is to identify sounds that are covered by noises. The team that identifies the most sounds before the opposing team wins.

At the beginning of the game, a leader is appointed for each team, who is responsible for collecting suggestions and responding on behalf of their team.

The workflow consists of a loop of an odd number of rounds in which an acoustic signal is emitted to all participants via a loudspeaker. At the beginning of each round, a different noise and sound is uploaded in the system (Figure 1), with the noise set to 100% level and the sound set to 0% level. This makes it impossible to identify the sound at the beginning of the round. We use only easily identifiable sounds from everyone's everyday experience, such as a dog barking, a bird chirping or a musical instrument playing.

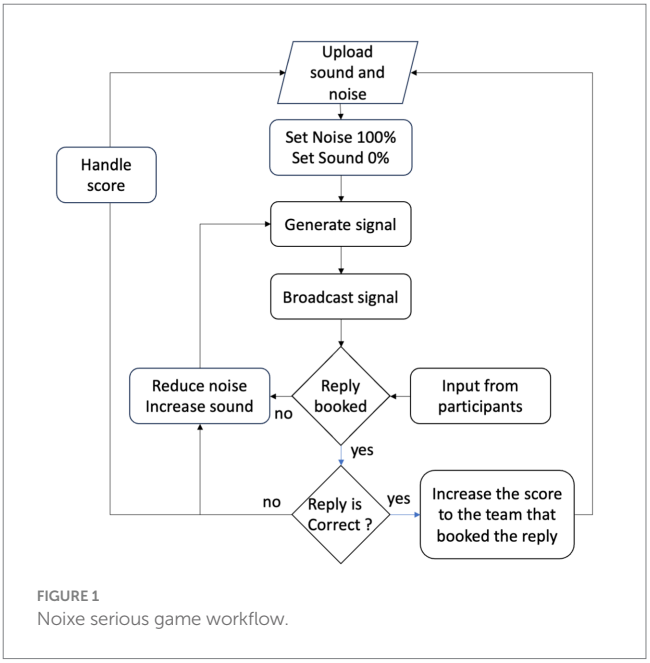

FIGURE 1
Noixe serious game workflow.

During each round, while the participants are still trying to figure out which sound it is, the balance between sound and noise in the emitted signal is slowly changed by increasing the sound level and decreasing the noise level.

This process creates a general tension that excites the participants. As soon as the noise becomes audible, the participants in each team begin to discuss the possible solution. At the same time, they have to make sure that the other team does not overhear their discussion, which creates a sense of belonging to the team and further motivates the game participants.

Once the team has agreed on a possible answer, the team leader books the answer pressing a quiz button and then proposes the solution. If the answer is correct, the team receives a point, and the game can move on to the next round.

Once all the rounds have been done, the winning team is appointed and presented with a reward which generally consists of a gadget.

3 Materials and equipment

To let players experience the masking effect in a standard outreach environment such as classrooms, gazebos, or open-air events, and exclude binaural detection one single monophonic acoustic source is positioned frontally to the participants. Headphones can also be used to send exactly the same signal to each headphone side, but we preferred a small public address (PA) system. In fact, using a PA system all participants are simultaneously involved in the activities and interact among them, while headphones would isolate them from the environment and the other participants. In addition, we wanted to be sure that the sound pressure within the headphones cannot, in any way, damage the ears of the participants. Possible (although only remotely) mistakes in devices connections or glitches in the recordings could trigger theoretically unpleasant effects. This, of course, can happen also with a PA system, but in that case, the sound pressure will be dispersed in a larger area and not directed only into participant's ears (Figure 2).

Throughout each round, while teams are still trying to figure out what is the hidden sound, the balance of sound and noise in the signal that is output from the PA system is varied using an external device we call the 'ship's wheel' (Figure 3). Turning the wheel, the level of noise can be decreased and concurrently the level of sound can be increased.

In order to avoid team leaders pressing the quiz button by mistake or out of time, we introduced a security lock on the quiz button. This needs to be reset at the end of each round but allows to avoid endless and vibrant discussions on the possibility that the system did not react properly.

Participants can see which team can answer looking at a large monitor where a circle appears with the corresponding color (red or blue). Similarly the operator can see which team has booked the answer on a large colored led near the 'ship's wheel' (Figure 4).

3.1 Technology

The game was implemented using a PC, connected to a large display and to a PA system. An external box hosts an Arduino board and some dedicated electronic circuitry. The box was made by means of laser cutting techniques and hosts a big flashing light that changes its color (using RGB controllable Leds) to that of the team that booked the reply. The box hosts also the connections of the two big quiz buttons, one for each team and the 3D printed 'ship's wheel'. This controls a potentiometer, connected to an analog input pin. The push buttons (quiz buttons and reset button) are simply connected to ground and to digital inputs, in pull-up mode. The RGB Led is an addressable model WS2812B, controlled with the open library FastLED.h.

The Arduino board collects the input from the wheel and the buttons; controls the RGB Led and sends and receives commands

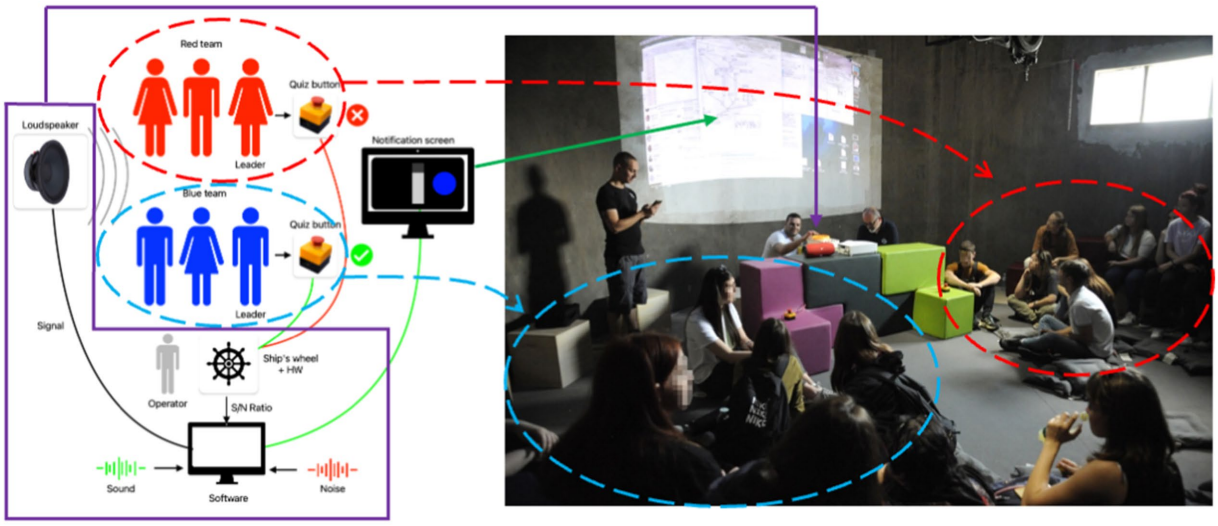

FIGURE 2
Noixe serious game schema and event example (Photo, courtesy of the Center for the Promotion of Science, Belgrade, Republic of Serbia).

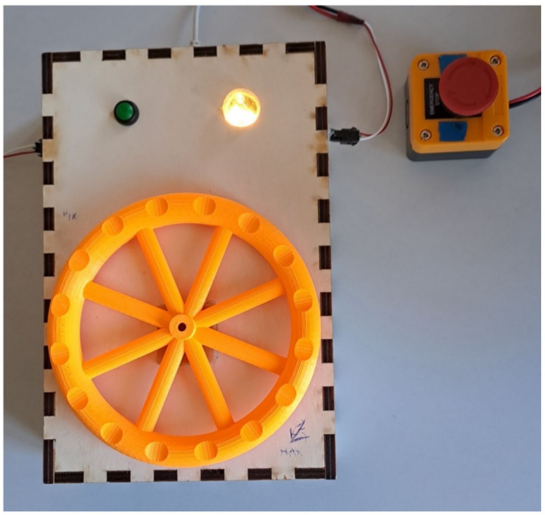

FIGURE 3
Close-up of what we call the 'ship's wheel' device (left). Turning the ship's wheel the operator changes the balance between noise and sound allowing the sound to be progressively intelligible. On right of the image, it is possible to see a close up of the quiz button that allows the team leader to book the answer and exclude the other team.

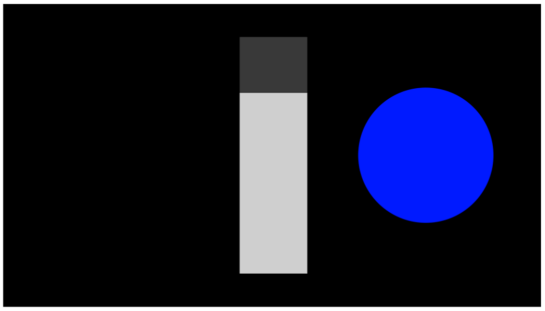

FIGURE 4
A well visible screen shows a vertical bar indicating the balance between noise (grey) and sound (white). When one of the teams books the answer, the screen notifies with its corresponding color who is entitled to answer.

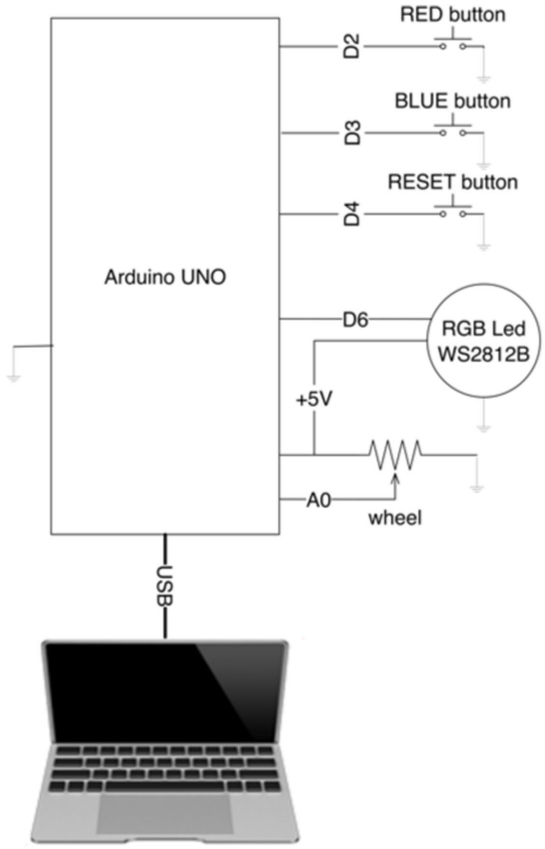

FIGURE 5
Noixe serious game electric scheme.

through the USB serial link. In Figure 5 it is possible to see the electrical diagram.

The Arduino software is based on a state machine algorithm. It starts in "LOCK" state, waiting for the wheel to reset. When the wheel is in the initial position (full noise), the system switches to "READY" state. Here the volume level is read and sent through the USB as a text message "Vn," where n goes from 0 to 100.

If one team presses the red or the blue button, the system enters a "RED" or "BLUE" state, sending a text message "R" or "B." When the round is over and a new sound sample has been loaded, pressing the green reset button the system switches back to the initial state and sends a message "X."

On the PC side, we developed a specific software using Processing (a graphic environment based on Java) that receives text commands through the USB cable and displays on an external monitor the levels of noise and signal as a crossfade bar. When a team presses a quiz button, the software notifies which was the quickest team playing a sound, changing accordingly (blue or red) the color of a large circle in the external monitor for the participants, and the LED in the wooden box for the operator (Figure 6).

The technology described so far does not address the actual interactive sound generation, which is demanded to another software developed using Pure Data (PD). PD is an open-source visual programming language for multimedia. Hardware, Processing and PD scripts are linked through Musical Instrument Digital Interface (MIDI) connectivity. MIDI is a standard to transmit and store musical information such as musical notes, timings and pitch information.

PD scripts are commands that can be translated to a visual environment where they are shown as a workflow. There, each variable is expressed in its numerical form or as a graph (Figure 7). When one of the PD script developed within the Noixe project is launched, a hidden sound is uploaded in a slot and its level is set to zero (Figure 7 marker 1), while a noise, set to maximum level, can be uploaded either as a sound, or in the case of white noise can be generated directly within using the ~noise PD object (Figure 7 marker 1). Once sounds are uploaded the PD script listens for MIDI messages sent from the Processing software that receives commands from the Ship's wheel on the Hardware box. When the operator turns the ship's wheel the balance between sound and noise is changed in order that the sound becomes more intelligible. When the leader of one of the teams presses

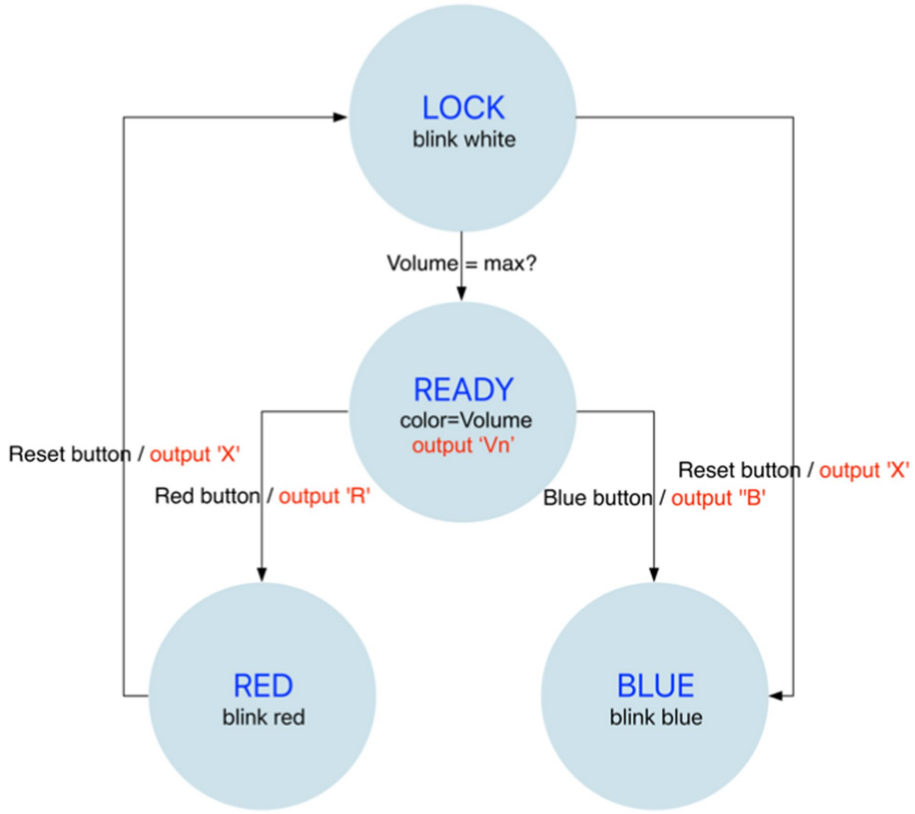

FIGURE 6
Noixe serious game status scheme.

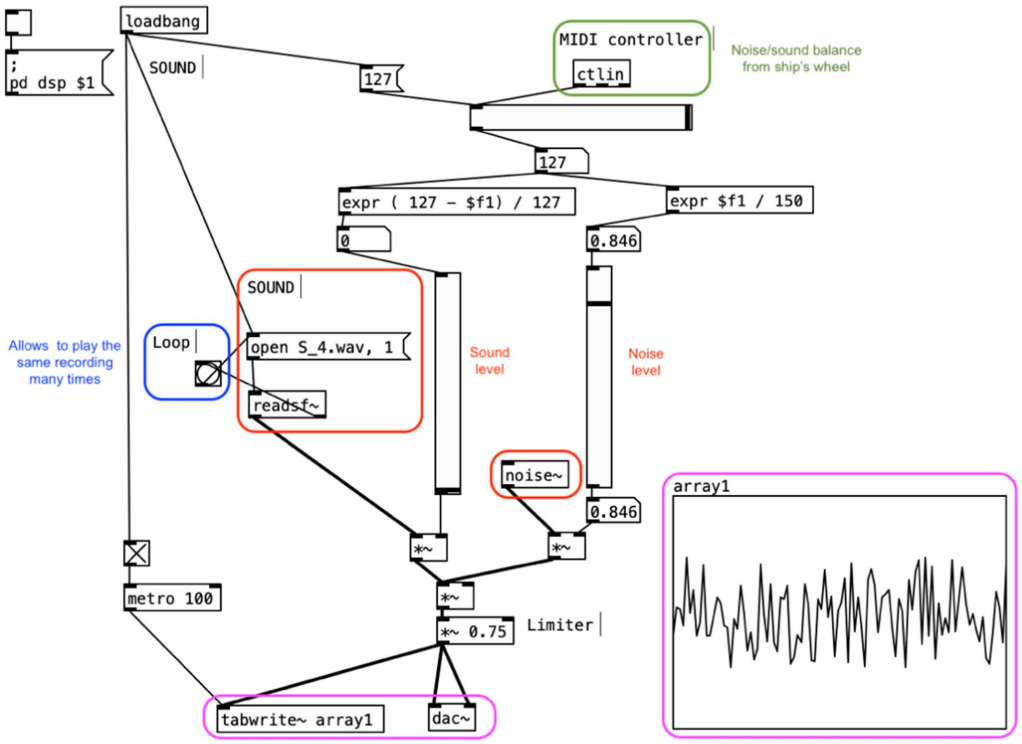

FIGURE 7
Pure data (PD) script that generates interactively the output waveform (purple boxes), mixing the masking noise and the hidden sound (red box) played indefinitely (blue box), upon a balance value provided by the external hardware (green box).

the quiz button, every part of the system gets frozen, until the answer is given.

3.2 Web based version of the game

During the SARS-CoV-2 pandemics, playful activities such as that described above were almost impossible to organize. In the area where our team locates most of its initiatives (Italy) the government opted to follow a mitigation strategy that involved policy actions based on "social distancing," including a full society "lock-down," and restrictions on freedoms of movement and meeting. In order to continue with the outreach and sensibilization activities on the topic of underwater anthropogenic noise we developed a web-based version of our playful activity that can be accessed at the following URL: https://noixe.ogs.it.

The web portal of the initiative proposes an initial introductory video where all the concepts are explained. The video is an excerpt from the frontal lesson we present at the beginning of every Noixe event. A presenter explains some basic concepts to understand the issue of underwater anthropogenic noise pollution making use of several animations and images. After the user is acquainted with the concepts proposed in the video, the portal allow the user to run the web-based game.

While devising this new approach to the playful activities, we had to consider several limitations of the media in comparison with the live setup version. One of the main problems was related to the possibility of having truly synchronic interactivity among multiple participants. Internet connectivity is not fully available everywhere and differences in its access might generate a digital divide due to income and opportunity inequalities for disadvantaged groups of people. This suggested opting for a single user asynchronous game where no time lag can compromise the game experience.

The schema of the game is the same as in the case of the live setup. At the beginning of each round a noise completely covers a sound. Clicking on a button the noise is reduced and the sound increased. While this happens, also the score the user gets from answering correctly is reduced. The less the noise is reduced the higher the score per round. Eventually the user is provided with a final score that can be confronted with fellow friends and school mates. The web version was developed in JavaScript and embedded in the web site of the Noixe project.

4 Results

The Noixe project has been running since 2018. During this time we have had the opportunity to meet more than a thousand participants of different ages, the vast majority of whom were students from primary, middle and high schools. Most of our live events took place in the city of Trieste, where our research institute is based, as part of science fairs such as the EuroScience Open Forum 2020, the European Citizen Science Association 2020 or the annual TSNext event. We also regularly take part in open days at many schools. In 2022, we were invited by the Center for the Promotion of Science of the Republic of Serbia to hold several Noixe events in Belgrade during the Month of Mathematics science fair. These events were attended by a large number of school classes from all over Serbia. At the same time, several online events were organized under the auspices of the Italian Ministry of Education to introduce the web-based version of Noixe to schools throughout Italy. These opportunities were very important to test the design of the outreach events, understand the impact on the audience, observe what was missing and improve the workflow.

4.1 Focusing the approach

At the very beginning of the project, the outreach activities were formatted as standard frontal lessons lasting approximately 20 min each. The presentations were held with the aid of standard projection slides, which reported on the current state of scientific research on this topic. We observed a general interest by the audience probably due to the fact that the topic is on average new and in the case of some school classes, due to the expectations grown thanks to the previous introduction and contextualization done by schoolteachers. If that format was appropriate, although not particularly exciting, for adults or high school students, we soon realized that, notwithstanding the efforts in being simple and 'catchy', it was very difficult to attract the attention of the younger participants. This was particularly evident in science fairs, where too many stimuli distract the participants and make it difficult to concentrate, sometimes even for the presenter. A new interactive approach was needed, where participants were to be captivated by an activity and motivated by the relationship with other participants.

4.1.1 Different concepts to explain need different approaches

Having well in mind the power of games as a learning tool, we then tried a first intrusion into the territory of fun, organizing a series of playful activities that could be associated to the theme we were handling. As mentioned above, these activities use the familiar children's games Chinese whispers and a role-play game that mimic a classroom, reinterpreted to explain concepts such as communication and noise. In our experience, these games were very effective in linking something we all experienced in our youth, to a scientific explanation of a phenomenon.

On the contrary, we have found that the phenomenon of masking is very difficult to explain using playful activities, such as those mentioned above, only. After some unproductive experiences, we then decided to test a more structured approach based on the computer supported serious game described in the materials and methods section. There, participants are motivated by competition in a quiz-like environment and an operator/game leader controls the noise and sound balance and steers the game.

4.1.2 The role of participants' age

The reactions to the serious game have been always enthusiastic except for the cases of some high school classes. We have found, as a matter of fact, that students in this age group often think that learning through play is only for children. If not considered, this can drive to annoying situations where many can be distracted or even bother the rest of the group. On the contrary, if this problem is taken into account, we have found that the attitude generally changes very quickly as the game progresses and by the third or fourth round of the game, the fun wins out over the reputational concerns. To address these cases and other difficulties in steering the events, we realized that

essentially two strategies can be adopted, and namely (i) tuning the score mechanism and (ii) adding further and deeper technical explanations on the phenomenon of masking.

4.1.3 Score handling to improve participants motivation

As we mentioned before, the rules of the game provide that the team that identifies the sound first is awarded one point, but what happens when the answer is wrong? There are actually several possible rules that can be used. In this it is important to underline that how to score wrong answers needs to be decided and described to the participants since the very beginning of the game otherwise their reactions during the game can be unpredictable.

After some experiences in submitting the serious game, we realized that score handling can be used to improve the motivation of participants.

The easiest way to handle mistakes is to simply overlook them while remaining in the same round and continue to rotate the ship's wheel in order to reveal more sound while lowering the noise. We found that this approach works well with motivated participants, when the game is very satisfying for everyone.

In some cases, when it becomes evident that participants are not able to identify a specific sounds or when they risk to lose the tension, it is necessary to move quickly the quiz to the next round, switching to a different sound/noise couple without awarding any point to the teams. This decision must be taken by who is in charge of managing the event and can be based only on personal sensibility and common sense. This approach has the disadvantage that the game can end too early. To mitigate this problem, we always keep a few spare sound/noise pairs ready, in order to increase the number of rounds.

In the not-so-rare case of individuals disrupting the rest of the team, or participants simply trying to answer randomly, we found very useful a protocol where a mistake, not only results in the team not being awarded a point, but rather a point being deducted from the team score. In this case, the other members of the team usually reprimand the recalcitrant member, and the game, in most cases, continues smoothly. This can be the case of high school students not yet captivated by the game. In order to let participants feel more comfortable, we found very useful, in these cases, to insert into the game flow, mostly at its beginning, additional stopovers that allow to delve into specific scientific topics with a detail that could match the skills of that age group. This focusses their attention especially when direct questions are posed to them.

We found that a consolation prize is always to be prepared in advance especially with very young participants, in order to relieve frustration of the losing team. In addition, we also found very useful to have quick explanations of each concept before and after each activity and ask few basic questions to the audience. These questions allow to understand what all participants have learned and if the message behind the activities arrived and has been internalized. These moments can be used by the losing team also to show off and recover from any possible regret before leaving the event.

4.2 Types of masking sounds

One topic we have researched thoroughly is the question of what kind of masking sounds could be used in the serious game.

In the first four rounds of the game, we use white or pink noise as the masking sound. White noise is a random signal with the same intensity at each frequency. Pink noise is also a random signal where instead the energy at each frequency falls off at roughly 3 dB per octave. The choice depends on the acoustics of the venue. Indoors we usually use white noise, outdoors pink noise is generally preferred.

In the following rounds, we replace random noises with anthropogenic noises. This is a very interesting field to explore since human capacity of identifying hidden sounds covered by such type of well known noises often reserve amazing surprises. We have experienced extensively with sound recordings of household appliances such as vacuum cleaners, washing machines or hair dryers with excellent results, but focusing on anthropogenic underwater noise, we found it very helpful to use some recordings of ship engines of different sizes. Engine size is important because it determines the spectral extension and shape of the produced sound. This means that different engines mask other sounds differently and this can be used to explain the different impact masking can have on different marine species.

Also in this case, while choosing the sound and noise set, we must consider carefully the ability of our hearing system to unmask sounds leveraging brain's ability to dynamically rewire itself anatomically and neurochemically upon incoming information (Attarha et al., 2018). Following Vassie and Richardson (2017), masking, in certain cases, allows even to focus on a sound or exclude it from a background, or to improve our concentration, task performance and attitudes.

4.3 Measuring participation and impact

Throughout the development of the Noixe project, we endeavored to find methods to measure the willingness to participate in the activities on the one hand, and the impact of the initiative on the participants on the other. In the first case, this could have helped us to choose the approach that better fits the needs of the different target groups, in the second case it could have helped us to understand whether our efforts can be effective in improving awareness of anthropogenic noise.

Given the many factors that influence participant attention, it was extremely difficult for us to develop a quantitative method to measure participation. Live events for school classes are subject to external social dynamics that are introduced into the event and that can strongly influence the course of the activities. Other factors such as the context in which the events take place, e.g., science fair, classroom or open space, can also influence participant attention. We tried several times to present questionnaires to participants, but they were regularly disregarded, even when the audience seemed enthusiastic.

When we started working on the web-based version of the game, on the one hand we were very concerned that we might lose the attention of online participants, but at the same time we were more optimistic that we could find a metric for participation and attention given the fact that a software would be used. The online events, similarly to the live events, are based on an introductory part where the concepts are explained. Once this part is completed, participants can start playing the online version of the game. As a first attempt at a metric, we wanted to compare the number of participants in the introductory online events with the number of those that later played the online game. Unfortunately, this was difficult to implement in

practice, as it was not possible to determine the number of participants in the introductory events, since participants were not logged as individuals, but as groups, classes or even schools. A second metric we attempted was to record the number of users who reached the end of the game. Since the rounds are sequential and participants are forced to go through all rounds, reaching the end of the game can give an indication of the acceptability of the method and the success of its web implementation. To our relief, we found that all web participants reached the end of the game. Another approach we tried to implement was based on the possibility offered by the web version of the serious game to skip a round if the noise and sound pair was too difficult to guess. We thought of measuring the average time taken to move from round to round. We soon realized that this was not useful, as people's habits and attention are very difficult to categorize, especially during lockdowns, so this metric cannot be representative of attitudes towards the game in this case. The only option was to ask the participants directly about their experiences with small talks. All the answers we received were very encouraging, although of course it was not only an unstructured and qualitative evaluation, but also a very incomplete one that might have been distorted also by our presence.

To address these limitations, we took a different approach and invited Noixe participants to take part in further voluntary activities related to anthropogenic noise. Voluntary participation in these additional activities could be a measure of their involvement and of the effectiveness of Noixe. These activities essentially consist of measuring anthropogenic noise in urban areas with a cell phone app we developed. Although this is not strictly about underwater noise, the concepts behind it and the awareness-raising process for these issues are the same. After all Noixe events, both live and online, we asked participants to download the app and take measurements in their areas. We received always a very lively response and a very large database of measurements was collected. In particular at the events in Serbia almost 15.000 values were received. These data will soon be the subject of further publications. Even if this cannot yet be regarded as a quantitative measure of the impact of Noixe, it is very encouraging.

5 Discussion

We are confident that our work has answered most of the research questions posed at the beginning of our project. In relation to research question 1 (RQ1), we found that top-down science education initiatives aimed at increasing awareness and knowledge of anthropogenic underwater noise can be effective, but only in the case of adults who are already motivated to participate. In contrast, playful activities and serious games almost always prove to be very effective, although we also found that these events cannot be based on a one-size-fits-all approach, which is in line with other previous experiences, such as (Mylonas et al., 2023). In fact, each concept that needs to be explained may have different requirements for the process that allows participants to experience and internalize it. For example, we found that explaining the concepts of communication and the disturbance of communication can be done using simple playful activities, in our case, children's games such a 'Chinese whisper' or the role play of a teacher trying to reach a listener while others are shouting. However, we found that is not easy to explain more complex concepts, such as masking, using playful activities only. This can be due to the need of controlling with precision how the change in a parameter is experienced by participants (in our case the balance between sound and a masking noise). Since it is very difficult to control how voluntaries can produce noises with real sources such as their voices, we found more convenient to generate synthetically the masking effect using a PC controlled audio device embedded in a structured serious game such as that described above.

In relation to RQ2, we found that each event where the topic is proposed can have its peculiarities that suggest sometimes specific revisions to the design of the outreach activities in order to attract the attention of all participants. In particular we noticed that a crucial element in this sense is the participants' age, e.g., primary school students have a different knowledge level and developmental stage than high school students. Solutions that involve formal operational skills would exclude younger participant but at the same time solutions based on a concrete operational approach only would induce reputational concerns in high school students that will think they do not 'look' grown-up enough. On the other side of the age range, we noticed no decline in the engagement in playful activities for learning for adults, which is in line with similar experiences such as for example Greipl et al. (2019). In this perspective, several studies found positive impacts of playful activities for learning and even on well-being in the elderly (Nguyen et al., 2017). In our experience, in fact, all adult participants were extremely keen to participate to all the activities, either if they were, teachers, relatives to young participants, or simply alone. We have found that it is convenient to introduce a reference person to facilitate activities, this is extremely important to explain scientific concepts, but also to motivate the participants, defuse conflicts and possibly involve the teachers.

Considering all this, and in relation to RQ3, we found that although very difficult to assess quantitatively, we always received positive feedback from participants. All participants in the online version completed all rounds, even if they sometimes skipped some rounds that were too difficult to attempt. In general their willingness to participate to further citizen science initiatives collecting large amounts of data can reassure regarding the effectiveness of the approach we used.

6 Conclusions and future work

This work confirms that playful activities and serious games can be very effective in raising awareness and knowledge in the public to the issue of anthropogenic underwater noise. At the same time, we found that simpler concepts such as communication and noise can be easily addressed in role-playing or customized games, while more complex concepts such as masking require a more controlled environment. The difficulty of understanding this concept depends largely on the age and background of the participants. While this may seem to suggest that the approach to reaching participants needs to be differentiated, we have found that a serious game based on a competitive quiz can strongly engage and motivate participants of all ages and backgrounds.

Building on the experience gained and in order to increase the number of participants engaging with the issue of anthropogenic underwater noise, we would first like to improve the web-based application we have developed. Better connectivity and new technologies will improve the interactivity of online games so that it

will be possible to move from an asynchronous to a synchronous experience where it will be possible to better utilize team dynamics and motivation. At the same time, we plan to develop a Noixe Serious Game Kit that can be easily replicated and used independently by any school or educational institution.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained for the publication of any identifiable images and/or data.

Author contributions

PD: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. MI: Conceptualization, Methodology, Resources, Software, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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