Multimodal Cueing in Gamified Physiotherapy: A Preliminary Study

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Abstract: Advances in mobile devices have made possible the adherence to healthy lifestyles and workout routines with less supervision from a professional, for example, a strength trainer or physiotherapist. Mobile health games in particular can help individuals with chronic conditions and disabilities who require physiotherapy and rehabilitation to stay motivated and encouraged during their physiotherapy process. We developed a mobile game application, *Neblina Wrist Physio* that works with a wearable motion sensor to look at the effect of multimodal cueing, i.e. using stimuli to facilitate movement *initiation* and *continuation*, mechanisms on wrist physiotherapy exercises. The results of our study showed that cueing in a gamified physiotherapy environment is an effective means of keeping users entertained and engaged. At the same time, the impact of cueing modalities in improving the quality of gamified physiotherapy exercises appears to be affected by the difficulty of the exercise and the specific game.

1 INTRODUCTION

In guided fitness and physiotherapy, concise instructions and feedback are needed so that patients can both safely and effectively execute specific exercises (Schönauer et al., 2011). Cueing is one of the known methods of guidance in physical therapy which can help a patient to perform activities more effectively. Cueing has been defined as using stimuli (either temporal or spatial) to help in the start or continuation of a movement (Nieuwboer et al., 2007) or simply as giving information as to what a particular exercise should look like or how it should be carried out (Horstink et al., 1993). Although studies have shown the efficacy of physiotherapy can be improved by the addition of cueing techniques (Nieuwboer et al., 2007), the use of an inappropriate modality or excessive information, which may be the case when using multiple modalities, may lead to excessive cognitive workload. Combining different types of feedback or cueing can convey a better understanding of a task since humans naturally interact with multiple modalities. While multimodal cueing can keep patients informed, engaged, and even entertained, excessive information can be distracting, and confusing (Baldwin et al., 2012). Thus a balance needs to be found to determine which cues or which combination of cues can provide motivation and help a patient to effectively perform their exercises.

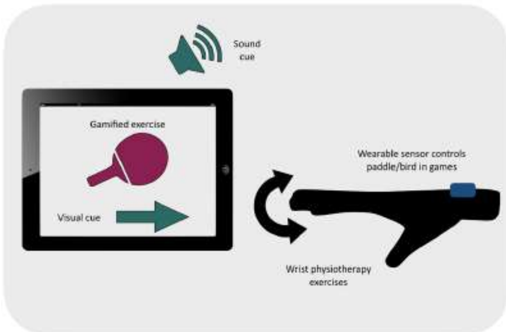

Figure 1: To explore the effect of cueing in physiotherapy we designed an application that works with a wearable sensor for wrist exercises.

Physiotherapy can be a painful and tiring process involving a series of exercises that patients must repeat over a long period. Unfortunately, patients often get bored after a short period of time and lose motivation making physiotherapy less effective. One solution that has been widely used in recent years to encourage patients to do their exercises at home is to *gamify* the exercise routines. Gamification is defined as adding game elements (e.g. rewards/scoring, com-

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petition, and levels) to a non-game context in order to make a rather boring task like physiotherapy more entertaining, engaging, and interesting (Marczewski, 2013). Games and mixed reality (e.g. augmented or virtual reality) can be an ideal medium to incorporate physiotherapy exercises with different cueing modalities.

In this paper, we describe a preliminary study investigating real-time cueing (visual or auditory) in a gamified physiotherapy environment (see Figure 1). To explore this, we developed *Neblina Wrist Physio*, an iOS mobile application consisting of two well-known games (*Breakout* and *Flappy Bird*) that are played by performing wrist exercises while wearing Motsai's Neblina™ sensor.

1.1 Neblina Motion Sensor

The Neblina™ core module is a low-power self-contained Attitude and Heading Reference System (AHRS), Inertial Measurement Unit (IMU), and Vertical Reference Unit (VRU) module with wireless connectivity developed by Motsai (see Figure 2). It uses a Bluetooth connection to connect to smartphones, tablets and other devices. It also has extremely efficient power management and low-energy operation making it ideal for exploring motion in wearable technology devices[1]. For our research, we used the AHRS functionality of the Neblina™ sensor.

Figure 2: The Neblina™ motion sensor compared to a Canadian one-dollar coin size-wise.

2 RELATED WORK

In the following section we explore different cueing modalities and gamification in physiotherapy. It should be noted that some researchers use the terms cueing and feedback interchangeably. Although strategies for feedback and cueing are similar, the moment at which the stimulus is provided differs. Whereas cueing is the use of external stimuli to facilitate movement during *initiation* and *continuation* (Nieuwboer et al., 2007), feedback is used based on a person's performance [of a movement] *during* or *after* an action. In the related works described below, we choose the term that was used in the paper being described.

2.1 Modality

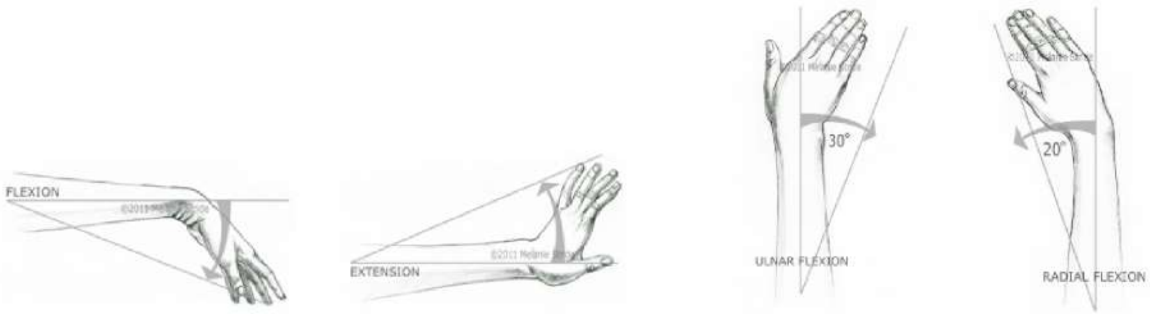
Different modalities, e.g., visual, auditory, or somatosensory, can be used for cueing. In general, visual cueing provides more useful information; however, auditory information is processed more quickly[2]. In movements where extra mobility is required, directing attention to visual cues might negatively affect a physiotherapy process. In these cases auditory or somatosensory cues are preferable. In the specific context of health, the cueing and feedback that is normally given by a professional is visual (e.g. demonstrating the proper way to make a move), auditory (e.g. giving verbal instruction), or somatosensory (e.g. moving a person's limb into the right position or applying pressure to a specific area of the body) (Sousa et al., 2016). The emergence of computer-vision and wearable sensors is enabling automated cueing and feedback without the need for constant human supervision. In these cases, visual cueing has been defined as the addition of non-content information to visual representations and can have various formats including graphics (e.g. arrows, coloring, flashing, etc.), on-screen narrations and/or texts (Lin and Atkinson, 2011). The most studied type of computer-generated auditory cueing is rhythmic (Gallagher, 2017) for example the use of an underlying beat in music (Ford et al., 2010) to increase stride length and cadence in participants with Parkinson's Disease.

2.2 Wearables, Cueing and Gamification in Physiotherapy

Wearable sensors are becoming more and more frequently used in rehabilitation. Gallagher (Gallagher et al., 2015) investigated auditory cueing, visual cueing, feedback, and directed attention for cycling in healthy adults and those with Parkinson's Disease (PD). The results showed that whereas for healthy individuals only audio cueing and directed attention increases pedaling speed, for PD patients all 4 conditions affect pedaling rate positively. Another

[1] https://motsai.com/solutions/neblina/

[2] https://www.otpbooks.com/greg-dea-feedback-and-cueing-2/



(a) (b)

Figure 3: (a) Extension and Flexion. (b) Ulnar and Radial deviation. Figures from (Larcombe, 2015).

study (Dowling et al., 2010) demonstrated the use of wearable sensors in gait modification for people with knee osteoarthritis (KO). The authors examined which type of real-time feedback (verbal or sensor vibration feedback) is most effective in improving gait and found that vibration feedback was better than verbal. Nikmaram *et al.* (Nikmaram et al., 2019) did a study on sonification (i.e., changes in musical pitch) in post-stroke rehabilitation. They used of each individual's affected hand movements by capturing data using sensors attached to the wrist and arm of a patient to play simple tunes. Although there was no effect of sonification on training overall, a small effect was found on movement smoothness. Doyle *et al.* (Doyle et al., 2011) used an iPhone as a motion sensor to investigate if exergaming can improve a patient's accuracy in performing exercises. Participants who played the exergame showed more accuracy over no feedback and limited video feedback environments. Garcia *et al.* (Garcia and Navarro, 2014) developed a mobile rehabilitation application using augmented reality (AR) and gamification to help individuals with ankle sprain injuries. Their results showed that using AR and gamification can increase motivation and adherence to rehabilitation routines. In a similar work, Shin *et al.* (Shin et al., 2014) developed a task-specific interactive game using virtual reality for post-stroke rehabilitation of upper body parts. Their system showed to be effective in improving attention, providing an immersive flow experience, and individualizing interventions during the rehabilitation process.

As seen from these related works, the context, intended population, and exercise can impact the effectiveness of gamification, cueing and participant engagement.

3 WRIST PHYSIOTHERAPY EXERCISES

Wrist injuries or wrist pains are very common in people who do sports or who do repetitive wrist motions (e.g. typing on a keyboard or working on an assembly line). In addition, wrist pain might be a result of sudden impacts or certain diseases such as rheumatoid arthritis, which mostly affects the elderly. Physical therapy is a common treatment for wrist disorders. Moreover, performing simple stretching and strengthening exercises regularly or as warm-ups before doing sports can help to prevent wrist injuries [3].

Two of the most common sets of wrist physiotherapy exercises are (1) extension and flexion and (2) ulnar and radial deviations. Extension is defined as raising the back of the hand and flexion describes the bending of the hand down so that the palm faces in toward the arm (Figure 3a). Ulnar deviation is the movement of bending the wrist towards the little finger's side. Radial deviation is the movement of bending the wrist towards the thumb's side (Figure 3b). Normal values for wrist range of motions are 71 degrees of extension, 73 degrees of flexion, 33 degrees of ulnar deviation, and 19 degrees of radial deviation (Kim et al., 2014).

4 USER STUDY

To study the impact of cueing modality preferences in gamified physiotherapy, we developed a wrist therapy application with different cueing modalities: visual, auditory and visual and auditory cues combined. The study involved participants playing two video games on an iPad while having the Neblina™ sensor placed on top of their hand as can be seen in Figure 4.

[3] https://medlineplus.gov/wristinjuriesanddisorders.html

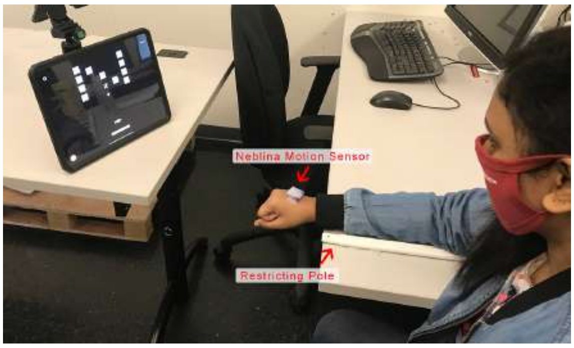


Figure 4: Setup of the user experiment.

Specifically, we had the following research questions: *Which cueing modalities (no cueing, audio, visual, or a combination of audio and visual) are best to improve physiotherapy exercise quality in a gamified environment?* and *Do users have fun and become more engaged in physiotherapy exercises when they are gamified?*

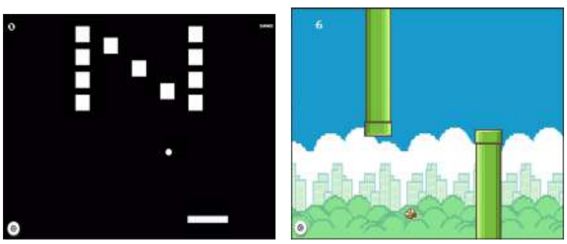
4.1 *Neblina Wrist Physio* App

To answer our research questions, we developed an iOS wrist therapy application consisting of two video games: *Breakout* and *Flappy Bird*.

4.1.1 Breakout Game

Breakout is based on a popular arcade game (Figure 5a). In this game, the user controls a paddle at the bottom of the screen to keep a ball from falling while popping blocks at the top of the screen using the same ball. In our version of the game, the paddle is controlled by Neblina™ sensor which is placed on top of the user's hand. Thus, the user has to do ulnar and radial deviations in order to play the game.

In the *Breakout* game the visual cue was given by arrows that pointed to the left or right indicating where the paddle needed to be moved to hit the ball. For auditory cueing, a voice saying ”Move left” or ”Move right” speaks while the ball moves downward indicating where the paddle needs to be moved. We also studied the combination of both cues.



(a) (b)

Figure 5: Screenshots of the *Breakout* game. (a) The *Breakout* game in *Neblina Wrist Physio* app. (b) The *Flappy Bird* game in *Neblina Wrist Physio* app.

4.1.2 Flappy Bird

Flappy Bird is a game, where traditionally, the user controls the bird by tapping on the screen and avoiding pipes appearing in the way (Figure 5b). In our version of the game, the bird is controlled by the extension and flexion of the user's wrist. In this game, extension of the wrist makes the bird fly higher and flexion of the wrist makes the bird fly lower. For this game, visual cueing was given using arrows pointing up or down while the bird is approaching a pipe and audio cueing was done by having a voice say ”Move up” or ”Move down” while the bird is approaching a pipe. The combination of cues was also studied.

4.2 Experimental Design

The setup for the user experiment required the user to place their right arm comfortably on a desk. A preliminary study showed that participants playing Breakout would tend to move their whole arm rather than just the wrist, therefore, two horizontal poles were taped to the desk to limit the movement of the user's arm. To perform the exercises correctly, the user's arm should stay still on a flat surface, thus the participants were instructed to leave their arm flat on the table and only use their wrist to move within the games. The participant's wrist was not placed on the desk so that it could move freely without any restrictions (Figure 4). In addition, for both games, the user can perform the exercises while making a fist or having their hand flat.

For both games, the Neblina™ sensor was placed on top of the user's hand and the speed of the game and sensitivity of the sensor were calibrated for each participant. Prior to the study users were first instructed on how to do the exercises and then asked to do each exercise without the system for 30 seconds. Each participant played each game for 2 minutes under four conditions: (1) no cue, (2) visual cue, (3) auditory cue and (4) visual and auditory cue combined. Thus each participant played 8 minutes of each game. The ordering of which game was played first, *Breakout* or *Flappy Bird* was alternated. Participants were able to rest before each round of the game and were told they should stop at anytime if they experienced any discomfort.

4.2.1 Pre-test Questionnaire

Prior to playing the game participants signed a consent form and filled out a pre-test questionnaire containing questions about participants' experience with wearable sensors, video games, and guided exercising. Example questions from the questionnaire include: *Have you done guided exercises or rehabilitation before? How often do you play video games? Do you have any experience working with wearable devices containing motion sensors (e.g. HMD, Smartwatch, Smart clothing etc.)?* and *Do you have any experience doing "gamified" fitness activities (e.g. Wii Sports, Kinect Sport Games, Zombie Run, Ingress, etc.)?* The full questionnaire was created using Google Forms and can be accessed at: https://forms.gle/uGLAxVFxrkkkY8gX7.

4.2.2 Post-test Questionnaire

After finishing the experiment, participants were asked to fill out a post-test questionnaire. In the post-study questionnaire we targeted participants' preference and feeling regarding cueing modalities for each game, and their perception of wearable sensors and the use of games for physiotherapy. In addition, they were asked about any further suggestions for improving the application. The post-test questionnaire can be accessed at https://forms.gle/J5xYSUZXeL5yZVyUA

5 RESULTS: USER STUDY

For the study, 10 healthy participants (4 females and 6 males, age 24 to 44) were recruited[4]. None of them had any major hearing, vision or wrist problems.

5.1 Participants' Background

According to the pre-test questionnaire, half (50%) of the participants love new technologies and try using them and 20% of them like new technologies but are not eager to use them. The rest of the participants might like or dislike them depending on the context (see Figure 6).

Regarding the experience with guided exercises or physiotherapy of any kind, 70% of the participants did not have any experience. Twenty percent of the participants had experience with conventional guidance methods, for example with paper instructions (e.g. sheet with physiotherapy exercises), a professional demonstrating exercises (e.g. in an aerobics class), and video instructions (e.g. a yoga YouTube video). Lastly, another twenty percent had experience using guidance with movement trackers or sensors. None of our participants had experience in doing guided exercises with augmented or virtual reality.

[4]Due to the COVID-19 pandemic and partial lock-down in Montreal at the time, we could only run subjects from within our bubble, thus limiting the study size and our ability to recruit subjects currently doing arm/wrist physiotherapy exercises.

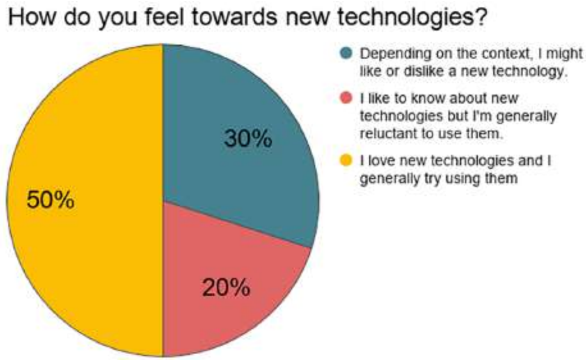


Figure 6: Users' feeling towards new technologies.

The pre-test questionnaire also showed that the general perception of gamified fitness activities was positive. From the 30% of the participants who had experience with them, 66.6% believed that they cannot be effective in improving general health but they are motivating. All of the participants believed that they are fun, engaging and interesting. Participants generally disagreed that games are frustrating, stressful or discouraging. On the contrary, subjects who had experience with team gamified fitness activities (20%) believed that doing fitness activities with a team in a gamified way can improve fitness and general health.

Regarding the use of video games, almost half of the participants (40%) rarely played video games. Twenty percent of them played video games more than 10 hours weekly and 30% of the participants played video games less than 3 hours weekly. 10% of the participants played 3 to 10 hours weekly. The majority of the participants (80%) used mobile devices for playing games. Almost half, 40% use a desktop computer and/or laptop to play and 10% of the participants use a video game console. With respect to the participants' general feeling during game playing, 70% of them felt entertained, 40% of them felt excited and another 40% felt relaxed. These differences of feelings could be due to differences in the type of game play (e.g. Tetris/Sudoku type games versus first-person shooter games).

In terms of wearables, we found that 70% of our participants have previously used a wearable device containing motion sensors (e.g. HMD, smartwatch, smart clothing) and 80% of them had experience with motion-sensing devices (e.g. Kinect and Wii).

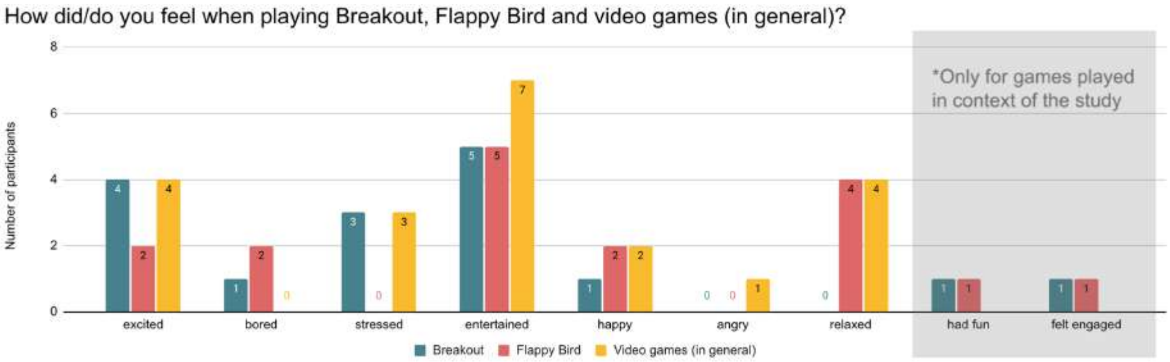


Figure 7: Users' feeling while playing *Neblina Wrist Physio* games.

5.2 Wearable Sensor

The post-test questionnaire queried users' perception of the Neblina™ sensor. Participants were asked to rate the precision on a scale of 1 to 5, five being very precise. We found that 90% of the participants rated the precision of the sensor to be greater than 3. The majority of participants (70%) believed that the sensor was easy to use and all of them felt comfortable using the sensor.

5.3 Perception of Gamified Physiotherapy

Generally, the participants favoured the idea of using a game for doing physiotherapy exercises. They all felt motivated and 90% of them felt that the study was fun, engaging, and effective; however, almost half of the participants (40%) felt the overall system was difficult to work with. This was mainly due to the fact that the sensor had to be attached to the wrist and calibrated, and thus could be alleviated in future studies with, for example, the use of a wearable bracelet. At the same time, all of the participants responded that they would use this type of system for physiotherapy or rehabilitation.

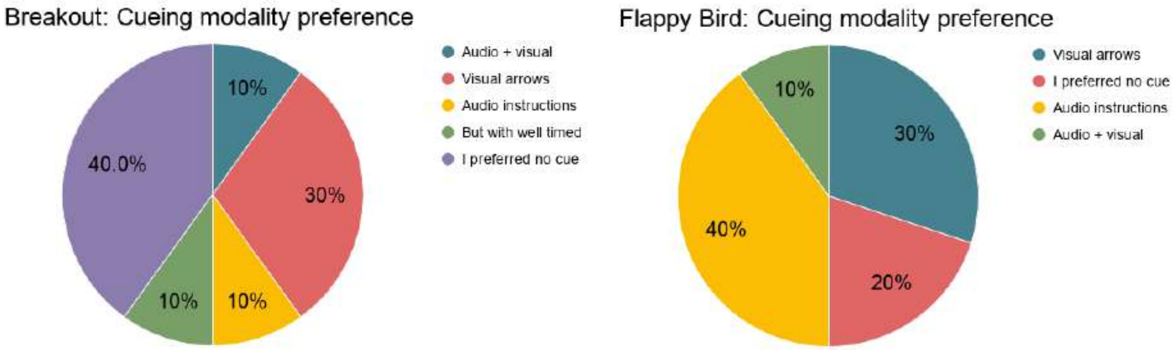
Regarding subjects' feelings during playing the *Breakout* game, albeit they mostly had positive feelings such as entertained (50%), excited (40%), happy (10%), had fun (10%), and were engaged (10%), 30% of the participants felt stressed and one subject felt bored. This result is more or less the same for the *Flappy Bird* game with one major difference, that nobody felt stressed during this game while 40% of the participants felt relaxed during this game. In addition, fewer participants felt excited and more felt bored. These results could have been expected since during the user study, the *Breakout* game was perceived to be more challenging for the participants in comparison to the *Flappy Bird* game. When looking at the participants' general perception of video games, the same participants that felt excited or stressed had answered in the pre-test questionnaire that games typically make them stressed or excited. Thus, these participants had the same perception of physiotherapy games as typical games played for leisure. Those participants who play games more often felt less entertained and more bored during the study likely since the main goal of these games is performing physical therapy exercises rather than entertaining users (Figure 7). Furthermore, based on the post-study questionnaire, less excitement for a game might result in boredom during the game (Figure 7).

5.4 Exercise Quality

Although we did not directly measure the quality of the wrist exercises we did observe participants. During the game, even though participants were asked to not move their arm and only use their wrists for the exercises in some cases of the *Breakout* game, they tended to shift their arm or rotate their wrists instead of doing ulnar and radial deviation in order to avoid losing. This might be directly connected to their level of excitement or stress while playing the game. We posit that the more engaged users become the more likely they are to focus on gaining points and doing well in the game than doing the exercise properly. Thus games need to be carefully designed in order to allow for proper movements and avoid more injury. One way to do this is to use games where the score is based on exercise quality.

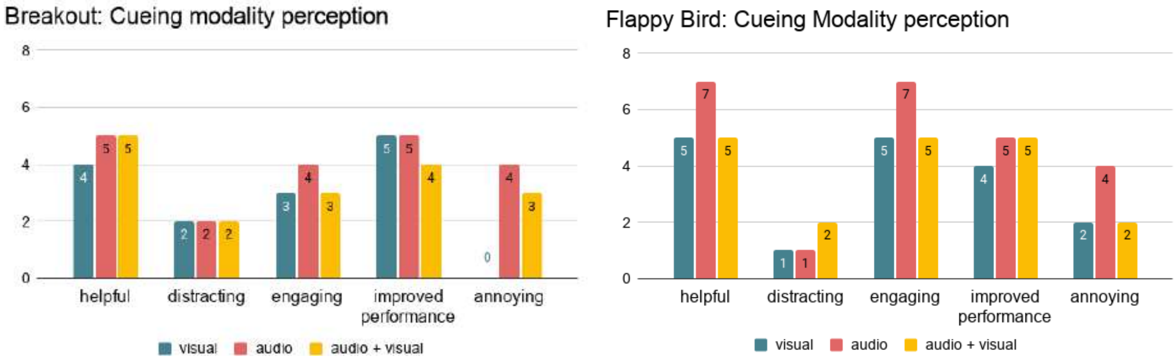
5.5 Cueing

We queried the users on their preference about cueing modality in terms of engagement, helpfulness in performance, and distraction. Overall, the favourite cue for *Flappy Bird* game was the auditory cue (40%), in comparison to no cueing for the *Breakout* game (Fig-



(a) (b)

Figure 8: Users' preference regarding the type of cue. (a) For the *Breakout* game. One participant preferred the combination of audio and visual, provided that they are timed better. (b) For the *Flappy Bird* game.



(a) (b)

Figure 9: Users' opinion of types of cueing. (a) For the *Breakout* game. (b) For the *Flappy Bird* game.

ure 8). A T-test showed that there were no significant differences between the two games in terms of users' opinion of cueing modalities (visual (p=0.4263), audio (p=0.3375), audio + visual (p=0.4766)). We summarize the results of the main findings in Figure 9.

5.5.1 Visual Cueing

For the *Breakout* game the majority of participants felt that visual cues were not distracting (70%) or annoying (80%). In addition, half of the participants sensed an improvement in their performance, and 40% of them felt it was helpful. For the *Flappy Bird* game, fewer participants (40%) felt the visual cue had a role in improving their performance but more subjects (50%) sensed it was helpful. Almost all of the participants agreed that the visual cues were not distracting (90%) or annoying (80%) for the *Flappy Bird* game. The major difference regarding visual cues between the games was the level of engagement; 30% of the participants thought that the visual cues had made the *Breakout* game more engaging, whereas this result is 50% for the *Flappy Bird* game. This difference is also likely due to the difference of difficulty in the game. One participant commented that the *Breakout* game was more difficult so the cues helped, whereas, for the *Flappy Bird*, which is more simple and easy to play, the cue had no impact and therefore was ignored.

5.5.2 Audio Cueing

For both games over a third of the participants (40%) felt that auditory cueing was annoying. This might be as a result of the fact that participants were focused on the visual elements of the games and having audio cues repeating ("up/down" or "left/right") became annoying. At the same time, by some participants the cues were deemed helpful and were felt to improve users' performances. Thus it seems they did not negatively impact the users' game performance. For both the *Breakout* game and *Flappy Bird* game, half of the participants felt an improvement in their performance comparing to visual cueing rounds. Half of the participants felt audio cueing was helpful for the *Breakout* game and this number increased for the *Flappy Bird* game to 70% which is also higher than the visual cueing. The majority of the participants agreed that audio cues were not distracting when playing the *Flappy*

Bird game (80%) or the *Breakout* game (70%). A major difference regarding the level of engagement with audio cues between the games was apparent. In terms of engagement, 40% of the participants felt that audio cues had made the *Breakout* game more engaging and 70% felt that for the *Flappy Bird* game.

5.5.3 Multimodal Cueing: Visual and Audio

In terms of the users' perception of both visual and audio cueing, while the combination resulted in the same perception for helpfulness (50%) and distraction (20%) for both of the games, the *Flappy Bird* game with both modalities was considered more engaging (50%) and more effective regarding improvement in performance (50%) compared to the *Breakout* game with both of the modalities. In addition, the *Flappy Bird* game was found to be less annoying (20%) than the *Breakout* game (30%).

6 DISCUSSION

The results of our work suggest that people believe gamified physiotherapy is engaging and can help in exercises. However, the design of these types of games requires its own set of considerations and a game's level of difficulty needs to be customized based on each individual's capabilities. Furthermore, consideration into using cueing for better timing and smoothness of the exercise should be considered in future work (Benoit et al., 2014). The impact of cueing on cognitive load needs to be customized as well. As one of the participants mentioned "... I ignore them [visual cues for the Breakout game] because it takes longer for me to process visual cues than play based on my assumptions...". This reflects some of the previous studies that show that visual cues may take too long to process and should not be used when visual attention should be paid elsewhere.

Although our population believed that more challenging games might be more exciting and engaging, this may not be the case with an elderly population. With more engaging games people might pay more attention to scoring rather than correctly performing the physiotherapy exercises. Thus, for more engaging games a possibility for future work would be to include pose estimation, and use of feedback to show a user when an exercise is not being performed correctly (Christiansen et al., 2013; Ayman Hassan et al., 2020; de Araujo et al., 2017). Gaming mechanisms where users lose points for not performing exercises correctly could also be considered but must be balanced with the motivation of users.

In terms of limitations, our user study was conducted during the COVID-19 pandemic. Since this study required participants to place a wearable sensor on their hands, it limited us in terms of finding more participants from diverse backgrounds, or those who were currently doing rehabilitation exercises. Our study also only included two cueing modalities (i.e. visual cueing and auditory cueing). The next step of this work will be to not only explore the effect of haptic cueing and the combination of haptic with auditory and visual cueing but also the effect of feedback modalities on basic and more challenging physical therapy exercises. Moreover, we will use in-game scores as a quantitative measure for assessing users' performance.

7 CONCLUSIONS

There is considerable research potential regarding providing guidance in a virtual environment for physiotherapy exercises. In addition, the emergence of computer vision methods and wearable motion tracking devices has provided various ways of collecting users' movement data. Still, several concerns remain that need to be addressed regarding the clinical effects of cueing and other forms of guidance on gamified physiotherapy movements. Most prominently, we currently lack understanding of the connection between in-game performance and cueing and whether this in turn impacts enjoyment and ultimately adherence to physiotherapy routines. Although our study shows promising results regarding the use of cueing with basic gamified physiotherapy exercises and a healthy population, it is currently unclear whether our method will hold true for a more complex physiotherapy routine and for participants who present with motor deficits and are going through an actual physiotherapy process. In addition, since a number of physical therapy exercises need the patient to be more active and move more often during an exercise, the use of other cueing modalities such as haptics might be more beneficial than visual cues. Moreover, providing feedback to show if the user is performing exercises correctly can continuously improve the users' performance as was demonstrated in previous studies (Ribeiro et al., 2011; Christiansen et al., 2013). Future investigations should examine whether having feedback along with cueing can have the same or even a stronger effect on users' adherence to routines and quality of movements and exercises.

REFERENCES

Ayman Hassan, H., Hussein Abdallah, B., Ahmed Abdallah, A., Osama Abdel-Aal, R., Reda Numan, R., Khaled Darwish, A., and El-Behaidy, W. (2020). Automatic feedback for physiotherapy exercises based on PoseNet. *Informatics Bulletin, Faculty of Computers and Artificial Intelligence, Helwan University*, 2(2):10–14.

Baldwin, C. L., Spence, C., Bliss, J. P., Brill, J. C., Wogalter, M. S., Mayhorn, C. B., and Ferris, T. K. (2012). Multimodal cueing: The relative benefits of the auditory, visual, and tactile channels in complex environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 56(1):1431–1435.

Benoit, C., Dalla Bella, S., Farrugia, N., Obrig, H., Mainka, S., and Kotz, S. A. (2014). Musically cued gait-training improves both perceptual and motor timing in parkinson's disease. *Frontiers in Human Neuroscience*, 8.

Christiansen, R., Contreras-Vidal, J. L., Gillespie, R. B., Shewokis, P. A., and O'Malley, M. K. (2013). Vibrotactile feedback of pose error enhances myoelectric control of a prosthetic hand. In *2013 World Haptics Conference (WHC)*, pages 531–536.

de Araujo, F. X., Scholl Schell, M., and Ribeiro, D. C. (2017). Effectiveness of physiotherapy interventions plus extrinsic feedback for neck disorders: A systematic review with meta-analysis. *Musculoskeletal Science and Practice*, 29:132 – 143.

Dowling, A. V., Fisher, D. S., and Andriacchi, T. P. (2010). Gait modification via verbal instruction and an active feedback system to reduce peak knee adduction moment. *Journal of Biomechanical Engineering*, 132(7).

Doyle, J., Kelly, D., Patterson, M., and Caulfield, B. (2011). The effects of visual feedback in therapeutic exergaming on motor task accuracy. In *2011 International Conference on Virtual Rehabilitation*, pages 1–5.

Ford, M. P., Malone, L. A., Nyikos, I., Yelisetty, R., and Bickel, C. S. (2010). Gait training with progressive external auditory cueing in persons with parkinson's disease. *Archives of Physical Medicine and Rehabilitation*, 91(8):1255–1261.

Gallagher, R. (2017). *Cueing, feedback and directed attention embedded in a virtual environment modulate temporal and spatial bicycling features of healthy older adults and people with Parkinson's disease*. PhD thesis, Rutgers University - School of Health Professions.

Gallagher, R., Werner, W. G., Damodaran, H., and Deutsch, J. E. (2015). Influence of cueing, feedback and directed attention on cycling in a virtual environment: Preliminary findings in healthy adults and persons with parkinson's disease. In *2015 International Conference on Virtual Rehabilitation (ICVR)*, pages 11–17.

Garcia, J. A. and Navarro, K. F. (2014). The mobile rehapp^{TM}: an ar-based mobile game for ankle sprain rehabilitation. In *2014 IEEE 3nd International Conference on Serious Games and Applications for Health (SeGAH)*, pages 1–6.

Horstink, M., De Swart, B., Wolters, E. C., and Berger, H. J. (1993). Paradoxical behavior in Parkinson's disease. In *Proceedings of the European Congress on Mental Dysfunction in Parkinson's Disease*.

Kim, T. S., Park, D. D. H., Lee, Y. B., Han, D. G., Shim, J., Lee, Y. J., and Kim, P. C. W. (2014). A study on the measurement of wrist motion range using the iphone 4 gyroscope application. *Annals of Plastic Surgery*, 73(2):215–218.

Larcombe, B. (2015). Improve Your Forehand Loop by Relaxing the Wrist.

Lin, L. and Atkinson, R. K. (2011). Using animations and visual cueing to support learning of scientific concepts and processes. *Computers & Education*, 56(3):650 – 658.

Marczewski, A. (2013). *Gamification: A Simple Introduction*. Andrzej Marczewski.

Nieuwboer, A., Kwakkel, G., Rochester, L., Jones, D., van Wegen, E., Willems, A. M., Chavret, F., Hetherington, V., Baker, K., and Lim, I. (2007). Cueing training in the home improves gait-related mobility in parkinson's disease: the rescue trial. *Journal of Neurology, Neurosurgery & Psychiatry*, 78(2):134–140.

Nikmaram, N., Scholz, D. S., Großbach, M., Schmidt, S. B., Spogis, J., Belardinelli, P., Müller-Dahlhaus, F., Remy, J., Ziemann, U., Rollnik, J. D., and Altenmüller, E. (2019). Musical sonification of arm movements in stroke rehabilitation yields limited benefits. *Frontiers in Neuroscience*, 13:1378.

Ribeiro, D. C., Sole, G., Haxby Abbott, J., and Milosavljevic, S. (2011). A rationale for the provision of extrinsic feedback towards management of low back pain. *Manual Therapy*, 16(3):301 – 305.

Schönauer, C., Pintaric, T., and Kaufmann, H. (2011). Full body interaction for serious games in motor rehabilitation. In *Proceedings of the 2nd Augmented Human International Conference*, AH '11. Association for Computing Machinery.

Shin, J., Ryu, H., and Jang, S. H. (2014). A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: a usability test and two clinical experiments. *Journal of NeuroEngineering and Rehabilitation*, 11(1):32.

Sousa, M., Vieira, J., Medeiros, D., Arsenio, A., and Jorge, J. (2016). Sleevear: Augmented reality for rehabilitation using realtime feedback. In *Proceedings of the 21st International Conference on Intelligent User Interfaces*, IUI '16, page 175–185. Association for Computing Machinery.