Sonifying motor skills with PIZZICATO, a game for motor behavior research

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***Abstract*—Learning motor skills is essential to many different aspects of life, from big movements needed for sports to small and simple movements used in the rehabilitation of stroke patients. In recent years, sonification, i.e. using sounds as feedback for actions, has been researched as a promising technique for studying motor behavior. In particular, we explore how to use sonification to make the process of learning motor skills accessible and engaging. We posit that an interactive and gamified environment can increase the engagement in that process. Moreover, an enjoyable setting is more likely to stimulate repetition, an indispensable feature of any learning endeavor. We, therefore, designed and developed PIZZICATO, a rhythm-based serious game that leads players to move their arms and hands to actively play music. The game uses a common webcam to track your hand movements: pinching one finger to the thumb at the right position and moment will play musical notes that pleasantly add up to a full musical track. Our player tests have shown that players find PIZZICATO accessible and engaging, and report that playing the game gives them a strong sense of agency. PIZZICATO was developed in collaboration with neuropsychology colleagues, who are now starting to use it as a flexible tool for motor behavior research, both for diagnostic and rehabilitation purposes.**

***Index Terms*—serious game, sonification, motor skills, motor behavior, rehabilitation**

I. INTRODUCTION

In most aspects of our lives, *motor skills* allow us to perform tasks that require voluntary control over movements of our joints and body segments. While using these motor skills might be intuitive and effortless to many people, there are situations where considerable effort is required. Relevant examples range from simple movements, like those used in motor rehabilitation, to complex movements, such as those used in sports. In all of those situations, finding methods to aid in rehabilitation and the motor learning process can make a significant difference. The use of sonification, here understood as the use of sounds as feedback for specific actions, has shown promising results in recent years, improving the process of learning motor skills [1]. However, it is still unclear how sonification influences this process. So far, research linking sonification and motor skills has not focused on making it accessible to the broader public.

During a rehabilitation process, motor learning is mostly achieved through extensive repetition of motions. This can be tedious and discouraging, thus compromising the effectiveness of the process. On the other hand, if properly motivated, challenged, and engaged, we can practice the same actions repeatedly for longer periods, without a sense of monotony. This is precisely what happens when playing games.

We posit that a serious game, carefully combining entertainment and learning, could provide an engaging and accessible way to stimulate and improve the motor learning process. Moreover, such a digital game could also provide an excellent framework to collect extensive player data, invaluable to further investigate to which extent that process is impacted by sonification. The research question we approach is thus: *How can a serious game provide an accessible and engaging way to analyze the impact of sonification on learning motor skills?*

To answer this, we designed and developed PIZZICATO, a serious game centred around rhythm. It gently leads the player to produce musical notes by moving their hands and fingers. For this, the game uses a standard webcam that identifies and tracks the position and movements of the player's fingers in the air. This low-threshold interface enables the player to give input via gestures, which is much simpler, more natural, and more intuitive than using a traditional controller or mouse. Moreover, the game tracks extensive data on the player's performance, which enables researchers to study and evaluate the effects of sonification on the learning process.

II. RELATED WORK

This section highlights three relevant aspects of previous research: (i) how sonification affects player behaviour, motivating the importance and relevance of studying sonification; (ii) the lack of accessible methods to study the effect of sonification on learning motor skills; and (iii) features and limitations of existing serious games using sonification.

A. Sonification research

Research on the role of auditory feedback in perceptual-motor processes has been gaining traction over the past decades. A literary review by Schaffert *et al.* looked at the interaction between sound and movement and concluded that auditory feedback has a profound influence on motor performance [2]. Such research has led to the integration of

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sound in rehabilitation and sports settings to improve motor performance.

Two different approaches have experimented with using audio to support a person's movements in a variety of tasks: sonification and synchronization. In the former approach, sounds are played when the person's actions are identified, while in the latter approach, the person adjusts the timing of their actions to match the timing of the sounds being played. Previous research on synchronization has not shown it to affect the behavioural performance of motor skills in people [3].

In contrast, more positive research results have been achieved with sonification. A study done by Peyre *et al.* [4] showed that sonification can improve temporal execution within a single session. This study was proposed for rehabilitation in upper limb movement. There is a difference, however, between better performance and a higher learning rate. While people may perform better with sonification, this does not prove that there is a permanent effect on the performance when the sonification is no longer present.

In a study on the effect of concurrent feedback during novel tasks, Dyer *et al.* [5] found that properly structured auditory feedback may not be subject to the *guidance effect*, which predicts that performance improves while accompanied by feedback, but is affected negatively when feedback is left out. It was noted that when participants got used to sonification, they still performed well in an immediate retention test without feedback. This indicates that sonification can help overcome the guidance effect, which can plague other forms of feedback during learning.

Sonification has been applied in many forms. A study by Dyer *et al.* [1] discusses whether the melodic aspect of sound information improves performance when learning a complex bi-manual coordination skill, or rhythmic sound information is already sufficient for optimal sonification. The study discusses three groups: one control group with no auditory information, one with purely rhythmic percussive sonification, and one where each movement triggers a separate note of a melody. The results show that the melodic sonification group performed best in task acquisition and immediate retention. Furthermore, playing back the original melody for a brief time was able to reverse the decline in performance for the melodic sonification group after a 24-hour retention phase. Therefore, the study concluded that melodic sonification of movement can be highly beneficial to task acquisition.

Zatorre *et al.* [6] compared pleasurable music with neutral music and found that with a strong emotional response comes a bigger dopamine release. Furthermore, they theorized about how the brain functions when predicting music and found that the brain has mechanisms of reward associated with making a prediction and then having it confirmed to be correct.

B. Method setup complexity

Research on sonification has often used sophisticated methods, which raises concerns regarding accessibility. In an article written by Bevilacqua *et al.* [7], research is done on movement sonification for sensory-motor learning. They discuss sound- and movement-oriented tasks and summarize research setups that have been proposed to study these tasks. From the literature, it appears there are many different setups to research the effects of sonification on movement. However, they usually require either custom-made or specialized hardware and software. An example of this is the study by Dyer *et al.* [1], with its setup requiring a custom-made plank with carvings, custom-made gloves, a motion tracking system, and a separate software program to process the motion data.

C. Sonification serious games

There have been numerous games that use rhythm to aid the player in various ways [8]. Few of them, however, were expressly designed for scientific research purposes, and the vast majority of the games omit e.g. keeping track of player data and/or displaying sufficient performance measures. Moreover, those games also tend to use more constrained movements, such as tapping a finger on a screen or button.

A few serious games exist that specifically focus on sonification. Some of them aim at helping visually impaired people rather than aiding people with motor skills. For example, Berge *et al.* [9] extensively apply sonification in their audio-based version of a Pinball game, aimed at visually impaired people. To convey different game actions and mechanics, they employ techniques such as shifting pitches and varying volumes, while combining moving audio sources with HRTF-based sound spatialization. Radecki *et al.* [10] propose a way of converting images into sounds to support the understanding of the image, aimed at blind children. They integrated their sonification algorithm into two games: one game tests the ability to recognize shapes, the other tests the ability to track a point as it moves across the screen.

An example of a serious game that does propose the use of sonification in connection to motor skill learning is that developed by Volta *et al.* [11]. The game, aimed at teaching math to children, uses both visual and auditory modalities. It supports both single-player and collaborative movement challenges, to teach children angles and positions. A *Kinect* sensor is used to register the position and movement of players.

III. Game Design

Based on the state of the art presented in Section II, we conclude that, to the best of our knowledge, there is thus far no accessible serious game designed to investigate the effect of sonification on learning motor skills. We, therefore, set out to design and develop an accessible and engaging game for this purpose. This section lays out the principles we identified for its design, and the main design decisions taken to accomplish that goal, which resulted in the game PIZZICATO, presented here.

A. Core principles

In line with the research question expressed in Section I, the following four core principles were identified and kept central throughout our game design process:

- **Player Agency**: sound should be deployed as feedback for the player, ensuring that the game uses sonification rather than synchronization.
- **Accessibility**: the game should be playable by anyone at home, without the help of a third party or custom hardware.
- **Engagement**: players should stay engaged even after performing the same movement multiple times.
- **Measurability**: the game should collect data that makes it possible to analyze how sonification affects the learning process.

B. Game synopsis

PIZZICATO is a rhythm game in which each level consists of music, visually accompanied by a sequence of nodes on the screen. The players' input is captured by tracking their hand movements. They can pop a node by hovering their hand over it and pinching individual fingers together with their thumb. When a node is pinched, a corresponding sound is played. Each finger has an associated color: the color of a node indicates which finger pinch should be used to pop that node. At the start of a level, players get only a simple rhythm as a background track but, as they progress, this slowly builds up to a complete song. The result is a gameplay loop where the player 'creates' music by pinching emerging nodes at the correct time and in the correct order.

C. Core mechanics

We introduce three types of game mechanics used in PIZZICATO: its gesture input, the consequent sonification, and other types of feedback.

1) Gesture input

PIZZICATO tracks the gestures of a player's hand by means of a common webcam. Such cameras are ubiquitous, which makes it much more accessible as compared to previous research. Using this input sensor we can recognize hand and fine finger movements, giving the game-level designer large freedom to choose what type of motor skills to require from the player.

2) Sonification

An important game design decision regards discrete versus continuous forms of sonification. Continuous sonification presents multiple challenges which make it less optimal for a game. Firstly, it has to work with low enough latency to maintain player agency. Secondly, it needs to create a continuous sound that gives sufficient feedback to players without annoying or frustrating them. Its sound would need to be varied enough to keep players engaged for a long time, while also capable of adapting to varying motor skills. Ultimately, since researching sonification does not require it to be continuous, we chose to keep the focus on discrete sonification.

Sonification in PIZZICATO comes from the sounds that are played whenever the player pops a node. Importantly, the sound is played regardless of whether the player pinched the node at the correct moment or not. In other words, if sounds were only played when players are correct, it would no longer be sonification. The dissonance between a poorly-timed sound played and the background track is in itself a form of negative feedback. Since the player should be encouraged to make specific movements in a timely manner, the nodes sequentially appear on the screen in a particular location. This streamlining adds a gentle constraint on when and where the player can create sounds. Moreover, each node has a time window for which pinching is considered to be early, on time, or late. This time window is visualized by an outer ring around the node and a color. The outer ring slowly shrinks until it is the same size as the node: that moment is the ideal time to pinch the node, and that is further indicated by the node changing its color to green. If the player slightly delays pinching a green node, it changes to orange, indicating to them that they are slightly late. If the player waits even longer, the orange node becomes grey and shrinks until it disappears (see Figure 1). Finally, to avoid confusion and help keep players on track if they accidentally pinch the wrong node, the game also automatically removes all previous nodes created before a pinched node.

This timing further constrains players' progression, while guaranteeing their clear sense of agency.

3) Feedback

Three types of feedback are meant to gently guide the player into making the movements desired for each level. In addition, this feedback contributes to making the game more accessible

(a) (b) (c) (d) (e)

Fig. 1. Interaction with nodes: a) node has just appeared and outer ring starts shrinking; b) outer ring has shrunk; c) node changes to green: pinch is considered on time; d) node changes to orange: pinch is considered late; e) node is no longer interactable and vanishes.

Fig. 2. Visualization of the player's hand, as captured in PIZZICATO: each finger has its own color, used by a node to indicate which finger it should pinched with.

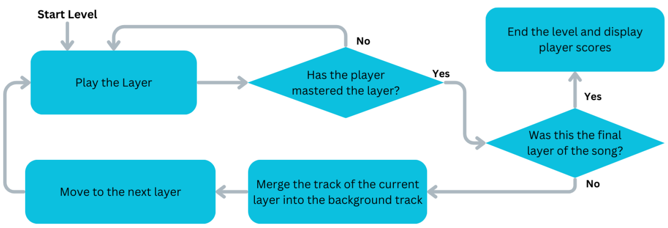

Fig. 3. The game loop of a level

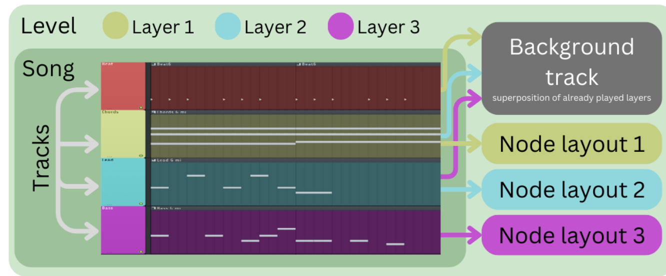

Fig. 4. Each level features a song that is made up of four tracks, one on each layer. Every layer associates a track to a unique node layout. Playing through one layer involves listening to the background track, while timely popping its nodes, as they are laid out for you. After each layer, the completed track gets added to the background track.

and increases the engagement of the player.

- **Visual Feedback:** This is given by the nodes, which sequentially appear on the screen at specified moments and locations, 'announcing' which upcoming movements the player is expected to perform. This is an easily understandable and very versatile format, suitable to accommodate new motor skills. In addition, the node timing mechanic uses a shrinking outer ring and color to indicate when to interact with a node, as shown in Figure 1. Finally, the player's hand being tracked is also permanently visualized to let them see where it stands in the game space; see Figure 2. In this way, the player can easily translate their understanding of the game mechanics to play multiple different levels with varying hand movements.
- **Auditory Feedback:** In addition to the sonification discussed above, this mainly consists of the song being played as a background track. The correct timing to pinch the nodes is 'dictated' by this background track, which helps the player time their pinching and perceive their performance. Naturally, the song also helps players stay engaged, as music often contributes to alleviating boredom during repetitive tasks.
- **Scoring System:** This display of how well the player is performing aims at increasing the sense of engagement. It consists of a bar at the top of the screen, graphically showing the player's progress. It indicates the number of nodes they have already pinched on time, and the threshold to pass the level. Additionally, at the end of the level, the player's performance on each track is shown on a scoreboard screen, which allows for comparison with other scores, possibly instilling a sense of personal or competitive outperformance. Finally, there is a visual streak system that shows the player their longest uninterrupted streak of timely pinched nodes.

D. Level design

The game mechanics described above are flexible and, therefore, convenient to build up the level progression of PIZZICATO. We decided to apply it stepwise, by incrementally superimposing several tracks that together build up a song. Figure 3 depicts the basic game loop of a PIZZICATO level. Each level has a corresponding song, which consists of several layers. Each layer associates one track (e.g. beat, chord, lead, bass) to a node layout (i.e. the corresponding timed sequence of node positions), so that each node, when pinched by the player, will produce a pre-defined note of the track.

At each layer, the player is asked to play alongside a background track by pinching the nodes of that track on time. If the player performs well enough to reach the layer's progress threshold, they move on to the next layer. In that case, the most recently concluded track gets merged with the background track, which is then played in the new layer, where the player is challenged with a new node layout. Typically, later layers are more complex resulting in an increase in difficulty over time. This build-up of layers helps increase player engagement by enabling the repetition of multiple movement patterns, under the guidance of the same song, instead of requiring them to quickly switch levels. Upon completion of the whole level, the player is shown feedback on their performance via the scoreboard screen.

Levels can be designed such that the nodes follow specific patterns (e.g. to assist with desired movement rehabilitation), or to more directly investigate sonification (e.g. its effect on the rhythmic component by concentrating the nodes around the same area), or in such a way that it seems as if the nodes are placed at random. All this flexibility can be used to steer the difficulty of a level. Figure 5 shows an example of a PIZZICATO level.

E. Customization

In the general options menu, the player can customize a large number of settings, including the following:

- **Fingertip Size**: the distance of the player's hand from the camera may vary depending on the setup. As a result, different hardware setups might result in fingers being too small or too large on the screen. This setting is important because fingertip collision detection depends on the size of the fingers, and should hence be adjustable for different setups.
- **Node Size**: adjusted in case the player cannot reach the required fine level of precise hand movements to pinch the nodes.
- **Toggle Sonification**: results in the current track being played regardless of what the player does. This is required

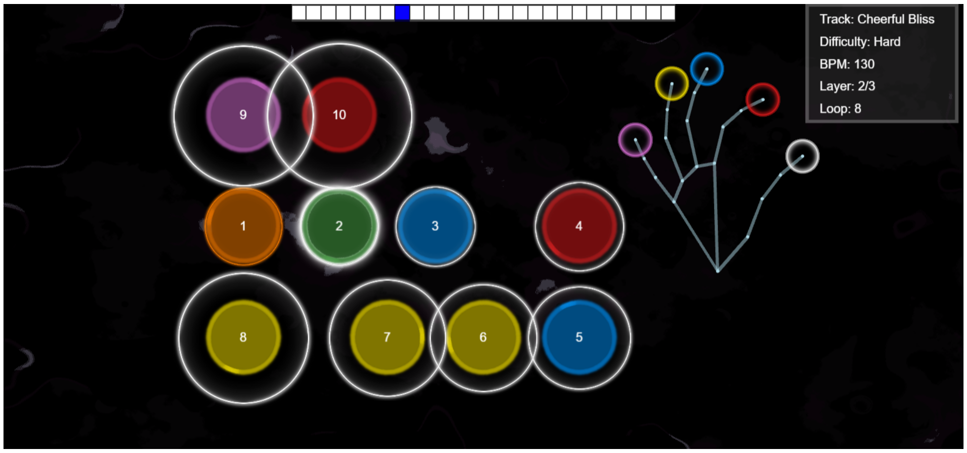

Fig. 5. A screenshot of a difficult PIZZICATO level, depicting a variety of nodes aimed at various fingers, and at different stages of their 'life'

to have a control group when conducting research.

- **Toggle Layer Progression System**: toggles automatic progression to the next layer so that the players' experience can be made identical for research purposes, i.e. allowing playing the same layer a fixed number of times.

IV. Gathered Data

For each node processed during a play session, data is recorded, allowing for an accurate timeline of the player's performance to be stored. This data, made available in a CSV file, can be subsequently analyzed for research purposes. Presently, the data stored for each node includes the following:

- **Layer ID**: the layer the node is in.
- **Node ID**: the index of the node in the layer, ordered by chronological appearance.
- **Loop Number**: starts at 1 for each layer, and increments every time the player fails to progress to the next layer.
- **Player Time**: the time (in seconds, relative to the start of the layer) when the node was pinched by the player.
- **Correct Time**: the time (in seconds, relative to the start of the layer) when the node should have been pinched.
- **Classification**: the way the node interaction was classified: *Correct*, *Late*, *Early* or *Miss*.

As mentioned in Section II, previous studies that utilized serious games to investigate the learning rate of players used a variety of performance measures. These studies show that the specifics of the particular measures are less important than the extent to which they reflect the player's performance on the given task(s) [12]. In the case of rhythm games, the temporal accuracy of the player's input is a common measure [8].

PIZZICATO gathers and assesses the temporal accuracy of the player (timing error) and derives a general measure of how well the player did (fraction of nodes classified as correct). Collecting and analyzing similar performance metrics allows the results and conclusions to be better compared with previous research. In addition, the remaining information collected provides additional context to the data. For example, such data points can be useful for studying performance related to particular layers or songs, the effect of regular or larger movements, etc. With enough data one could, for example, detect both failure and success patterns across different cohorts of players. We are currently collaborating with neuropsychology researchers, setting up a variety of such experiments using PIZZICATO.

V. Technical Requirments

PIZZICATO makes use of Google's MediaPipe API [13], which offers a fast and robust hand-tracking solution via a webcam. MediaPipe can run on the CPU, although for older CPUs, the latency between movement and screen feedback may be high. Since low latency is a driving requirement when using sonification as feedback, it is advisable to run PIZZICATO on a machine with a GPU, on which MediaPipe can run with virtually imperceptible latency. Occasionally, devices with older GPUs (or laptops in power save mode) may also experience some degree of latency.

PIZZICATO can be played online[1] after granting it webcam access (tested on Chromium browsers under Windows 10 and MacOS 14). In addition, the game can also be downloaded[2] for offline deployment (Windows 10 only).

VI. Evaluation

PIZZICATO was developed with neuropsychology colleagues, and targets their motor behavior research, including diagnostic and rehabilitation. For that, however, the necessary protocols have to be followed, as well as careful and extensive preparation of appropriate game levels, before trials with real patients can take place. While that phase is still ongoing, we performed playtesting sessions with healthy individuals, to assess to which extent (i) players felt agency when playing PIZZICATO and (ii) players found the game engaging. This evaluation also helped us get a sense of the game's accessibility to young adults.

[1] https://pizzicato-game.github.io/
[2] https://bit.ly/44SVeKM

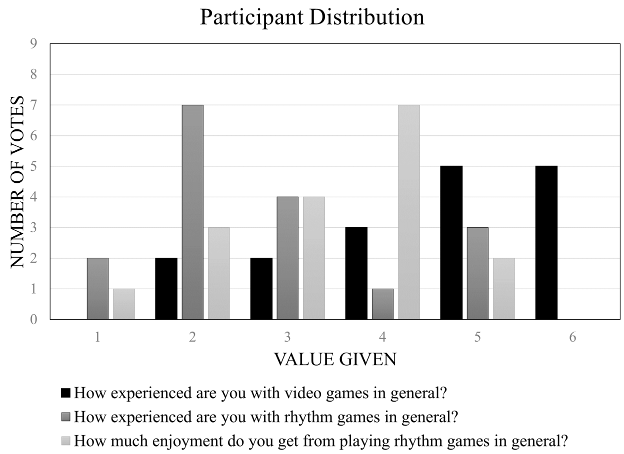

Fig. 6. Players' previous gaming experience

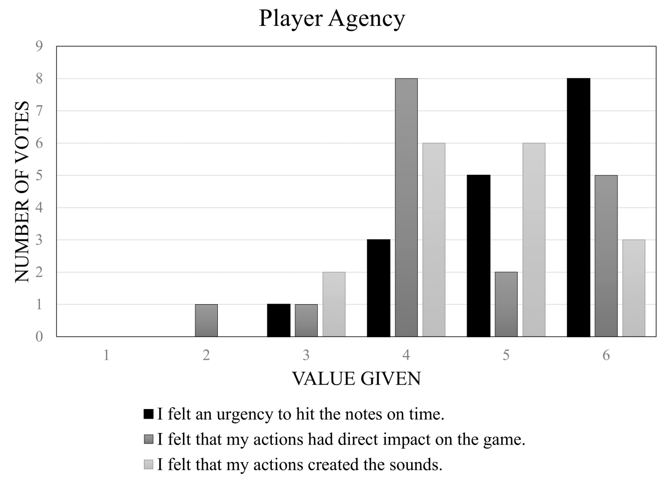

Fig. 7. Distribution of perceived agency reported

A. Method

The target group for the playtesting was young healthy adults aged between 18 and 30 ($n = 17$). Three different levels were used during the tests. Level 1 had simple patterns, a small amount of nodes to play per bar, and required using only the index finger for node pinching. Level 2 had slightly more complicated patterns to play and more nodes to play per bar. Lastly, level 3 had the most complicated patterns and the most nodes to play per bar. Both levels 2 and 3 sometimes require using a different finger for node pinching. These levels were created to slowly ramp up the difficulty level as the playtesters gained increasing familiarity with the somewhat unusual control input.

Players were given a maximum of five minutes to beat each level, after which they were handed a form to fill in. The first section of this form, about players' experience with music and games, aimed at assessing whether their previous experience influenced their performance with PIZZICATO and the remaining answers. It consisted of the following questions:

1) Do you play a musical instrument?
2) How experienced are you with video games in general?
3) How experienced are you with rhythm games in general?
4) How much enjoyment do you get from playing rhythm games in general?

We used a 6-point Likert scale [14]. The 6-point scale was chosen over the 5-point scale to explicitly exclude neutral answers, thus eliminating ambiguity and fence-sitting.

Next, players were asked how much they agreed with the following statements:

1) I felt an urgency to hit the notes on time.
2) I felt that my actions had a direct impact on the game.
3) I felt that my actions created the sounds.
4) The game challenged me to keep playing.
5) I want to play this game again.
6) I like the music in the game.
7) The controls were easy and intuitive to understand.
8) The game was easy and intuitive to understand.

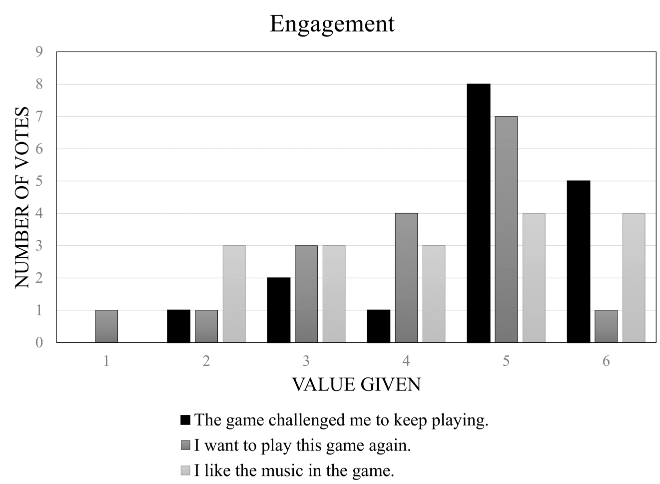

Fig. 8. Distribution of perceived engagement reported

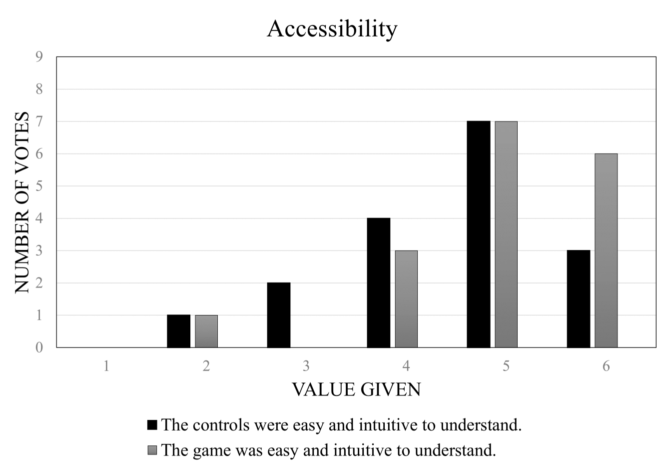

Fig. 9. Distribution of perceived accessibility reported

Statements 1-3 focus on player agency, statements 4-6 focus on player engagement and, lastly, statements 7-8 focus on the accessibility of PIZZICATO.

B. Results

Of the whole player group ($n = 17$), slightly more than half (53%) played a musical instrument. Regarding their prior gaming experience (see Figure 6), we see that although most participants have reasonable experience with games, only a minority of them report some considerable experience with rhythm games. The results for agency, engagement, and accessibility can be found in Figure 7, Figure 8, and Figure 9, respectively.

C. Discussion

The results in Figure 7 and Figure 9 show that both agency and accessibility are experienced highly by the players. The perceived engagement in Figure 8 is slightly more balanced but still shows that a majority of players found the game engaging. This difference may be because engagement is also largely determined by the game genre, while accessibility and player agency are mostly determined by the balance in game mechanics. In other words, if people dislike rhythm games, they will experience less engagement with the game, even though they may still rate it for high agency and accessibility.

Various playtest sessions have shown that the camera placement during the playtest considerably affects the player's performance. This is in part due to the perspective of the webcam, possibly requiring the player to make movements in a tilted plane, but is also because the game is calibrated to perform best at a certain hand-to-camera distance. An automatic calibration scene might thus help improve the accessibility of the game and is left for the next iteration of the game.

VII. CONCLUSION

Research on the effects of sonification on learning motor skills currently suffers from (i) using low-accessibility instruments, (ii) failing to collect sufficient, appropriate and usable performance data, and (iii) posing strong limitations to the possible movements the player can make. These constraints strongly limit the feasibility of larger, deeper, and more varied studies.

We presented PIZZICATO, a serious game expressly designed and developed to be an accessible and engaging tool to overcome the above drawbacks. The game uses a common webcam to recognize a wide range of motor skills and integrates sonification with rhythmic player movements, steered by a background track and accompanying visuals. Moreover, the game collects abundant data on the player's performance, and makes this easily available for analysis in a scientific research context, something most current sonification games do not do.

Our player studies so far have shown that PIZZICATO is both accessible and very engaging. Preliminary clinical research studies are presently underway, and more are in preparation. In the near future, PIZZICATO will be used as a tool to systematically assess motor learning (based e.g. on timing patterns, finger sequence, or location) with the potential to vary the different settings in a very precise and controlled manner.

Another short-term goal is the development of an interactive PIZZICATO level editor, with which researchers and clinicians can develop different sets of levels and play sessions for specific target groups. After that, and in collaboration with physiotherapists, it should be viable to roll out PIZZICATO for rehabilitation purposes, thus helping patients recover motor functions in their hand and arm, for instance after a stroke or surgery. For this, a set of custom game levels should be developed, geared towards requiring small and precise movements, which are more fitting to people with limited motor skills and special needs.

Since PIZZICATO is accessible and extremely versatile, it seems especially suited to retain and engage patients over long periods, repeating rehabilitation exercises that are, otherwise, typically unappealing and boring. We, therefore, believe that PIZZICATO has the potential to make a difference, not only to researchers in laboratories and specialists in clinical practices, but also to many patients undergoing rehabilitation in their homes.

ACKNOWLEDGMENT

We thank Rebecca Schaefer and Marijn Coers, from Leiden University, for their great inspiration, enthusiasm, and support throughout this project.

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