BSc Creative Technology
Final Project

Virtual Reality Rowing with Sonification: An Exploration of the Effects of Sonification in a Virtual Reality Environment

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Abstract

This thesis explores the design and effectiveness of sonification, a form of non-verbal auditory feedback, to enhance rowing in a virtual reality (VR) environment. The research question addressed is: "How can we design effective auditory feedback in the form of sonification to enhance rowing in a virtual reality environment?" Exploring effective sonification designs within this new environment and understanding their correlation with participants' rowing behaviour will contribute to enhancing training and performance in rowing sports. Additionally, this study could provide valuable insights into the inconsistent success rate of sonification.

Methods involved data collection from twenty participants, who engaged in rowing sessions under different VR and Sonification conditions. The study utilised a mixed-methods approach, combining the quantitative data analysis of the force curve with qualitative assessments of user experiences. The force curve data were analysed to evaluate stroke form and differences between sound groups, while subjective evaluations were utilised to analyse user perceptions of the experience.

Results reveal a significant distinction in angular velocity between the two sound groups, indicating the possibility of sonification to influence rowing behaviour. However, stroke form and angular velocity showed no significant differences between sonification and no sonification conditions, suggesting the opposite. The VR environment and sonification were received as immersive and engaging by participants, who felt like it positively impacted their performance.

The discussion highlights the implications and limitations of the study, including the need for individualised feedback for rowers, potential learning effects among inexperienced participants, and considerations for prolonged VR usage. The study recommends further research on experienced rowers, personalised feedback systems, and the impact of feedback dependency on skill acquisition.

An important limitation is the incorrect implementation of the power curve due to the absence of drag factor calculations. Future research includes incorporating user characteristics and examining the effects of prolonged VR and sonification utilisation in addition to exploring different variables and evaluation methods.

In conclusion, this thesis contributes to the field by revealing the potential of sonification and VR to enhance rowing performance, but cannot give a clear answer on how to design effective sonification in a VR environment. Acceptance rate and appreciation are high for sonification and VR and differences in audio design suggest a potential impact on force output.

Keywords: rowing, sonification, virtual reality, auditory feedback, force curve, parameter mapping, angular velocity, performance

Contents

Chapter 1

Introduction

1.1 Background

Rowing is a popular sport that has been steadily growing in popularity in recent years. It is a low-impact, full-body workout that provides multiple health benefits to body and mind (LifeFitness, 2023). An important aspect of rowing is the ergometer, a specialised exercise machine which offers indoor workout options anywhere and anytime. The ergometer serves as a great substitute for on-water rowing and is able to track and measure the performance of athletes (Geer, 2018). There are various types of ergometers, such as the static concept 2 and the dynamic RP3. The RP3s are a more advanced version of ergometers that are better at mimicking the movements of the rower in a boat. As training on ergometers allows for real-time tracking of performance data and for close interaction between coaches and athletes, it creates an environment in which it is easier to provide feedback to the rowers.

Rowing is a sport in which feedback is an essential part of training and coaching. Monitoring the performance of athletes in real-time is challenging since it is a sport that demands a high level of coordination and precision as well as a required continuous effort. Hohmuth et al. (2023) state that subtle variances in technique can have significant effects on the performance of athletes. Improper form can cause injuries to the back and the shoulders (Sayer, 2023). Incorporating the right feedback at the right moment into training improves the athlete's execution of a movement, and thus performance (Postma et al., 2022). Sonification is a technique that can be used to provide real-time feedback to athletes (Schaffert, Mattes, & Effenberg, 2009). It is the communication of information through non-speech audio. This technique allows athletes to receive immediate and relevant information during training on form and other aspects without the need for visual cues (Van Rheden, Grah, & Meschtscherjakov, 2020).

Virtual reality is a technology that immerses users into an environment generated by a computer. A VR headset allows users to see a world different from their actual surroundings. It is a completely immersive experience used for gaming, training, and other purposes and offers endless possibilities in adjustments and applications (Iberdrola, 2023).

Recent studies in sports HCI illustrated that athletes and coaches use and are open to further use of virtual reality (VR) in training (Pastel et al., 2023). The integration of VR can enable certain advantages in sports training, especially in skill development and coaching as it can simulate real-life environments while being completely controlled and adaptable (Ruffaldi & Filippeschi, 2013). This graduation project is part of the "Rowing Re-imagined" project, jointly carried out by the UT and the VU, in which a research platform is developed for multi-person rowing in VR using RP3s. On the one hand, the research platform aims to offer a diversity of VR environments, tasks, and feedback for novel forms of training. On the other hand, the versatile setup can be used to systematically do fundamental research into the conditions and determinants of performance in rowing.

The effectiveness of sonification for both on-water rowing and indoor rowing is a subject of interest, but existing studies have shown inconsistent results. Research performed by (Schaffert & Mattes, 2015) with elite athletes demonstrated positive outcomes, while other studies involving similar sonification methods and participants with varying skill levels did not show significant improvements in velocity fluctuations or motor performance (Dubus, 2012; Minciacchi et al., 2016). The challenge is to design sonification feedback that can be implemented in the VR environment and to understand how the design influences the rowing cycle of the participants. Exploring effective sonification designs within this new environment and understanding their correlation with participants' rowing behaviour will contribute to enhancing training and performance in rowing sports. Additionally, this study could provide valuable insights into the inconsistent success rate of sonification.

1.2 Goal

The goal of this thesis is to explore the usage of sonification feedback in rowing on RP3s in a virtual reality environment. This has the potential to ultimately enhance and improve the current state of rowing training on ergometers and to create an experience for athletes that is closer to on-water rowing. The study is driven by three main objectives. First, it aims to explore different design options for sonification. Second, it seeks to assess the effectiveness of the auditory feedback. Lastly, it focuses on evaluating how the feedback and virtual reality affect the rowing performance and overall user experience of athletes.

The project starts with the existing platform, Virtual Reality for Virtual Rowing Training set-up (VR4VRT), which is continuously being extended. VR4VRT, which is a rich research environment for multi-person rowing, consists of a technological setup with two ergometers, a social VR setup in which two rowers can virtually row together in a single boat, initial measurement components to collect data on the rower's power/effort, and some initial virtual elements in the environment.

The focus of this project will be on effective auditory feedback as a new feature of the platform. Sonification could be an interesting approach for incorporating additional feedback into the system. It has already been successfully applied in the sport of rowing and has certain advantages over other forms of feedback. It has positive effects on the performance of the athletes during on-water rowing training sessions. The aim of exploring the design of the sonification is to improve the performance and training sessions of rowers in the virtual reality environment while advancing the knowledge of sonification's applicability and impact.

1.3 Research questions

The goal mentioned above resulted in the following main research question and subquestions:

1.3.1 Main question

How can we design effective auditory feedback in the form of sonification to enhance rowing in a virtual reality environment?

1.3.2 Sub questions

- What kinds of rowing-related interactive technology systems have already been created?
- What are the key parameters of rowing for which you can offer or can be translated into feedback?
- How has audio been shaped by research for feedback in sports?
- How does incorporating sonification impact the rowing behaviour of the users?
- How does incorporating sonification and virtual reality impact the motivation, engagement, and overall training experience of the users?
- How can the effectiveness of the sonification be measured and evaluated?

The research questions serve as the framework for this research paper. Firstly, the rowing-related work and state of the art will be addressed. To follow up, a literature review will be conducted in which a classification of sonification techniques will be discussed and a comparison of the specifications of the developed audio for the experiments will be performed. Furthermore, the effectiveness of the different techniques will be addressed and as to how they did affect the recipients. At last, a combination of the total effectiveness and limitations will be discussed in this review.

Thereafter, interviews will be carried out to find the most suitable audio feedback design. The design will be mostly based on the literature. Next, the library of sounds that is created will be explained, as well as the user tests which are simultaneously set up. Afterwards, the test results will be examined, followed by a discussion and conclusion. At last, future research recommendations will be given.

Chapter 2

Literature review

This chapter delves into the background research, the state of the art in rowing-related technologies, and an in-depth review of the relevant literature related to sonification.

2.1 The sport of rowing

Rowing is a water-based sport in which athletes utilise oars to propel a boat forward. Rowing first arose as a sport in London in the 18th century on the River Thames (*the Sport of Rowing*, n.d.). A few centuries later, the indoor rowing machine (ergometer) was developed in 1981 to mimic the on-water experience and provide insights into measurements (Geer, 2018). Rowing is a low-impact, high-intensity workout (LifeFitness, 2023).

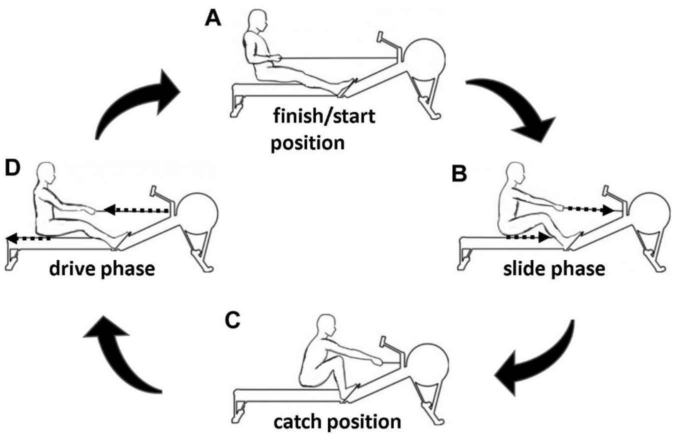


Figure 2.1: *The rowing stroke cycle in four stages*

2.1.1 Rowing stroke

Rowing is essentially a circular movement called the rowing stroke cycle. This cycle consists of four different stages that are constantly repeated (Nolte, 2011):

- The catch position.
- The drive phase.
- The finish position.
- The recovery phase.

These four phases on an ergometer can be seen in figure 2.1. The catch is the beginning of a stroke in which the rower leans forward while extending their arms and positioning their shins vertically. During the drive phase, the rower first fully extends their legs, then the hips, while maintaining good posture. Then they reach the end position of a stroke, called the finish, by pulling the handle to the lower parts of the ribs and leaning back slightly. Finally, the rowers return to the catch position by reversing all movements during the recovery phase. A rower generally performs between 24 and 30 strokes per minute (SPM) during workouts, while in races the SPM often exceeds 30. (Concept2, n.d.). Beginners are advised to start with a rowing stroke of around 20-24 SPM (Vigour Group Ltd, n.d.).

2.1.2 Rowing force

How the different parts of the body apply force during the cycle can be seen in figure 2.2.

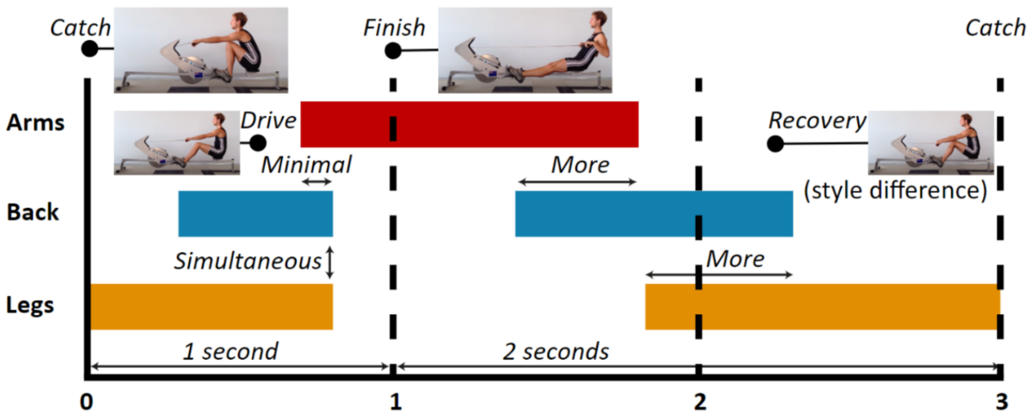


Figure 2.2: *The rowing stroke cycle represented by the muscle movements of arms, back, and legs over time*

The force curve also called the power curve, represents the application of force during a rowing stroke cycle. A smoother curve corresponds to a smoother application of force. The force curve gives rowers insight into their stroke movement and is useful in working on technique. An example of an ideal force curve displayed on an ergometer is given in figure 2.3. The ideal force curve has a soft entry with not too much force at the beginning. After that, continuous acceleration of the boat and constant force output is ideal. This will be visualised as a plateau on the curve. A smooth exit is necessary to keep the momentum. Keeping continuous speed and gradual acceleration is better than a too-high acceleration, which will result in more water resistance (Life Fitness, 2020). Having an irregular force output will result in a different-looking rowing curve, see figure 2.4. Losses in power are expressed by bumps in the curve. Too much or too little power at the beginning result subsequently in front-loaded and back-loaded curves.

Figure 2.3: *Display of an ergometer*

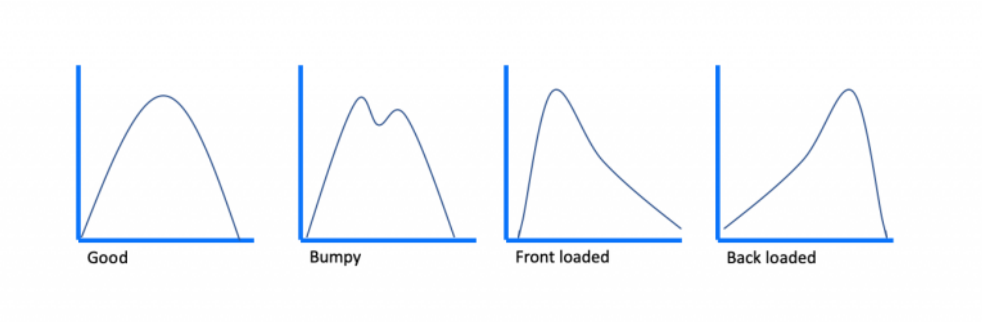


Figure 2.4: *Force curves based on different power outputs*

2.1.3 Virtual reality

As mentioned before, virtual reality is a technology that immerses users into an environment as if they are a character in a video game. This is done by using a VR headset, which allows the users to see a world fully generated by a computer. It is a completely immersive experience used for multiple purposes and offers endless possibilities in adjustments and applications (Iberdrola, 2023). Neos Metaverse is a virtual reality platform on which users can create their own content and experiences (*Neos Metaverse*, n.d.). It provides the necessary tools, and the current project is based in Neos.

2.2 State of the art

2.2.1 Rowing machines

The sport of rowing is continuously in development and several advancements in the area of technology and rowing exist. One of the more generally known by people is the ergometer, or indoor rowing machine as mentioned before in 2.1.3. The rowing machines come with digital displays that provide information on speed, distance, pace, heart rate, etc. Some are equipped with touch screens on which work-out related games can be played (Bullmore, 2023).

Figure 2.5: *Ergo meter with a water-based flywheel*

Rowperfect developed the RP3 rowing machine to better simulate the on-water rowing experience. These rowing machines are currently used for the project "Rowing Reimagined". In comparison with the more generally used ergometer, Concept2, the RP3 is superior in a few aspects. In terms of dynamics, it better simulates the rowing movement as both the bench and flywheel are able to move independently (*Home - RP3*, n.d.). The RP3 produces measured values at a slightly faster pace, which makes it more suitable for providing real-time feedback. However, it has a higher price tag, costing twice as much as a Concept2 (Redactie, 2021).

Figure 2.6: *Concept2 rowing machine (left) compared to an RP3 rowing machine (right)*

2.2.2 Mobile applications

Mobile phones are devices used by nearly everyone. Multiple mobile phone applications have been developed that can be connected to the ergometer. The rowing machines apps make it easier for the user to get updates on their performance and to track their progress over time (Raby, 2023). Most ergometers are equipped with a tablet containing such mobile applications. The applications provide real-time data insights for training, including details like force curves, and some even allow sensor integration such as heart rate monitors.

2.2.3 SmartOar

The *smartOar* is a type of advanced, wireless rowing equipment. Their oars are equipped with sensors that can track a multitude of variables regarding the athlete's performance. The force delivered during a stroke is measured in real-time and can be monitored by coaches, trainers, and athletes. Having insights into the force curve during on-water training helps better the performance of the crew (smartOar, 2022).

Figure 2.7: *The smartOar*

2.2.4 Fitness wearables

Rowing-specific fitness wearables refer to technology devices designed for rowers and boats to track technique, performance, fitness levels or bio-signals. The wearables can range from smart watches (Roux, 2022) and smart clothing (Dijkstra, 2018), to measurement and analysis devices like *Accrow* that can be attached to the boat (Cesarini, Schaffert, Manganiello, Mattes, & Avvenuti, 2013).

2.2.5 VR simulators

As mentioned before, virtual reality has endless possibilities for applications. One of the implementations is rowing simulators that can provide extra dimensions to the workout making it more interactive (HOLOFIT, 2023).

2.3 Audio feedback

Multiple systems have been designed to provide audio feedback for both on-water and indoor rowing training. An example is the acoustic feedback system *Sofirow* developed by Schaffert, Mattes, and Effenberg (2011a), which utilises MIDI (Musical Instrument Digital Interface) to translate the acceleration-time data of the boat into tones on the musical scale linking it to tone-pitch. The study demonstrated that it improves the mean boat velocities, increases the stroke rate and increases the rower's awareness of movements and motivation.

Figure 2.8: *Feedback system Sofirow*

2.3.1 Rowing parameters

The rowing parameters are the various measurable variables or factors that affect the performance of a rowing crew or individual. They can be divided into social and dynamic parameters.

2.3.2 Social parameters

Social parameters refer to the interactions and communication between crew members. These parameters include interpersonal coordination, communication, trust, crew phenomenology, team dynamic, motivation, sportsmanship and competition (Seifert et al., 2017). Since the effectiveness of the sonification will be measured by rowing performance and require one rower per user test, they will not be further covered in this review. They are not of importance to this project, as they cannot be effectively translated into audio feedback and investigating them would change the nature of the research.

2.3.3 Dynamic parameters

Dynamic parameters are more useful regarding this project and will be focused on. They refer to variables that are involved in rowing movements. These parameters include boat speed, boat acceleration, boat distance, stroke length, stroke rate, oar depth, oar angle, force curve, force provided by arms, legs and back, seat position, etc. (Minciacchi et al., 2016; Nolte, 2011; Schaffert & Mattes, 2015). A different approach of dynamic parameters is to look at an individual's bio-mechanics with parameters as aerobic and anaerobic power, as well as lower limb strength and power (Otter-Kaufmann, Hilfiker, Ziltener, & Allet, 2019).

Two important parameters are the stroke rate and the force curve. The stroke rate is often used by coaches to provide feedback as it tracks team performance in terms of efficiency and rhythm/cadence. A higher stroke rate equals high boat velocity but requires more effort from the team and can tire them out earlier. Training for an ideal and consistent stroke rate will better the performance. The force curve provides a direct indication of the performance of an individual athlete and can be used to optimise their stroke.

Overall, social and dynamic parameters play an essential role in the sport of rowing. Getting a better understanding of the parameters and optimising them leads to better performance and results on the water.

2.3.4 Feedback

Disclaimer: most of chapter 2.2 is copied from the literature review of the course Academic Writing.

In sports, feedback refers to information received by athletes regarding their performance or skills. It can be provided by the coach or athletes themselves and plays an important role in improving performance. There are different ways of providing feedback to an athlete. Regarding timing, feedback can take place before (demonstration or instruction), during (concurrent feedback or guidance) or after (immediate or delayed terminal feedback) the execution of a movement. Concurrent feedback is useful for boosting performance, particularly in the early stages of learning or when task complexity is high. Terminal feedback is preferred for both low and high task complexity. The frequency in which feedback is given can vary from continuous to less frequent. Feedback delivery methods include fading, bandwidth, self-selection, summary, and average. The one used in this project will be bandwidth feedback, which only provides feedback if the error surpasses a specific limit in a range of limits. This falls under the category of negative feedback, which helps with motor learning. On top of that, feedback schemes with feedback fading schedules can be explored as less feedback over time can prevent a dependency on the feedback.

Feedback can be provided on three different modalities: visual, haptic and auditory. Visual feedback can range from realistic to abstract visualisations. Haptic feedback can be either tactile or kinesthetic, where tactile feedback uses varying sensations and kinesthetic feedback supports body orientation. Auditory feedback can use properties of sounds such as pitch, timbre, and rhythm. Combining different modalities results in multi-modal feedback. (Postma et al., 2022). In this project, the focus will lay on auditory feedback in the form of sonification.

2.3.5 Sonification

Sonification is a form of auditory feedback that is commonly used in sport-related area research and is regarded as useful in providing feedback (Dubus & Bresin, 2015; Postma et al., 2022; Schaffert et al., 2009). Although sonification has been successful in studies, it has yet to be widely used in everyday applications in more complex manners (Neuhoff, 2019). It has been proven that sonification can be successful in both rowing and other sports (Dubus & Bresin, 2015; Maes, Lorenzoni, & Six, 2019; Minciacchi et al., 2016; Postma et al., 2022; Schaffert, Oldag, & Cesari, 2020). Sonification has an advantage over other forms of feedback in that it does not interfere with the visual spectrum, and it can be applied continuously in real-time without interrupting training (Masai, Kajiyama, Muramatsu, Sugimoto, & Kimura, 2022). There The effectiveness of sonification depends on the chosen utilisation (Schaffert & Mattes, 2015).

2.3.6 Sonification techniques

A variety of several successful sonification techniques have been developed, with some being more relevant for rowing. In the sonification handbook by Hermann, Hunt, and Neuhoff (2011), five different techniques are identified: audification, auditory icons, earcons, parameter mapping, and model-based sonification. The handbook specifies that parameter mapping and audification are the two primary techniques used in sonification. Since audification is not applied in rowing, this review will not further elaborate on it. Parameter mapping (PMS) is a method that utilises auditory parameters such as volume, pitch, and timbre to convey data in a way that can be easy to understand and display. This technique is almost exclusively used among rowing-related experiments (Cesarini et al., 2013; Dubus & Bresin, 2015; Minciacchi et al., 2016; Schaffert et al., 2009; Schaffert, Mattes, & Effenberg, 2011b), with some experiments using additional techniques such as earcons (Dubus, 2012) or auditory cues (Schaffert & Mattes, 2015). The studies reviewed did not mention any other categorisation systems, indicating that the system established by Hermann et al. (2011) is the accepted standard.

Different forms of PMS are being mentioned in the experiments like acoustic mapping (Schaffert et al., 2009), direct mapping (Dubus, 2012), continuous mapping (Dubus & Bresin, 2015), or pitch-related mapping (Schaffert & Mattes, 2015). However, these are just terms used to emphasise small deviations from the general method, such as different utilisations of variables, output, and timing of the feedback. While these deviations cannot be further categorised, a separate distinction in PMS can be made based on the various kinds of data that can be mapped. For example, one could divide the techniques between rower data (e.g., stroke rate, posture, and physiological data) and boat data (e.g., acceleration and velocity). Although experiments with physiological data in PMS have not been conducted yet, the continuous improvements in technology offer increasingly more opportunities to explore this and other areas (Dubus & Bresin, 2015). In conclusion, studies use several categories of sonification techniques with parameter mapping the most commonly used in rowing experiments.

2.3.7 Audio specifications of sonification

Depending on the chosen approach and parameters, various forms of audio sonification have been formed. The sonification can either consist of audio that is prerecorded or audio that is being synthesised. Dubus (2012) employed two models of prerecorded audio in his study. The first uses the sound of a car engine, while the other model utilises the sound of the wind, both with the volume of the sounds representing boat speed. The other two models in this study utilised synthesised sounds, with one model using a basic sound frequency connected to boat velocity, and the other model using MIDI with musical instruments to represent velocity and acceleration peaks (e.g., pizzicato strings for speed and drum hit/bell ring for acceleration). Similarly, the acoustic feedback system *Sofirow* utilises MIDI to translate the acceleration-time data into tones on the musical scale linking it to tone-pitch, where the middle c-tone represents zero (Schaffert et al., 2011b). A study conducted on ergometers translated movement data to sound features such as frequency (pitch) and amplitude (volume) of a MIDI sound. The data consists of the variables grip force, footrest forces, grip pull-out length, and sliding seat position (Minciacchi et al., 2016). At last, Cesarini et al. (2013) mapped acceleration magnitude to sound pitch using a 12-tone scale. The studies reveal that similar methods and factors are utilised in the development of auditory feedback, with acceleration being the most frequently used.

When designing auditory feedback for purposes like performance and movement optimisation, certain requirements should be met. Firstly, the sound produced must appropriately represent the movement being measured. Secondly, qualitative changes in the movement data should be perceivable and differences should be easily identifiable through changes in the sound. Lastly, the resulting sound should be aesthetically pleasing to the listener (Schaffert et al., 2009). In a subsequent study, Schaffert and Mattes (2015) stated that design should include clarity, discrimination, compactness, consistency, detectability, and comprehensibility to improve usability.

On the other hand, other studies do not specify detailed requirements for the audio and simply indicate that it should be audible for humans or able to block external noise (Minciacchi et al., 2016). There appears to not have been established a set of standardised rules regarding the requirements when designing auditory feedback. However, it is generally understood that variables and criteria like perceivability and identifiability are important considerations so those will be considered in this review.

2.3.8 Effectiveness of sonification

The effectiveness of the sonification feedback can vary depending on its specific design and intended purpose. The main approach relies on using objective measures to evaluate the different feedback models. Schaffert has researched sonification in rowing for the past 15 years, from setting basic sound design requirements (Schaffert et al., 2009) to modifying her *Sofirow* system to a smartphone-based application (Cesarini et al., 2013). All her studies demonstrated that sonification is an effective tool for on-water rowing, as objective results showed improvement in mean boat velocities, more consistent stroke rate and time structure of the acceleration curve, shorter recovery phases, and increasing stroke frequencies (Schaffert et al., 2011a, 2011b; Schaffert & Mattes, 2015). In a similar fashion, rowing with masked hearing led to a reduction in movement precision as the stroke-to-stroke deviation increased significantly when the rowers wore noise-cancelling headphones (Schaffert et al., 2020). This further accentuates the importance of sound feedback on rowing performance. As sound feedback appears essential for rowing, sonification seems to be an excellent additional implementation to feedback methods for rowing.

Although Schaffert's research found significant positive outcomes of auditory feedback, other studies were less successful. An evaluation of four different sonification models on indoor rowing concluded that none of the models had a significant effect on the objective measure of velocity fluctuations (Dubus, 2012). Dubus and Bresin (2015) evaluated the same models on-water and found that, despite the stroke rate of a few athletes being affected by the models, they had no noticeable impact on the measurement of velocity fluctuations and thus no significant impact of sonification could be observed. Similarly, Minciacchi et al. (2016) utilised motion capture technology and found no significant improvements in individual motor performance using sonification on ergometers. Dubus, Minciacchi, and Schaffert used different mapping methods for sonification feedback, with Dubus and Bresin (2015) mapping velocity to the centre frequency of a trill and velocity to pitch, and Minciacchi et al. (2016) mapping ergometer variables to frequency and amplitude, while Schaffert et al. (2009) mapped acceleration to pitch. This difference in approach could explain the difference in results. Another explanation could be that Schaffert mainly made use of elite athletes while others also incorporated novices. While studies have objectively shown sonification to be an effective tool for on-water rowing, the effectiveness of feedback designs may vary based on their mapping methods.

However, solely relying on objective measures can constrain the total evaluation, as it fails to incorporate subjective measures that give valuable insights into the experience of rowers. Schaffert et al. (2009) used a multitude of subjective evaluations to assess the sonification models, particularly in the beginning stages of their research. Interviews with athletes and coaches revealed a high level of acceptance and appreciation, with rowers reporting being more self-aware of their movements, able to detect errors, and more motivated to improve their performance, and coaches noting improvements in team synchronisation and overall performance (Cesarini et al., 2013; Schaffert et al., 2011b; Schaffert & Mattes, 2015). Furthermore, despite that the four sonification models of Dubus showed no significant impact on performance in both indoors and on-water rowing, interviews with athletes and coaches showed a high level of acceptance for incorporating this type of feedback into training programs (Dubus & Bresin, 2015; Dubus, 2012). Dubus (2012) even showed that rowers were able to distinguish basic characteristics of the rowing cycle and differentiate between novice and expert rowing by listening to the sonification samples created from other rowers' movement data. In conclusion, based on the subjective evaluations, it can be conducted that sonification is regarded as a useful tool for on-water rowing.

2.3.9 Conclusion on sonification

The objective of the literature review performed was to identify successful sonification methods in the context of the sport of rowing. Studies have shown that parameter mapping sonification feedback is an effective tool to implement for training in rowing. This type of feedback provides athletes with immediate and continuous feedback that is not visually distracting and improves their execution of movements. Additionally, it increases self-awareness and improves overall performance and team synchronisation. However, the success of sonification is highly dependent on the chosen mapping technique, with acceleration to pitch being the most successful in previous studies. While not all studies have been successful objectively, subjective evaluations have shown positive results, with athletes and coaches reporting a high level of acceptance and appreciation for sonification feedback. Although sonification has proven to be effective in rowing and other sports, there is still potential for improvement with the continuous advancements in technology. Overall, sonification has the potential to revolutionise the way athletes train and improve their performance.

There are however several limitations in the literature on sonification technology. Firstly, the research has not extensively covered the limitations of sonification technology itself. Schaffert and Mattes (2015) have briefly mentioned that the understanding of sonification and auditory displays varies among individuals due to differences in their perceptual abilities. This raises the question of whether sonification technology is good enough compared to other feedback techniques and whether it will be widely used in the future. Neuhoff (2019) mentioned that there is no reported widespread everyday use of sonification in sports and speaks of the challenges sonification must overcome in order to be utilised in a universal manner. However, the studies used in this review do not address any of these challenges or provide a plan for widespread adoption, but upcoming research should.

Moreover, none of the studies has explored the potential implications of sonification in sports, such as an over-reliance on feedback systems which could hinder skill development. Future research could explore if this leads to a loss of mastery and virtuosity. Additionally, Schaffert's requirements for the sonification design only focus on the effect it has on performance and do not address the potential drawbacks of sonification, such as sensory overload or distraction. Although Schaffert mentions that the design should be aesthetically pleasing, the drawbacks are not specifically mentioned. To address these limitations, follow-up studies should examine this issue and incorporate the long-term effects of sonification on on-water rowing training programs. The studies should also include more assessments with rowers of different experience levels. While successful sonification techniques have been identified, unanswered questions still exist that future exploration could provide insight into how sonification technology can be most effectively applied in the sport of rowing.

2.4 Hypotheses

After reviewing the relevant literature and exploring similar projects, the following expectations were established.

Research question: How does incorporating sonification impact the rowing behaviour of the users?

H1: Users will demonstrate a better rowing technique when receiving audio feedback, which is evidenced by smoother and more consistent force curves.

H2: When users are exposed to audio feedback that deviates from the ideal rowing curve, the resulting power curve will exhibit measurable deviations as well.

Research question: How does incorporating sonification and virtual reality impact the motivation, engagement, and overall training experience of the users?

H3: The introduction of real-time audio feedback will lead to a quantifiable increase in motivation and engagement levels among users.

H4: The incorporation of the virtual reality environment will result in a more immersive and enjoyable experience for users compared to a non-virtual reality environment.

With these four hypotheses in mind, this research aims to investigate the effects of the incorporation of sonification on rowing behaviour and the experience of users. The study will give insights into the potential gains of utilising real-time audio feedback and VR in the training sessions of rowing.

Chapter 3

Methodology

In this chapter, the methodology will be presented. First, the Design Process for Creative Technology will be explained, as it functioned as the general structure of the performed study. Subsequently, this chapter covers the study setup and requirements.

3.1 Design process of CreaTe

Mader and Eggink (2014) suggested a design process that consists of four phases: Ideation, Specification, Realisation, and Evaluation. The process is portrayed in figure 3.1 and combines components from the classical models that consist of a divergence and convergence phase and the spiral model. Divergence involves defining the design space, while convergence focuses on narrowing down the design space until a specific solution is found. These approaches are incorporated into ideation, specification, and realisation. The spiral approach, on the other hand, guides the sequence of design steps that do not follow a strict order and involve problem understanding and definition, project planning, idea generation and evaluation, and reflection. This model is present throughout the ideation and specification.

3.1.1 Ideation

During the ideation phase, a pool of ideas for a product or solution is created. The outcome of this phase is a more developed project idea, along with a clear understanding of the problem requirements. The objective of this project is to design an effective sonification technique for rowing in a VR environment. In the ideation phase, it was decided that this will be done by creating a library of sounds which corresponds to the power curve.

3.1.2 Specification

During the specification phase, multiple prototypes are created and user tested to receive feedback quickly. These prototypes are used to explore different design options. User evaluations can help find new insights or functionalities. All these processes contribute to determining the final project concept.

3.1.3 Realisation

In the realisation phase, the goal is to take the product specification and turn it into a physical final product by breaking it down into smaller parts. Those parts will be created,

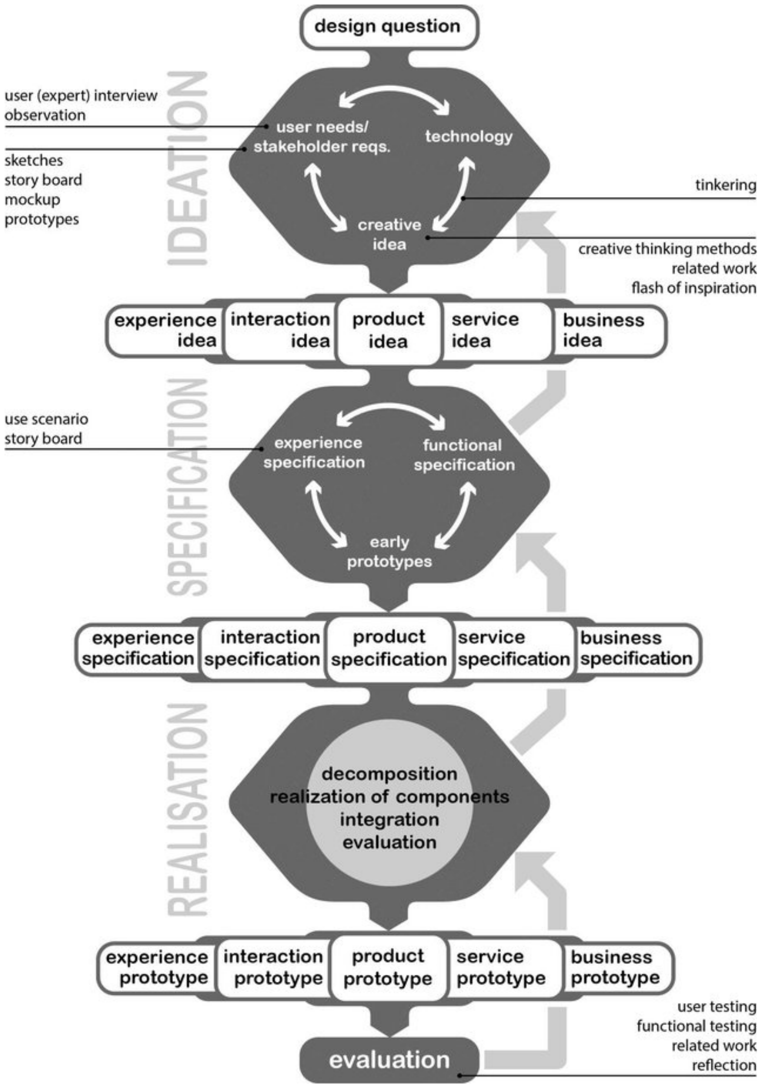


Figure 3.1: *The Creative Technology Design Process*

put back together and evaluated. The main focus is to make sure the final product matches the original specification.

3.1.4 Evaluation

The evaluation phase involves functional testing, verifying whether all original requirements are met, user testing, related work, and reflection. These different aspects are all important to evaluate the final product.

3.2 Ideation

As stated in 3.1.1, the ideation phase provides room for the generation of ideas and to develop project concepts. During this stage, the project requirements will be established.

3.2.1 Brainstorm with professional athlete

Following the collaborative brainstorming session with a professional rowing athlete from the *Euros* rowing club, Table 1 was created. The athlete has an impressive background in lightweight rowing, having been involved in professional competitions since 2018. The table lists a multitude of sounds, variables and actions which could be used in the sonification process.

Sounds	**Actions**		**Stroke cycle**
Water splashing	Pulling oars	Power output / intensity	Catch position
Single splash	Colliding oars	User's technique	- Oars in water
River rapids	Oars hitting water	User's form	- Knees bent
Wind blowing	- Properly	User's posture	- Straight arms
Heartbeat	- Improperly	Start rowing session	Drive phase
Boat creaking	Speed of gliding seats	End rowing session	- Push legs
Whoosh sounds of wheels	- Fast	User's heart rate	- Bring oars to chest
- High sound	- Slow	Reaching milestone	- Lean back
- Medium sound	- Consistent	Speed	Finish position
- Low sound	Acceleration	Nothing goes wrong	- Lean back further
Oars colliding	Increasing stroke rate	Power curve	- Oars to chest
Oars clicking	Slowing down	Power stroke	Recovery phase
Oar clicking cleanly	Decreasing stroke rate	Peak moment	- Oars release from water
Oars loosen		Stroke length	- Extend arms forward
Oar loosen cleanly		Total power	- Bent knees
Distortions		Percentage peaks	
Almost no sound		Power curve till peak	Run (distance boat stroke)
Zoof sounds		Curve from peak	
Vroom sounds		Optimal curve	
Whoosh sounds		Seat position	
- Intensity can differ		RP3 position	
Metal clanging		Handle position	
Clicking sound		Back position	
Bird chirping			
Applause			
Whistle blowing			
Horn blowing			
Water dripping			
Rhythmic drumbeat			
Ocean waves			
Coach voice			
Breathing sounds			
Birdsong			
Waterfall			
Bubbles			
Bell chimes			
Rowing team chants			

Table 3.1: *Results of the first brainstorm session*

We found a multitude of potential sounds that can be used and classified into the following categories:

- Environmental effects: such as water, wind, and birds.
- Ambience sounds: including cheering, clapping, chanting, and musical instruments.
- Rowing sounds: from the boat, oars, seat, and other materials.
- Motion perception effects: including whoosh, zoof, and vroom.

Because of the focus on rowing performance, which is evaluated by the rowing movements, a brainstorming session with an audio expert on the motion perception sounds was conducted.

3.2.2 Brainstorm with audio expert

From the brainstorming session with an audio expert, several possibilities for the audio design were established. The sound feedback could be divided into two parts. For teaching purposes, there would be a simple sound that provides feedback on how to row. This could be regarding technique, pace, speed, power output, rowing curve, etc. We came to the agreement that it would be a simple "whoosh" sound, that had also emerged as a motion perception sound in the previous brainstorming session. To create this, a white-noise wave could be altered until you get the desired effect. The desired effect is the idea of a sudden/quick motion representing the "whoosh" sound. It was advised to use the program *Reaper* for the development of sound feedback. There should be multiple files of whooshes, all slightly different in sound. These can give feedback on different aspects related to rowing.

It was suggested to use FMOD for this interactive part of the whoosh sound alterations. Real-time sound synthesis is an option that was not recommended. The technology for that is still too complicated. It would be easier to have the sounds in advance that can be played and customised in real-time in the system. Then apply filters in FMOD so that the sound adapts to the user. It was advised to start with the development of the interactive sounds and wait with developing the second segment.

The second sound would be an audio fragment that functions as a reward sound. This would be an ambience sound that would be pleasant for the participants to listen to. That is the desirable sound that a user would hear after a certain amount of correctly executed rowing strokes. Only if something goes wrong do you go back to the functional whoosh. This ambience sound should change throughout the whole experience, indicating that the rowers are moving through spaces. This could include the sound of sheep or a primary school with playing children. Incorporating musical elements will get satisfaction from the users. Still, the rhythmic effect should be kept in the second sound to set the tempo for the user. This can be done with a drummer's hand or the lapping of water.

Pitch was seen as an influential variable with which feedback could be provided to the user. Although not regarded as the best choice. It was difficult to find a suitable option to provide adaptive feedback with and it was advised to simply start experimenting with the variables. The expert noted that it would be interesting to develop an adaptive music system, but considering the time frame, that will not be possible. The system will always start with the whooshes as it calculates the bpm based on the rowing rhythm, then slowly fades the functional sound over to the reward sound while still keeping the pace. The reward sound should also do something more than just providing ambience. A drum could for example indicate the rowing tempo. Environment-free sound.org was given as a website that provides decent sound samples to work with.

According to the rowing expert, there are two factors to play with and shape the feedback around. Feedback can be provided on whether the rowing curve is properly executed or on the general pace of the rower. This can be done by for example linking the tempo to a beat or by adjusting the speed of the rowing curve to suit different people.

The feedback system could be tailored to include personalisation, as every individual differs in size and preferences. Do you need shorter whooshes for shorter persons? The pace and movement are dependent on the individual, and with something like that, you can play on the basis of an ideal rowing curve. A user could select their favourite song and determine the tempo of the rowing session.

In conclusion, the session with the audio expert provided a solid foundation to start with the development and implementation. Following the previously mentioned outlines will result in a well-rounded feedback system that offers an immersive, engaging and personalised experience to the user during their virtual rowing session.

Figure 3.2: *Rowing setup*

3.3 Design specification

3.3.1 Rowing setup

The rowing platform of Rowing Reimagined was first built in 2016 and has undergone multiple iterations. The current setup was developed last year by Jordi Weldink and Casper Sikkens, who revised the whole project thoroughly. The project continues to expand as around ten students are currently involved in the development.

Physical environment

The setup used for this project consists of one RP3, the valve index VR headset and controllers, three Tundra Trackers, four base stations and a wireless noise-cancelling headphone. A data cable is connected to the RP3 for reading out the flywheel input directly into

Figure 3.3: *VR headset, controllers and trackers*

the computer. The setup also contains a disinfection station that makes use of ultraviolet light to kill germs and bacteria. See figures 3.2 and 3.3.

Trackers The devices used in the project to track the spatial data of the seat, the machine, and the handle are the Tundra Trackers (*Tundra Labs*, n.d.). These trackers are more compact and have a better battery life compared to the HTC Vive Trackers that were previously used in the project.

Base stations To enable wide-area tracking with minimal errors, the project uses four Base Station 2.0s. These are utilised for accurately tracking the locations of controllers, headsets and trackers. Each station is mounted on tall pillars positioned in the corners of the room and should be at least 2 meters in height and pointed downward at an angle of approximately 30 degrees, see figure 3.4. Each individual component should be visible to at least two base stations to enable tracking. The Play Space (the area occupied by base stations) is essential for the operation to function properly. A minimum Play Space of 2.5m wide and 4.5m long is recommended for one machine, in addition to space for the computer, monitor, etc (Sikkens, 2023).

Figure 3.4: *Base station*

Digital environment

The digital environment of the project is set in Neos (*Neos Metaverse*, n.d.). This was done because the program supports multiplayer features better than Unity (UnityEngine, n.d.). Neos is run through the online gaming platform Steam, which includes VR support known as SteamVR. Once users perform a quick room setup, SteamVR translates the input from the trackers and base stations to the digital space.

Web sockets The Neos environment is supported by two web sockets. One is responsible for the communication of variables between Neos and the RP3 and the other one is responsible for logging the user outputs into a text file once the rowing session has begun.

3.3.2 Project concept

After exchanging ideas with the supervisors and the experts, the following project concept was formulated. A library of the same sounds will be created that corresponds to the different dynamic parts of the rowing curve. It is expected that this will have a positive outcome on the movements of the rowers as the sounds allow them to optimise their power curve. This will be explained thoroughly in 4.1. The sound will be provided in real-time and will play parallel to every rowing stroke performed. The sound will consist of a whoosh sound that feels intuitive to the rowers and are a dynamic expression of the power curve. In addition, a second set of sounds will be created to explore the possibility of influencing the rowing behaviour of the participants in a negative manner.

3.3.3 Preliminary requirements audio

Based on the background research on other sonification models, a few preliminary requirements were set for the design of the audio:

- **Clarity;** The information content is translated quickly and accurately and the sound that is produced must appropriately represent the movement being measured.
- **Compactness;** The information presented is reduced to the task-relevant essential minimum. This will prevent the user from getting too much information. It is essential to design audio feedback carefully to avoid distracting from the experience or becoming annoying.
- **Comprehensibility;** The meaning is easily understandable without extensive learning and is unambiguous. This also means that qualitative changes in the movement data should be perceivable, and differences should be easily identifiable through changes in the sound.
- **Intuitive;** Sounds should be intuitive to the rowers. Rowing sounds are from on-water environments like wind, water and boat sounds. These are movement-based sounds that are inherently present when rowing. Therefore, sounds from musical instruments are excluded.
- **Aesthetically pleasing;** At last, the audio must be both pleasing to listen to for the user and aiming to be harmonic relative to the performed rowing stroke.

Chapter 4

Implementation

In this chapter, a detailed description of the implementation and realisation of the project will be provided.

4.1 Audio design

For the project, two different sound fragments were composed. As the project uses participants with no or little rowing experience and the rowing stroke of a beginner should be around 20-24 SPM, it was chosen to make the sounds 3.0 seconds long (20 SPM). For composing the sounds the digital audio workstation *Reaper* was used (Reaper, n.d.). The sounds consist of a simple white noise wave from which the high tones are filtered. This causes the sounds to resemble the sound of water or wind and to sound less shrill. Fade-ins and fade-outs were added to create a sound structure and add the signature whoosh sound of a wave as can be seen in figures 4.1 and 4.2. The most common drive-to-recovery ratio is roughly 1:2 and this is translated to sound 1 in having the volume peak at 1.0 seconds. For the second sound we choose to have a 0.33 to 2.67 ratio to see if this would affect the rowing curve. Regarding the second hypothesis, it is expected that the force curve of the rowers will become more front-loaded when the second sound is used.

4.1.1 Adaptive factor

One of the requirements of the audio was that it should be adaptive to its users. To achieve this a system was implemented that nudges the user to a rowing stroke of three seconds. The system will calculate the mean time of the last five rowing strokes and use that to play the according sound fragment. A total of 20 audio fragments were made of the same sound ranging from 0.3 seconds to 6.0 seconds long with a difference of 0.3 seconds per fragment. Once the mean stroke time is calculated the system will play the fragment that is 0.1 closer to 3.0 seconds fragment. If a participant has a mean stroke time of 3.6 to 3.9 seconds, the audio fragment of the 3.3 seconds will be played during the next stroke. If the mean stroke time is 2.1 to 2.4 seconds, the audio fragment of 2.7 seconds will be played. When the mean time is between 2.7 and 3.3 seconds, the audio fragment of 3.0 seconds will be played.

Earlier iterations of the code utilised a method that made use of the SoundTouch library (Woudenberg, 2021). This method was able to convert the audio fragment in real-time without the need for a library of sounds as is used in the current version. However, buffering the sound added a delay, as it cost more processing time. Furthermore, it added

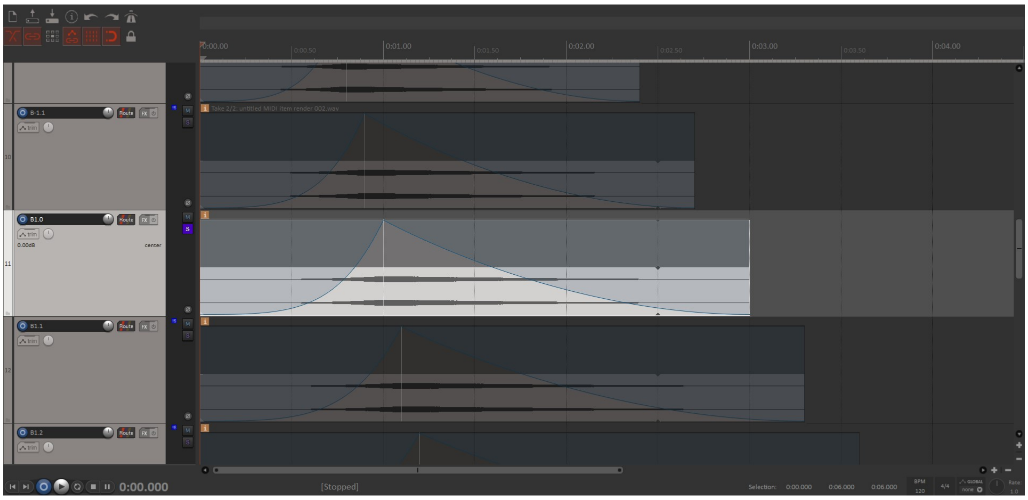


Figure 4.1: *Sound fragment 1 in Reaper*

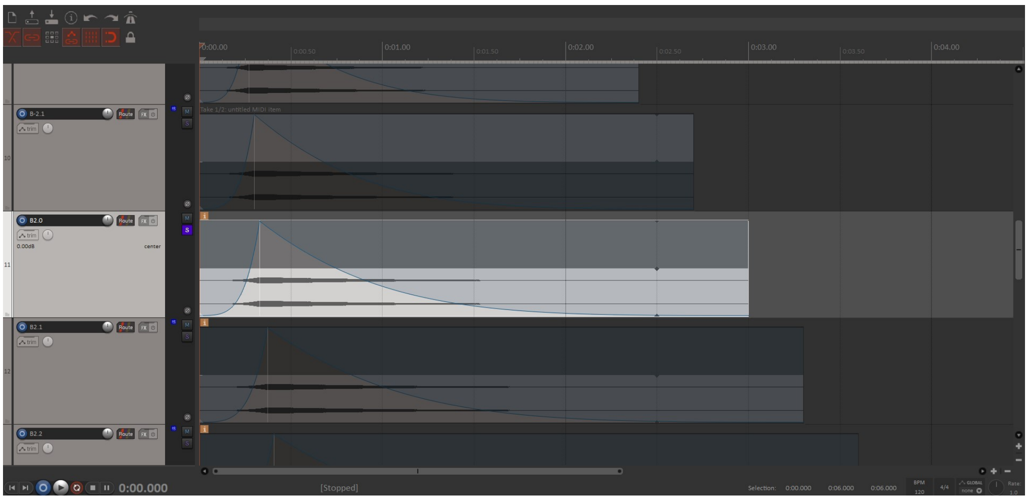


Figure 4.2: *Sound fragment 2 in Reaper*

an extra layer of noise over the sound which could not be filtered as the original sound was composed of white noise. That is why the other approach was chosen.

4.2 Realisation process

The current digital environment is set in Neos. As almost all aspects are coded inside this program, it was first attempted to process the sound in that environment. However, Neos does not offer many functionalities regarding audio modification besides playing a sound and does not support plug-ins like FMod as Unity does. For those reasons, it was chosen to modify the web socket that is responsible for the communication between the RP3 and Neos. The web socket no longer obtains values from Neos to check which phase the rower is currently in, but directly calculates it from the linear velocity acquired from the RP3. The web socket does not require that Neos is running in the background anymore. Additionally, the web socket code was updated so it can also perform the operations necessary for audio modification.

4.3 Data collection methods

The previous project version used the second web socket to write all the data into a text file. However, for the socket to work, Neos must be running simultaneously. A second data-gathering method was added in the first web socket addressing the dependency on Neos. This method calculates and records the following variables:

- time; the measurement of the duration of the session in seconds.
- stroke count; the number of rowing strokes performed.
- currentDt; the time between flywheel impulses from the RP3.
- currW; the angular velocity of the flywheel in rad/s.
- linearVel; currW translated to the speed of the boat in m/s.
- total stroke time; the time the current stroke is in progress in s.
- average stroke time; average time calculated from the last five strokes in s.
- drive time; the time the current drive phase is in progress in s.
- recovery time; the time the current stroke phase is in progress in s.
- SPM; the average number of rowing strokes, calculated from the last 5 strokes.
- power; the force calculated from the currentDt and currW.
- state; the state the rower is in, either drive (1), recovery (2), or idle (0).

The gathered data is immediately written to CVS files, see figure 4.3. These are appropriately named based on the condition, see 5.1.3, and participant. A data point is collected per impulse of the RP3 machine. The flywheel has four equally spaced magnets that the machine uses to calculate the velocity of the wheel. An average of thirty data points are collected per second, depending on the speed of the flywheel. The data of the CVS files is used for the data analysis later on.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Time	Stroke cou	currentDt	currW	linearVel	Total stro	Average st	Drive time	Recovery	SPM	Power	State
2	0,00054	1	0,021535	72,94268	0,008611	0,000538	2,203464	1,075296		27,22985	7,66E-05	1
3	0,041655	1	0,021325	73,65871	2,577697	0,041654	2,203464	1,075296		27,22985	2055,307	1
4	0,08263	1	0,020986	74,84894	2,619349	0,082629	2,203464	1,075296		27,22985	2156,559	1
5	0,12283	1	0,020595	76,27036	2,669092	0,122829	2,203464	1,075296		27,22985	2281,769	1
6	0,161958	1	0,020171	77,87528	2,725256	0,161957	2,203464	1,075296		27,22985	2428,864	1
7	0,200409	1	0,019742	79,56712	2,784462	0,200408	2,203464	1,075296		27,22985	2590,63	1
8	0,238462	1	0,019319	81,3079	2,845381	0,238458	2,203464	1,075296		27,22985	2764,411	1
9	0,274974	1	0,018912	83,05624	2,906564	0,274973	2,203464	1,075296		27,22985	2946,6	1
10	0,311124	1	0,018515	84,83861	2,968939	0,311123	2,203464	1,075296		27,22985	3140,4	1
11	0,346438	1	0,018141	86,5866	3,03011	0,346437	2,203464	1,075296		27,22985	3338,539	1
12	0,381268	1	0,017794	88,27784	3,089295	0,381267	2,203464	1,075296		27,22985	3538,013	1
13	0,415578	1	0,01748	89,86478	3,14483	0,415576	2,203464	1,075296		27,22985	3732,268	1
14	0,449245	1	0,01719	91,37968	3,197845	0,449244	2,203464	1,075296		27,22985	3924,219	1
15	0,482619	1	0,016925	92,80984	3,247893	0,482616	2,203464	1,075296		27,22985	4111,37	1
16	0,515412	1	0,016676	94,19504	3,296368	0,515411	2,203464	1,075296		27,22985	4298,218	1
17	0,547766	1	0,016447	95,50591	3,342242	0,547765	2,203464	1,075296		27,22985	4480,176	1

Figure 4.3: *Example of collected data in a CVS file*

Chapter 5

Evaluation

In this chapter, the design, user tests and results of the study will be discussed.

5.1 Study design

To answer the various research questions 1.3, the following study set-up was created. The study utilised a mixed-methods approach as it collected both quantitative and qualitative data. It obtained quantitative data via the two web sockets connected to the RP3 and the trackers. On the other hand, qualitative data was gathered through post-assessment interviews with the participants.

5.1.1 Participants

A total of 22 individuals with no or little rowing experience participated in the study. They differed in age, ranging from 20 to 28 years old, in height, ranging from 160 to 190 centimetres, in weight, ranging from 55 to 105 kilograms, and in gender, with 9 out of 20 being women and 11 out of 20 being man. Among them, 75% practice sports, with going to the gym, playing volleyball, and football being the most frequent. On average, the participants exercised 2.35 times per week, and rated their fitness levels to be 2.9 out of 5 in terms of their physical condition. Additionally, 60% of the participants had previous experience with rowing, both on-water rowing and on the ergometer in the gym. Almost all (95%) participants had prior virtual reality experience, ranging from gaming to development, with 60% experiencing motion sickness from time to time. Two of the participants were used for pilot testing. Each user test took around 40 minutes to one and a half hour, depending on the individual and the occurrence of errors.

5.1.2 Protocol

Upon arrival, the participants are welcomed and introduced to the practitioner and the project. After answering a few demographic questions and signing the informed consent, a short explanation video is shown demonstrating the proper technique of a rowing stroke. The participants will first have a two-minute warming-up session on the RP3, during which they have the opportunity to adjust themselves and receive feedback on their rowing stroke execution if necessary. Following the warm-up, the participants will perform four separate rowing sessions of three minutes in different conditions. Between each session was a two-minute break, which allowed the participant to catch their breath. If needed, the breaks could be extended. This was to make sure that the participants felt mostly the same at the beginning of each session. Afterwards, a post-assessment interview was conducted to gather information about the experience and any additional topics of interest. For the fully detailed user test protocol, please refer to appendix A.

5.1.3 Conditions

The conditions incorporate the use of virtual reality (VR) or non-virtual reality (N_VR), with or without sonification (S). The conditions are as follows: VR, VR_S, N_VR, and N_VR_S. The order of conditions was randomised per participant with an online tool (List Randomizer, 2023). One of the key objectives was to investigate the effects of sonification and the virtual reality environment on the rowing experience and performance. While sonification is explored as an addition to the virtual reality platform, it is still crucial to separately assess the impact of the designed audio feedback. The VR environment is a moderator variable that can influence the effect of auditory feedback on rowing performance. This will subsequently influence the rowing behaviour and the experience of users, hence the selection of the four different conditions to investigate these components.

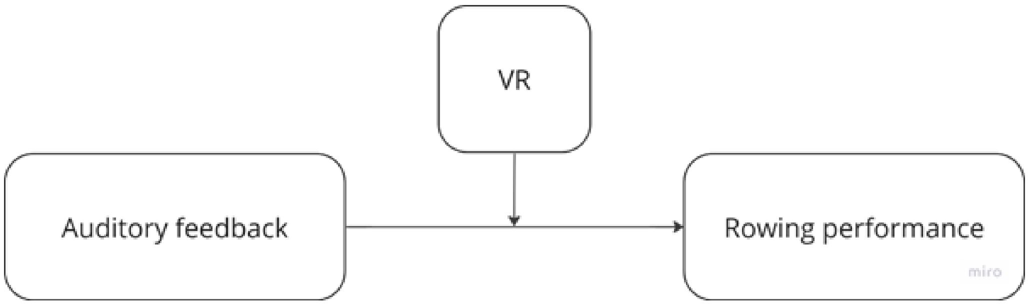


Figure 5.1: *Schematic of the relation between auditory feedback, virtual reality and rowing performance*

5.1.4 Pilot tests

The two pilot tests showed multiple errors in the system and study setup. During the first test, the online environment failed, so only the N_VR and N_VR_S conditions could be tested. Both sessions were five minutes long, but that was afterwards adjusted to three minutes as the participant was too exhausted. To test each participant four times for five minutes would be time-consuming. This would increase the overall duration of the sessions, and result in a need for a longer break time. The participant noted that the sound design was fine and no further alterations were needed. However, the volume of the sound could have been lower. Additionally, there could have been better communication between the practitioner and the participant as some aspects of the study were unclear.

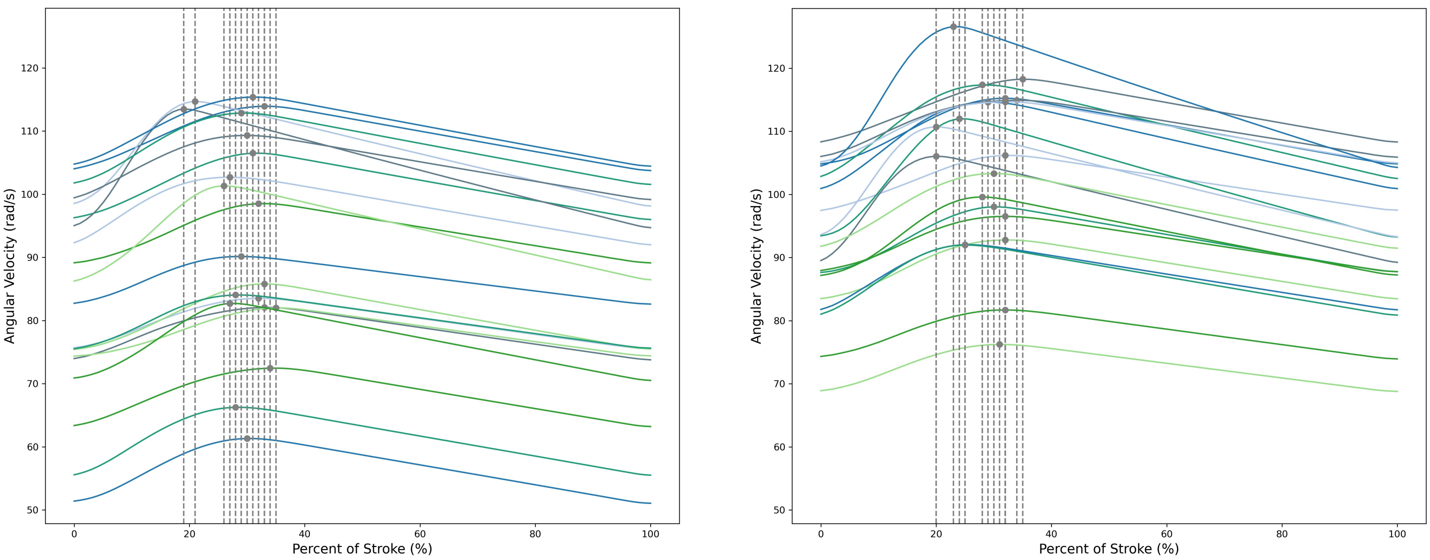
During the second pilot test, the online environment worked accordingly. However, I got logged out of the system. To prevent this from happening again a secondary account was used during the user tests. It was noted that the explanation video was useful, but that additional remarks during the warming-up session were welcome. Additionally, the participant did not perceive the sound as feedback. instead, it was interpreted as a background sound that functions as ambience to make the experience more immersive. Instructions on how to listen and follow the sound were added before beginning. The function of the sounds was not mentioned to the participants. Furthermore, the noise-cancelling was not turned on during the session. A list was included to check every aspect before starting a user test.

5.2 Results and analysis

To address the main research question: *"How can we design effective auditory feedback in the form of sonification to enhance rowing in a virtual reality environment?"* a mixed-method approach was utilised. Twenty different individuals underwent four different conditions in random order. The research aimed to investigate the different design options for auditory feedback, assess the effectiveness of the designed feedback, and see how the audio affects the overall experience of the participants. The expectations for the study can be seen in section 2.4.

5.2.1 Data analysis

To assess the effectiveness of the sonification, the rowing behaviour of the participants was examined. This was done by analysing the collected data in the CVS files. The data of the files underwent a manual filtering process to correct errors. In addition, the last stroke of every session was excluded from the files since the participants stopped rowing during that stroke, resulting in invalid data that cannot be used. The key variables are the angular velocity of the flywheel, the current stroke, and the time. These three are used to calculate all other variables of interest. All calculations and generation of charts were done using *Jupyter Notebook* (Jupyter Notebook, 2023). Initially, the angular velocity of the participants was mapped over time to look for deviations in their rowing strokes. The total amount of rowing strokes performed differed per participant, ranging from 60 strokes in some sessions to over 100 strokes in others. It was chosen to exclude the first twenty rowing strokes for each participant to ensure consistency and to remove potential variations. Those initial strokes varied more in pace, length and form, likely due to that the participants needed time to adjust to the rowing movement and to get comfortable with the task.



(a) *The interpolated means of all strokes for the conditions N_VR_S and VR_S for sound group 1*

(b) *The interpolated means of all strokes for the conditions N_VR_S and VR_S for sound group 2*

Figure 5.2: *Comparison of interpolated means for sound groups 1 and 2*

In order to maintain consistency among participants, it was decided to use 40 strokes per participant for the data analysis if possible. The last 10 strokes of the total amount of strokes were also excluded to eliminate the potential effects exhaustion could have on the results. the remaining strokes were again mapped over time to look for any irregularities. Interpolation is used to estimate values between existing data points and to fill in the missing data points. Not all strokes are performed in the same time frame, and interpolation is needed to ensure that every stroke is as long as the other. This guarantees an accurate comparison of the form of the rowing stroke curves between participants. After interpolating the strokes over 100 data points, the mean and standard deviation were calculated and mapped for every session. Plotting the means of every participant in the different conditions allowed for a straightforward visual comparison of the results. These can be seen in figure 5.2 for the two sound groups. Examples of the different generated charts of one participant can be seen in appendix B.

	Groups	F-value	p-value	Significance	Degrees of freedom	
					Group	Total
Feedback	Sonification No sonification	3.0994	0.0822	No	1	79
Sound	1 2	0.2687	0.6072	No	1	39
VR	With VR Without VR	0.2747	0.6017	No	1	79

Table 5.1: *Table with ANOVA calculation results performed on the position of the graphs (x-axis)*

The statistical analysis focused on the values at the top of each mean line. During the ANOVA analysis, the x-axis values of the tops to perform multiple calculations. The three categorisations that were assessed included: between sonification and no sonification, between sound 1 and sound 2, and between with or without virtual reality. The results of the calculations are summarised in table 5.1. However, there was no significant difference observed between the different conditions of each category, as indicated by the p-values being greater than the chosen significance level of 0.05.

	Groups	F-value	p-value	Significance	Degrees of freedom	
					Group	Total
Feedback	Sonification No sonification	1.0155	0.3167	No	1	79
Sound	1 2	4.7267	0.0360	Yes	1	39
VR	With VR Without VR	0.0132	0.9089	No	1	79

Table 5.2: *Table with ANOVA calculation results performed on the position of the graphs (y-axis)*

For a second assessment of the same categories, it was investigated whether there were any significant differences in the angular velocity. The angular velocity serves as a good representative of the power output of a rower. For this analysis, the y-axis values of the tops were utilised. The results of the calculations are represented in table 5.2. A significant difference was observed between sound 1 and sound 2, while the other categories showed no significant difference.

The analysis regarding the feedback utilised the combination of conditions VR_S and N_VR_S to form the "Sonification" group, while VR and N_VR were considered the "No sonification" group. For the virtual reality category analysis, the conditions VR and VR_S were combined and classified as "With VR", and N_VR and N_VR_S were combined and classified as "Without VR". The analysis concerning the two sound groups, the conditions VR_S and N_VR_S were grouped together for both, with participants 1 to 10 forming the "sound 1" group and participants 11 to 20 forming the "sound 2" group. Performing an ANOVA analysis comparing the angular velocities of the two sound groups with the data of the No sonification sessions showed no significant difference. The different conditions were combined to increase the number of observations and achieve a more accurate calculation. Performing the analysis with only VR_S compared to VR, excluding the non-VR results, or examining other non-combined combinations did not show any significant difference. These calculations are presented in appendix C.

5.2.2 Post assessment interviews

From the post-assessment interviews, a few general opinions can be derived which are categorised into the following:

Impact of virtual reality

The VR environment was enjoyable and immersive. This helped most of the users with performing the task at hand and increased their concentration. A sense of realism was provided because of the environment, which made the experience more engaging. In addition, participants noted that time seemed to pass more quickly during the rowing sessions in VR. Because of the increased immersiveness, participants were less aware of their movements. Non-VR allowed for a better focus on technique and body movements. On the other hand, being able to see their limbs caused confusion among participants with moving in the right order. They felt that being immersed in VR caused them to have a better rowing performance, the movements felt more natural and intuitive. This helped them to enjoy the experience. However, during the first VR experience, most participants needed to get accustomed to the environment as it was noted by some to be distracting at first.

Impact of sonification

The first and foremost opinion of the sonification was that it has an effect. Nine out of ten participants told that they felt like the sound feedback was actually helping them. The feedback was assisting them in maintaining their tempo and rhythm. On the question: "Can you explain to me what you thought the sound in the headphones was for?" most answered that they thought it was to help them with their rhythm and tempo, but also thought it was meant to simulate water and waves and added an ambience function. It was noted that the sound provided cues for timing and coordination. This, as well as the increasing immersive effect it had, caused participants to have an improved focus and attention to the task. Being able to focus on a sound made the participants less aware of their own individual movements, but more aware of how to perform the whole rowing stroke. They felt like rowing came more naturally with sound feedback and it felt more intuitive as they had the feedback to rely on. The sound was generally received as rewarding and motivating, but a few individuals found it to be disruptive or too intrusive at times, potentially due to high volume. Furthermore, the sound quality was noted to vary among sessions as there were occasional glitches and delays. They were not too distracting for most participants.

Overall experience

The participants were overall enthusiastic to take part in the study. They generally enjoyed the rowing experience, regardless of the different conditions they were put in. Participants noted feeling safe in the testing space. The presence of sonification and virtual reality helped with engagement and motivation. Virtual reality with sonification was preferred over the other conditions. However, it was noted that performing the task in virtual reality could prove to be challenging for extended periods of time. The fatigue levels of the participants varied per individual and throughout all tests and conditions but did not impact the overall experience in a negative manner.

Chapter 6

Discussion and conclusion

This chapter will elaborate on the discussion of the results. Furthermore, the implications and limitations of the study will be addressed. Finally, the future research directions and recommendations are outlined.

The study was driven by three main objectives: exploring different design options for sonification, assessing the effectiveness of the auditory feedback, and evaluating how the feedback and virtual reality affect the rowing performance and user experience. In alignment with these objectives the main research question of *"How can we design effective auditory feedback in the form of sonification to enhance rowing in a virtual reality environment?"* was formulated. This question guided the study of the exploration and assessments of the sonification designs and their application in the virtual reality environment to enhance the rowing training experience.

6.1 Summary of findings

The data analysis focused on examining the rowing behaviour of participants through the angular velocity data. Although no significant differences were observed in stroke form between conditions, a significant difference was found in the angular velocity between the two sounds that were utilised in the study. However, the differences were not significant between sonification and no sonification, or with or without VR.

Participants generally found the VR environment immersive, enjoyable, and engaging. VR helped with performance, but some needed time to adjust to the new environment. Sonification was perceived as helpful for maintaining tempo, rhythm, and technique, providing cues for timing and coordination. It improved focus and attention to the task, making rowing feel more natural and intuitive. Participants were generally enthusiastic about their experience and preferred VR with sonification over the other conditions.

6.2 Discussion of results

6.2.1 Objective results

The study's results revealed several interesting findings that did not always align with the initial expectations. At the beginning of the study, several hypotheses were formulated, one of which posited that users will display a better rowing technique when receiving sonification. This would have been evidenced by smoother and more consistent force curves. However, upon reviewing the results, there was no visible difference between the force curves of rowers with and without sonification. The data analysis performed has no visual indications of an improved rowing technique among participants. Nonetheless, upon analysing figure 5.2, it becomes apparent that in the second sound group, the angular velocity of the rowers appears to be on average consistently higher. This would imply potential differences between the two sound groups.

After the ANOVA evaluation, it becomes evident that there is an actual significant difference between the mean angular velocities of the two sound groups. This indicates that the second designed sonification audio causes the participants to have a generally higher power output throughout their sessions compared to the participants who were subjected to the first sound. This can be explained by the drive-to-recovery ratio that is used for the second sound. The second sound utilised a ratio in which the peak volume is reached in 0.33 seconds instead of 1.00 seconds. It was presumed that for participants who are exposed to audio feedback that deviates from the ideal rowing curve, the resulting power curve will exhibit measurable deviations as well.

The curves for the second sound were expected to be more front-loaded than the curves of the first sound. Despite this not being the case, there is a significant difference between the curves of the two sounds. The absence of a significant difference when comparing the two sound groups with the data of the "No sonification" conditions indicates that the distinction does not solely lie between the two groups of participants. Instead, the difference between the two groups only becomes apparent when they are exposed to the audio feedback. Unlike Minciacchi et al. (2016), who utilised motion capture technology and found no significant improvements in individual motor performance using sonification, these results indicate that whether auditory feedback can influence rowing behaviour is dependent on the design of the feedback.

On the other hand, it is surprising that a significant difference was present between the two sound groups, but not when comparing the data of the "Sonification" conditions to the "No sonification" conditions of the second sound group. It would be expected that since the second sound group had a higher power output compared to the first group, the second group would also have a higher power output in the "Sonification" conditions compared to the "No sonification" conditions. However, this is not true. Additionally, comparing the "Sonification" conditions to "No sonification" conditions gives no significant differences for all participants indicating that the audio feedback was not effective. These contradicting results on whether one can influence the rowing behaviour of an individual are surprising and cannot be explained with the current analysis.

The unchanged form of the curves can be explained by two possible reasons. First, it simply costs an individual a certain amount of time to perform the rowing movements and the observable difference can not be seen in the form of the power curve. However, the potential difference could be seen in the exerted amount of power, indicated by a higher-lying curve. Second, it is likely that the power curve calculation is not correctly implemented in the current system, leading to visualisations that do not accurately represent a real power curve. This could mean that changes in the curve like becoming front-loaded or back-loaded are simply not visualised, but could still be present in the background.

The other ANOVA evaluations revealed that it does not matter whether the participants had a rowing session with or without virtual reality, as there was no significant difference between the angular velocities or the form of the curves. This reveals that VR does not influence the rowing behaviour of individuals according to this analysis method.

Comparing the present study and its findings to previous studies, several similarities can be pointed out. Just like the studies in the literature review, this study utilised the sonification method parameter mapping. It has been the only method that has proven to yield significant results (Schaffert & Mattes, 2015). In the audio design of the current study, parameter mapping is not explicitly utilised in the traditional sense. The study makes use of an adaptive audio system that selects pre-composed sound fragments based on the rowing stroke time of users. The mapping of parameters is not being used to convey data information but rather to select the appropriate audio fragments.

The success level of sonification varies across studies, as is also demonstrated in this study. Although this study only showed a significant impact on an unexpected part of the rowing behaviour, it still managed to get significant results.

6.2.2 Subjective results

Despite the fact that not every previous study was successful in obtaining objective significant results (Dubus & Bresin, 2015; Minciacchi et al., 2016), their subjective measures showed a high acceptance rate and appreciation. The introduction of real-time audio feedback was expected to lead to a quantifiable increase in motivation and engagement levels among users as well. This was seen back in this study as participants enjoyed the rowing experience, with sonification and VR enhancing engagement and motivation.

Furthermore, the subjective evaluations provided other valuable insights. It was expected that the incorporation of the virtual reality environment would result in a more immersive and enjoyable experience for users compared to a non-virtual reality environment. The post-assessment interviews revealed that the environment was more immersive and enjoyable as participants noted that time passed by faster, that they were less aware of their actual surroundings, and that they felt like they were actually rowing.

Additionally, during the pilot test, some aspects of the study were unclear to the participants, as little instructions were given over the sound feedback. Given that the participants were inexperienced rowers with little understanding of the rowing technique, they might have struggled with understanding the conveyed formation through the sounds without proper explanation. However, the participants interpreted the sound as background sounds that function as ambience which made their experience more immersive. This means that the sound design was successful to be perceived as intuitive by the participants. The user tests showed that the sound was also comprehensible and clear, as users noted to understand the conveyed message of the sound once a short instruction was given. The sounds were also both intuitive and pleasing to listen to, making the sound design comply with all the preliminary requirements, see 3.3.3.

Even though it cannot be seen back in the objective results, the sonification was still preferred as helpful. This can be explained by the fact that participants may have had different subjective experiences when it comes to understanding and perceiving information. Not being accustomed to receiving represented data through sound as opposed to the commonly used visual representations, could have caused the participants to still perceive the sonification as effective.

Lastly, most of the previously done research was conducted with athletes or rowing professionals, while this study conducted its research with inexperienced rowers. The positive reactions of the participants indicate that sonification can be a potential tool for novice and inexperienced rowers.

6.3 Implications and limitations

The current study revealed several implications and limitations. One significant implication is the potential for a learning effect to be present among the participants, considering they were inexperienced rowers. Despite the participants going through a warming-up session and the order of conditions being randomised per participant, which both should prevent the learning effect, it cannot completely eliminate the chance of the effect being present. Improvements in rowing performance may still be experienced by participants over time. Furthermore, the inexperience among rowers may have influenced the outcomes and generalisability of the results.

Another implication is the characteristics of the participants. The current system does not discern between rower characteristics such as length, weight, and power and in VR all rowers are mapped in the same avatar independent of those attributes. This can influence the results in unforeseen manners. Individual differences in physical characteristics and rowing abilities could even influence how participants interact with the sonification feedback and the virtual reality environment. This could potentially affect the overall effectiveness of the system.

Additionally, the study did not make use of a control group as well as that the sample size of the study could have been bigger for more accurate results. Although the different conditions allowed for an extensive analysis of multiple variables, it could have caused a lack of blinding. As participants knew they were undergoing multiple conditions, they could have subconsciously behaved differently in the multiple sessions. This could successively influence the results.

Furthermore, There were some measurement limitations that could have influenced the results. Most were filtered out of the data manually, but some could have been missed causing slight alterations in the data. The system sometimes read the RP3 data input wrongly and registered an additional rowing stroke where there should have been one. The trackers drifted a lot in the virtual space and generated inaccurate spatial coordinates. Luckily, that data was not needed for the current analysis.

Similarly, the incomplete implementation of the power curve is a limitation. Currently, the drag factor that is used to calculate the power, is set to a fixed value in the system. In on-water rowing, the drag factor on the boat is dynamic and not static, but the calculations behind the drag factor were too difficult and time-consuming to implement.

Additionally, minor distractions from multiple sources were observed during the user tests. The small inaccuracies in the tracker and RP3 data caused some visual glitches in the VR environment, such as oars moving incorrectly and the boat accelerating at the wrong times. These inaccuracies also caused the sound fragments to play in quick succession, to be cut short, or to falter. Furthermore, the noise-cancelling headphones could not always filter out all external sounds. However, it is worth noting that participants reported that they did not experience these distractions as significant, causing them to have no influence on their rowing performance.

Lastly, the current sound system does not make use of predictive algorithms to anticipate a participant's next stroke. The system needs to process and calculates which audio fragment it needs to play based on the average stroke time. As a consequence, this results in occasional delays during the playback of the fragments.

Nonetheless, one cannot always account for every variable that could influence the results. The setup was constructed in a manner that permitted minimal interference during testing. Additionally, the current study made use of twenty participants tested in multiple conditions, trying to rule out as many influences as possible. The multiple conditions allowed for an extensive analysis in which conditions were combined, resulting in a sample size of 80 data points for some of the ANOVA calculations. Overall, the study was conducted in a precise and well-structured manner.

6.4 Future research directions

During the development of the project and analysis of the results, various ideas and challenges emerged, which can be addressed in the future. These points represent areas for improvement and potential matters the project can expand on.

The initial findings revealed that there was no significant distinction between the "Sonification" and "No sonification" conditions of the two sound groups, suggesting that the difference between the groups only was present when exposed to the audio feedback. Future research that includes a control group and increases the sample size per sound is needed to get more accurate results on the effects the different sounds had on their respective groups, as well as research that exposes participants to just one condition in total.

Future research should also aim to expand the investigation by exploring other influential variables like stroke per minute, stroke length, and oar stability. Additionally, researchers should plan to implement algorithms that predict when the next stroke is going to happen. This will prevent any delay in audio feedback that is being played to the users. Furthermore, the next study should make use of a correct implementation of the power curve together with measures to prevent errors in the data collection to generate the correct visualisations of the power curves. Furthermore, the glitches in the system should be resolved before further investigations are conducted. Other studies should have diverse sound systems that make use of feedback schemes and multi-dimensional sounds (2D, 3D sounds). The current system can become repetitive after a while and feedback schemes with different sounds could prevent that from happening. An example of this can be read in the brainstorming session with the audio expert (3.2.2), who suggested a system that includes reward functionality. There are countless possibilities regarding sound design that have not yet been utilised in research (T-labs Berlin, 2009)

Customisation to tailor the auditory feedback to individual users is another possibility interesting to explore. The goal is to create an engaging and enjoyable rowing experience, while also considering factors like fatigue levels, fitness levels and user characteristics. Being able to tailor the system to individual users can address these factors and ultimately ensure a better rowing experience. Simple things such as participants being able to set their initial sound volumes, should be included. Incorporating rowers with different levels of experience, instead of using inexperienced participants would possibly provide new and more detailed user evaluations of the sonification design, resulting in a better feedback system. As it is a multi-person platform on which multiple users can row together, it would be a shame to explore the effects of sonification on groups and rowing teams in the virtual reality environment. On-water rowing does not give the easy possibility to personalise the sonification different people in a boat can receive. Previous research gave every rower the same audio feedback, while this setup allows the user to hear different sounds. Likewise, social parameters should be included to investigate the effects sonification could have on the interactions and communication between crew members, see 2.3.2.

The effectiveness of the sonification could also have been evaluated with different methods other than taking the top position of the curve. The standard deviation of the angular velocity per condition and participant could be investigated, to see if there are any significant differences. Additionally, the whole form of the curve could be examined with more advanced analysing methods. Furthermore, utilising all rowing curves, instead of just forty, can give new insights on how the rowing behaviour is affected. The current study also tried to exclude exhaustion, while it could also be worth investigating if sonification had any positive effects on performance when participants started to tire out.

Lastly, while VR with sonification was preferred among participants, prolonged VR use could be challenging. Future research should include investigating the negative effects of prolonged virtual reality usage, as well as looking into the ability of individuals to endure VR for longer periods. Prolonged testing of the system can also provide insights into how feedback dependency plays a role in skill acquisition among athletes. Feedback systems could potentially affect the virtuosity and mastery of the sport of rowing and further research is needed to investigate how.

6.5 Conclusion

This thesis has explored the design and effectiveness of auditory feedback, in the form of sonification, to enhance rowing in a virtual reality environment. Based on the quantitative analysis of collected data, it cannot be concluded for certain that the current sonification design had a significant effect on the rowing behaviour of the participants. However, there is a strong indication of the differences in audio design, where peak volume is placed, influences the power output of users.

The data analysis focused on assessing the rowing behaviour of participants through angular velocity data, comparing different conditions and sonification designs. This is the best current representation of power output, which provide valuable about their performance. The study found that there were no significant differences in power curve form between conditions, but a noteworthy difference in angular velocity was perceived between the two sound groups of the study. This reveals that the second designed sonification audio caused participants to have a generally higher power output compared to the first sound, indicating the potential for sonification to influence rowing behaviour. However, the study did not show a significant difference when comparing the "Sonification" conditions to "No sonification" conditions within the second sound group, leading to interesting and somewhat unexpected findings. Besides demonstrating a better rowing technique, most results matched the expectations.

The participants generally found the VR environment immersive, enjoyable, and engaging, feeling like VR contributed positively to their performance. The sonification was perceived as helpful for maintaining tempo, rhythm, and technique, assisting with coordination and timing. The participants were enthusiastic about the experience and clearly favoured VR with sonification over the other conditions, indicating a high acceptance rate and appreciation. All these results reinforce the potential for these technologies to enhance user engagement and motivation. Participants found the audio feedback intuitive, and helpful, and perceived it as effective, even though no significant difference was calculated between sonification and no sonification conditions.

For future research, it is recommended to expand the current and better the system. Exploring the effectiveness of auditory feedback on professional rowers, as well as investigating the potential for customising sonification to individual users, and diving into the effects of prolonged VR usage are advocated. Additionally, further research should determine different analysis methods, including other variables, to evaluate rowing behaviour and investigate the impact of feedback dependency on skill acquisition among athletes. The results of the study further substantiate the inconsistent success rate of sonification found in previous studies, but clearly portray the potential sonification has as a feedback system, specifically in the VR environment.

In conclusion, this study contributes to the field by demonstrating the potential of sonification and virtual reality as tools to enhance rowing performance by novice users. It also provides some valuable insights into how audio design can influence the rowing stroke cycle of individuals, opening up possibilities for future research in the design and realisation of sonification systems for sports and training domains. By addressing the implications and recommendations presented in this thesis, researchers can continue to enhance training and performance in rowing sports.

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Appendix A

This appendix presents the user test protocol, outlining all procedures applied during the testing phase.

VR Rowing with Sonification - User testing Protocol

Bart Blom – s2377004
Last update: 13/06/2023

Participant #…

Notes

Remaining questions

Semi-structured interview questions->Follow-up questions that can quantify aspects of sonification (maybe found in some of the questionnaires?)

Considerations

Do we talk about the purpose of the feedback or do we let them figure it out themselves?

Meeting points 13/06

User testing Protocol-Outline

Before starting the test (25 min)		
Check VR equipment	Trackers/controllers charged VR room setup 3 base stations connected VR headset switched on Computer having 3 linked trackers, incl. 1 Tundra tracker	5 min
RP3 setup	1-Check RP3 placement 2-Attach USB mini cable to computer (with cable protector) 3-Slide RP3 back and forth to check cable 4-Resistance level 5 for men; level 4 for women, can change depending on person's physique. 5-Check the seat extension i.e. wooden plank is firm when moving seat 6- Attach Machine, seat and handle tracker	2 min
Preparation materials for the rower	1-Have a filename named "P-x" to Participant number 2-Create empty files for data logger (*see data logger*) 3-Print out the brochure, informed consent, screening/demographics and research questionnaires 4-Get VR cleaning stuff including; VR face masks, alcoholic wipes and UV cleaner	1 min Already done
Set up online questionnaire		2 min
Setup Boat in Neos	1-Setup RP3 configuration for stroke and bow 2-Equip avatar 3-Test configuration in the boat 4-leave user on dock	10 min
WebSocket and internet connection	1-Check for suitable FPS in Neos (~60) 2-Run RP3_interface and data logger, check connection and printed in- and outgoing data	2 min
Test the RP3 interface (localhost:2070)	1-Find machine, select correct COM port 2-Check graph when rowing on RP3 3-Incoming data from Neos when switching from Drive to Recovery and back?	2 min
Test the data logger (CVSFile)	Perquisite test? Empty files + correct naming in folder Data	3 min
Randomized activities (within-subject)	Set training type to distance 300 seconds; if training on Non-VR set to Time 240-300 seconds	Already done

Welcome the rower (max 10 min)		
Introduction + brochure	Outline procedure Summarize rights of participation/data	2 min
Screening	Check suitability of the rower (VR experiences, motion sickness, sport experience)	2 min
Informed consent	Rights of participation	2 min
Demographics	Gender, age, length, weight	1 min
Explanation activity	Let participant set the RP3 physically	1 min
Rowing instruction	Show video https://www.youtube.com/watch?v=QPvYrfyGHi8	2 min

https://www.youtube.com/clip/UgkxttE4y6SHIED2ONbByFtjK3PdTJmg35Se

Rowing activity (20 min) *Use warming-up of 2 min to let participant get used to RP3's *Use VR warming-up, get participant used to VR with a "slow" experience *Before each activity; Start the stopwatch + save and select new file data logger + restart RP3 interface (+ switch to correct feedback mode) ** Non-VR mode includes setting the Propulsion disabled and Type training to time of 240-300 seconds		
Warming-up on RP3 (2 min) Warming-up on RP3 in VR (20 sec)	Stroke rate 20 spm	2 min
Non-VR rowing [N-VR] (5 min)	Setup**+ start stopwatch Rowing activity Small break	 3 min 2 min
VR rowing [VR] (7 min)	Setup* Rowing activity in VR (300 sec trial) Small break	1-2 min 5 min 2 min
VR rowing + Sonification [VR-S] (7 min)	Setup* Rowing activity in VR (300 sec trial) Small break	1-2 min 5 min 2 min
Non-VR rowing + Sonification [N-VR-S] (7 min)	Setup** Rowing activity	

Post-assessment (10 min)		
Semi-structured interview	Thoughts on sonification	
Closure		

Save collected data		
Finish up any written notes		
Reset the Neos world	Feedback disabled; new boat	
Save the CSV files to Office cloud		
Clean the RP3 and VR devices		

Error occurrences	
If avatar behaves erroneous	1. Go back to RP3 setup station and re-initialize trackers on the RP3 2. Unclaim seat and load new configuration on the seat.
If data logger does not correctly function	-Stop the session -Save the CSV file as "error_Px" -Start the session again …
User sees the head of the avatar it is wearing	Respawn in Neos, change avatar length, manually adjust Avatar Root or re-do Room setup
Drifting trackers	Potential causes to check: 1. Tracker close to being empty 2. Environmental lightning 'disturbing' the base station tracking 3. VR play space is not sufficient; check if trackers are being tracked near end of boundary, re-do by setting medium/large space calibration (developer settings) The Base station positioning closer/relative to the trackers, especially MachineTracker
Head pivot seems offset	Re-do setup; may have switched tracker roles
WebSocket errors	Unclaim the seat, restart the exe program, claim the seat again. If not solved, check the Websocket status in inspector or even red Logix nodes in the Websocket setup

Welcome

Introduction

- About this project
- Research goal
- Task: rowing

Brochure

- Show and summarize rights

Screening

Participant #...	
Do you practice a sport? If yes, which and how often per week?	
Desribe you fitness-level from 1 to 5	
Have you ever tried anything in a virtual reality environment before? If yes, please describe your experience.	
Do you experience motion sickness?	
Do you have experience in rowing? *(Preferably not)*	

Demographics

Participant #...	
What is your gender?	
What is your age? What is your length? What is your weight?	

Rowing Activity- Sonification

Rowing instructions

- Participant is shown instruction video on how to row (2 min)
- Participant is instructed to simply start rowing (3 min)

Warming-up; Serves as warming-up for the session, and getting used to the RP3.

VR warming-up; Either first without VR on the RP3, then VR getting used to immersion, then the combination. Or VR getting used to immersion, and learn rowing within VR setting.

Post-assessment

Interview questions

Can you explain me what the auditory feedback was for, and can you explain to me if it had any effect?

What did you like?

What did you not like?

Would you use the system?

Did you feel like the feedback helped you with rowing?

In-depth questions?

- *Based on provided answers or observations made during the session*

Closure

- Thanks the rowers for participating, and leave room and opportunity for an after talk or to ask questions regarding the session.
- Hand out the brochure

In-Depth questions

1. What are your thoughts on the design?
2. How was the experience?
3. What, if anything, surprised you about the experience?
4. What, if anything, caused you frustration?
5. How do you think incorporating sonification into the virtual rowing platform could enhance the training experience or contribute to research in this field?
6. What specific aspects of rowing performance do you think could be improved or optimized through the use of auditory feedback?
7. Are there any concerns or potential drawbacks that you foresee with the implementation of sonification in the virtual rowing platform? If yes, please elaborate.
8. Do you have any suggestions or ideas for additional features or enhancements that could be explored in the virtual rowing platform to further enhance the training experience or support research efforts?
9. How would you prioritize the importance of auditory feedback compared to other potential features or improvements in the virtual rowing platform?

Appendix B

This appendix presents various charts of one participant generated during the evaluation phase.

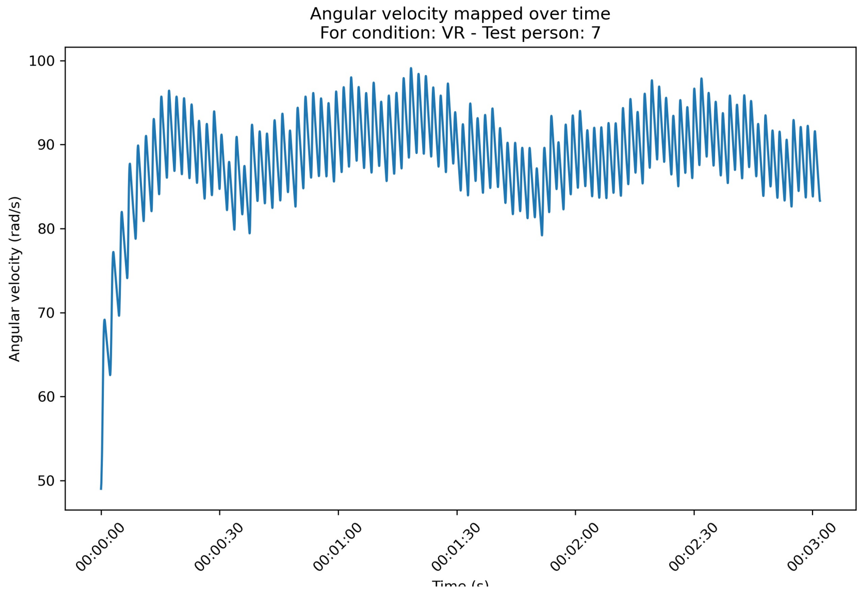

Figure 6.1: *Angular velocity mapped for all strokes over time for condition VR*

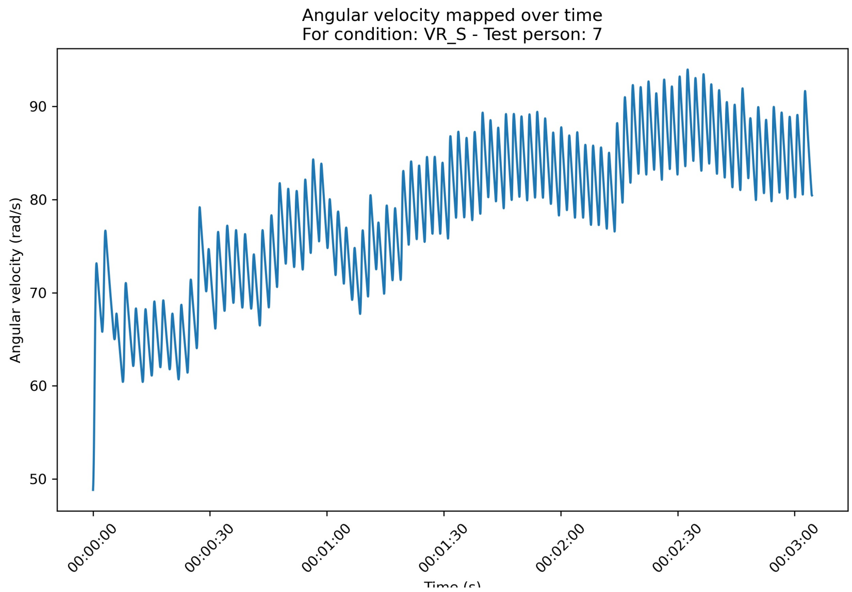

Figure 6.2: *Angular velocity mapped for all strokes over time for condition VR_ S*

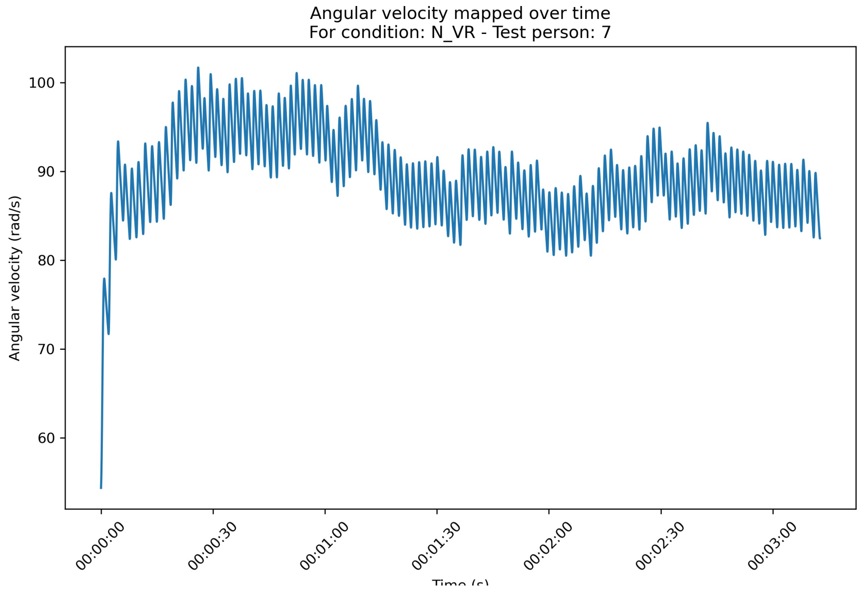

Figure 6.3: *Angular velocity mapped for all strokes over time for condition N_ VR*

Figure 6.4: *Angular velocity mapped for all strokes over time for condition N_ VR_ S*

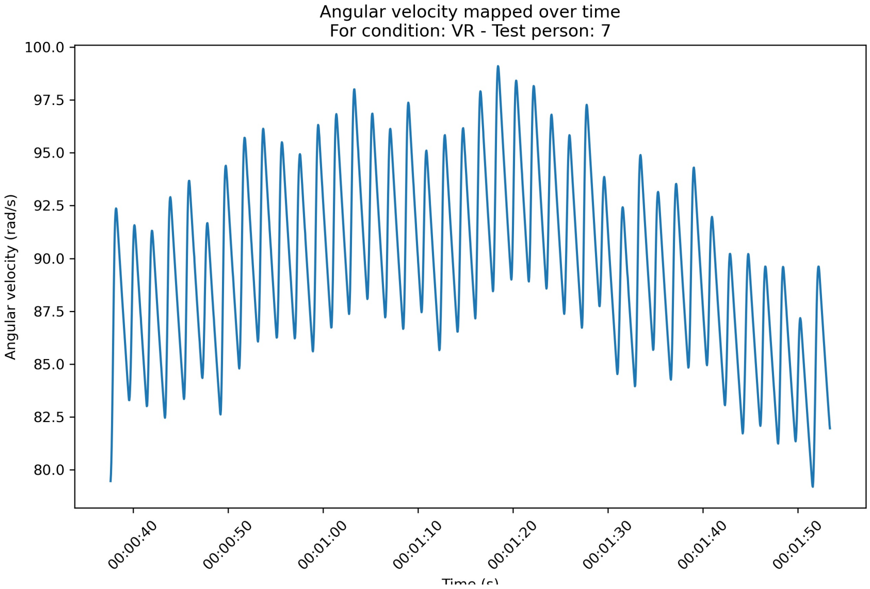

Figure 6.5: *Angular velocity mapped for 40 filtered strokes over time for condition VR*

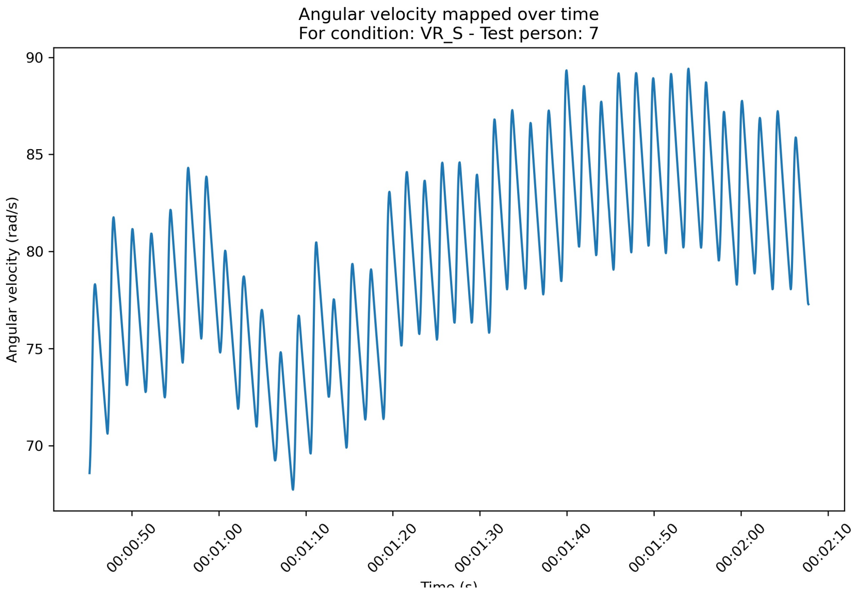

Figure 6.6: *Angular velocity mapped for 40 filtered strokes over time for condition VR_S*

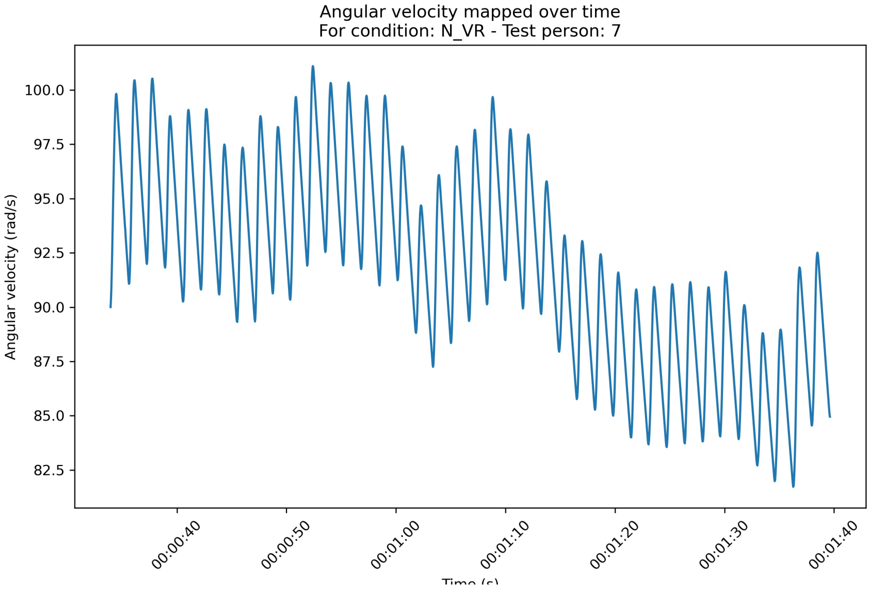

Figure 6.7: *Angular velocity mapped for 40 filtered strokes over time for condition N_ VR*

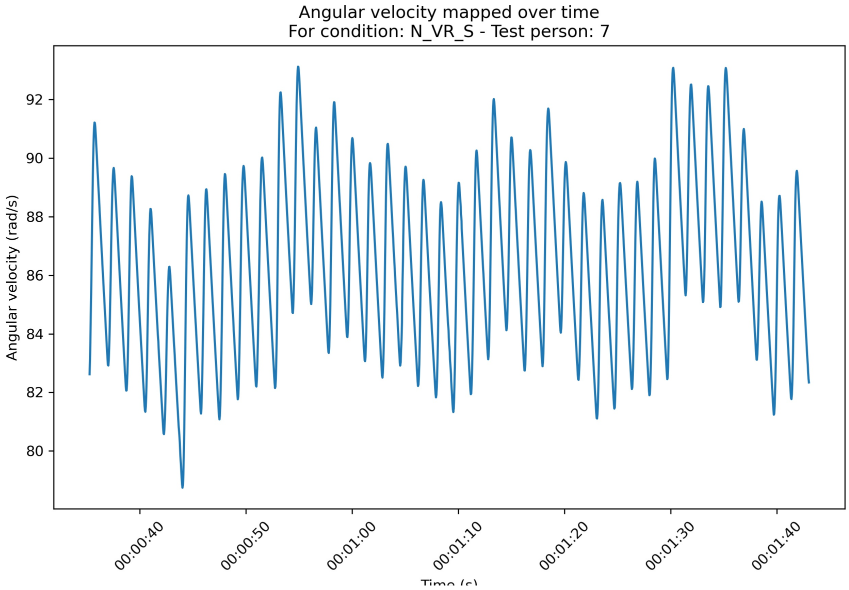

Figure 6.8: *Angular velocity mapped for 40 filtered strokes over time for condition N_ VR_ S*

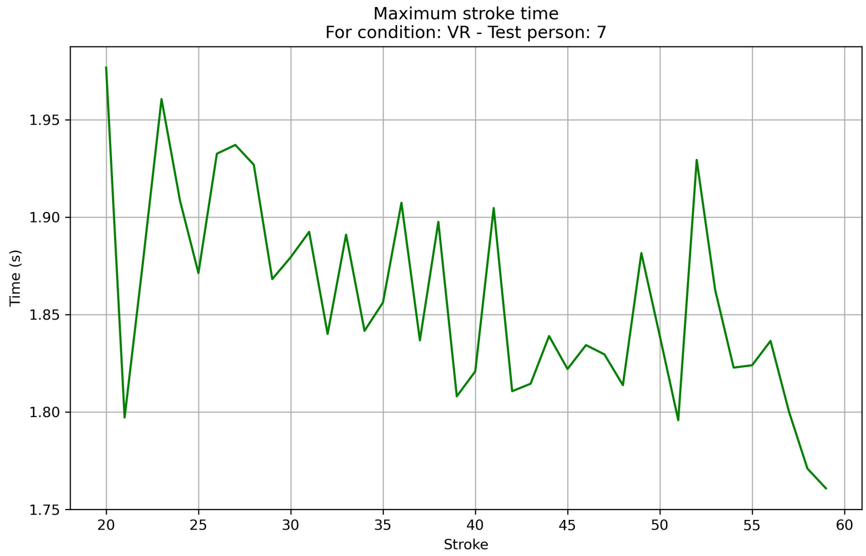

Figure 6.9: *Stroke time for 40 filtered strokes for condition VR*

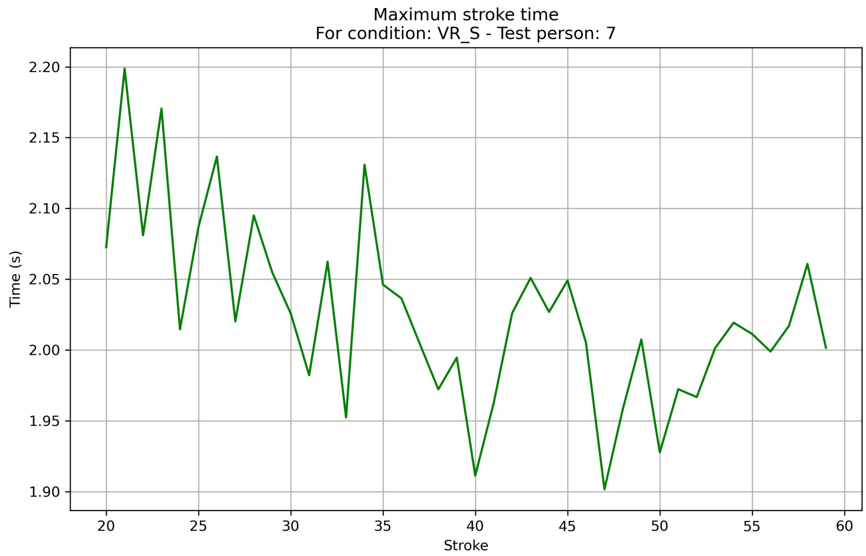

Figure 6.10: *Stroke time for 40 filtered strokes for condition VR_S*

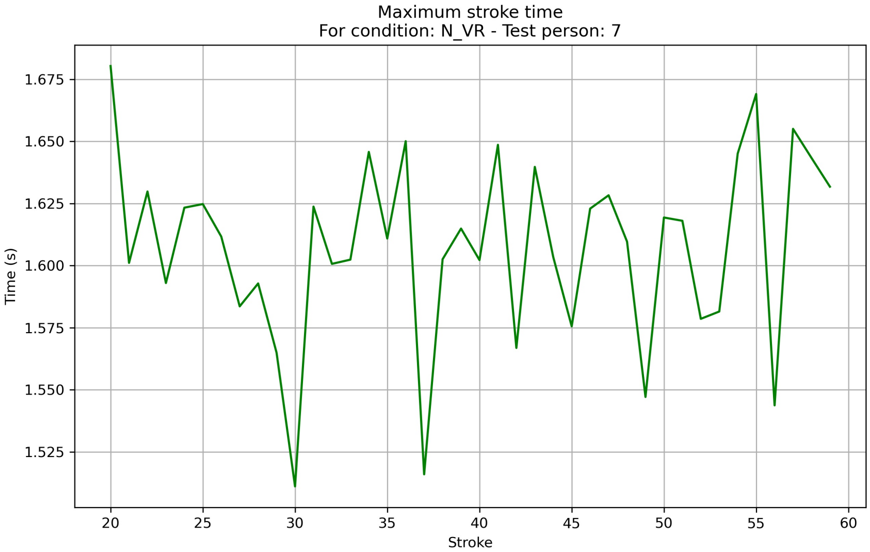

Figure 6.11: *Stroke time for 40 filtered strokes for condition N_ VR*

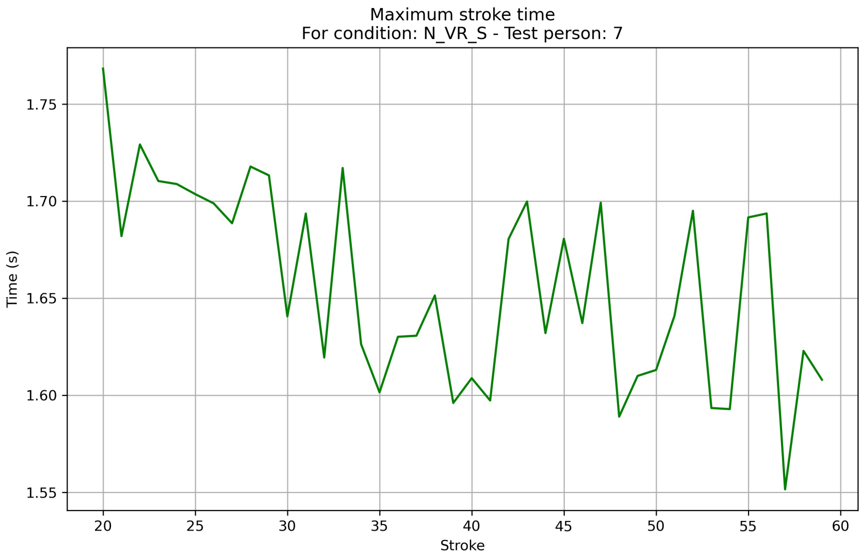

Figure 6.12: *Stroke time for 40 filtered strokes for condition N_ VR_ S*

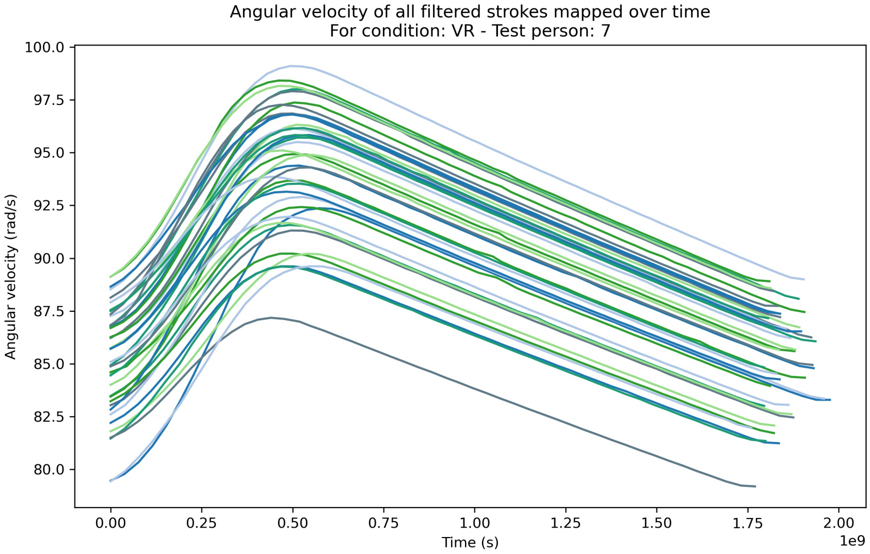

Figure 6.13: *Angular velocity mapped for 40 individual strokes independently for condition VR*

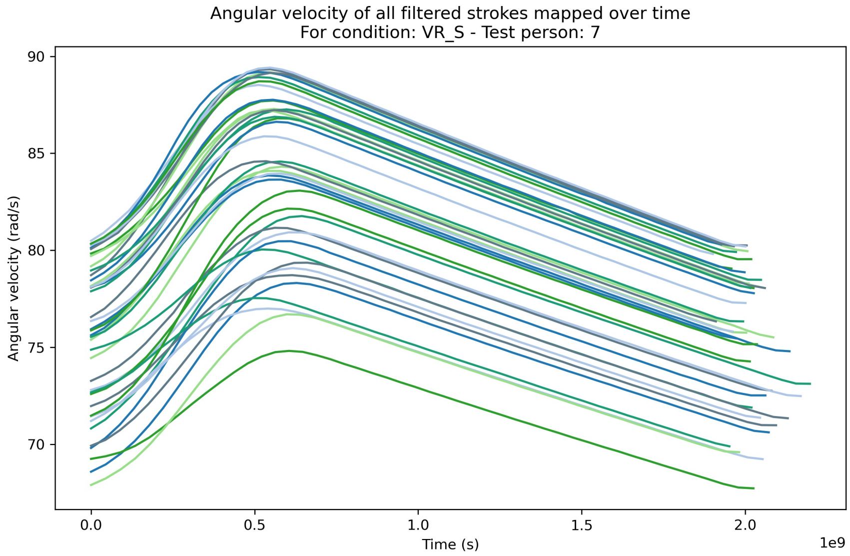

Figure 6.14: *Angular velocity mapped for 40 individual strokes independently for condition VR_S*

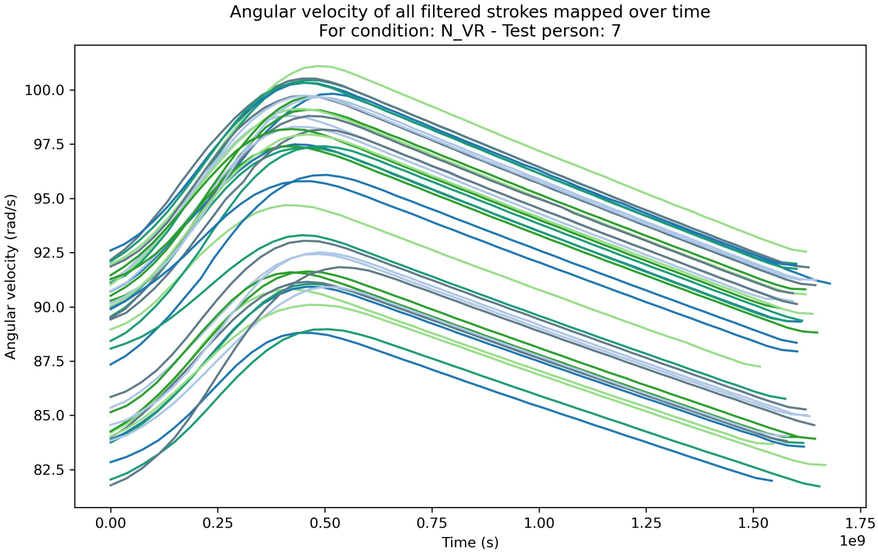

Figure 6.15: *Angular velocity mapped for 40 individual strokes independently for condition N_ VR*

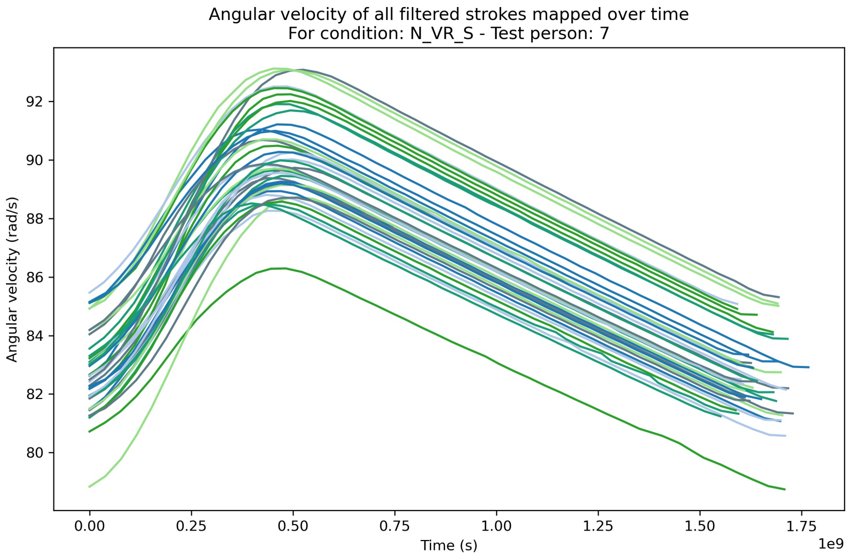

Figure 6.16: *Angular velocity mapped for 40 individual strokes independently for condition N_ VR_ S*

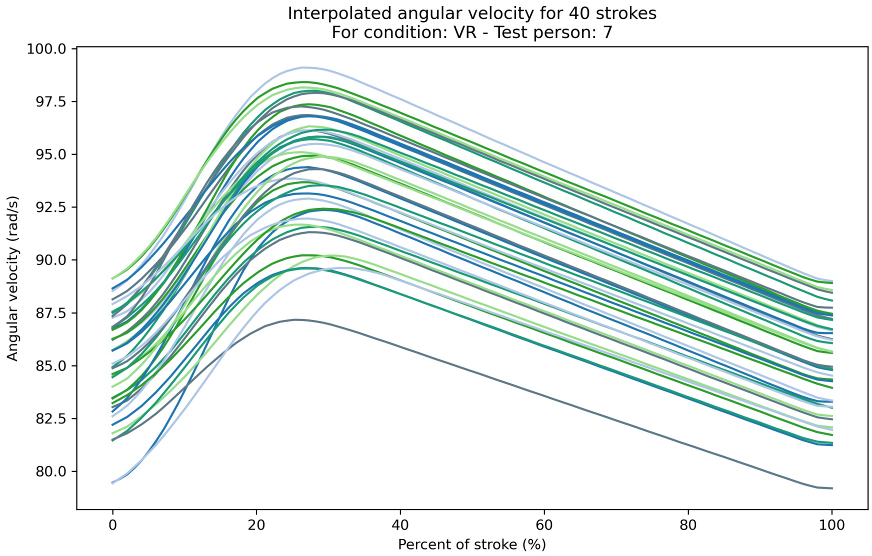

Figure 6.17: *Interpolated angular velocity mapped for 40 individual strokes independently for condition VR*

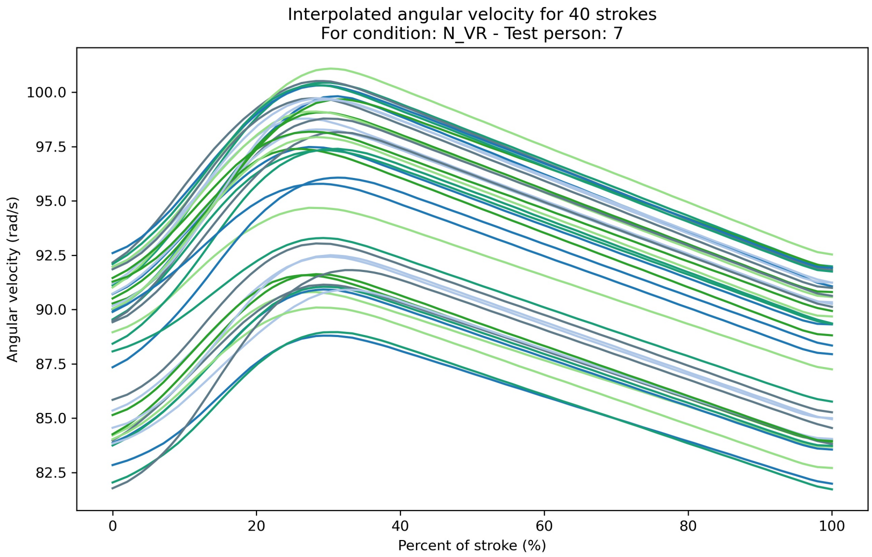

Figure 6.18: *Interpolated angular velocity mapped for 40 individual strokes independently for condition N_ VR*

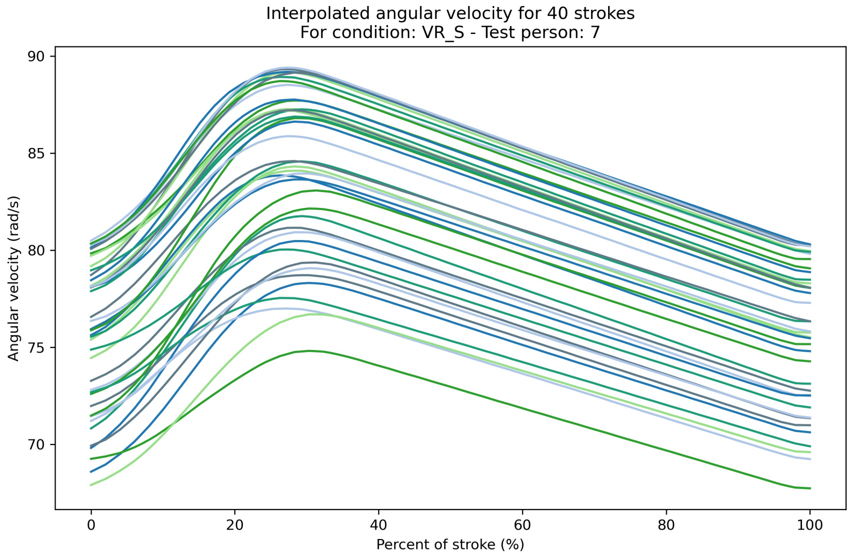

Figure 6.19: *Interpolated angular velocity mapped for 40 individual strokes independently for condition VR_S*

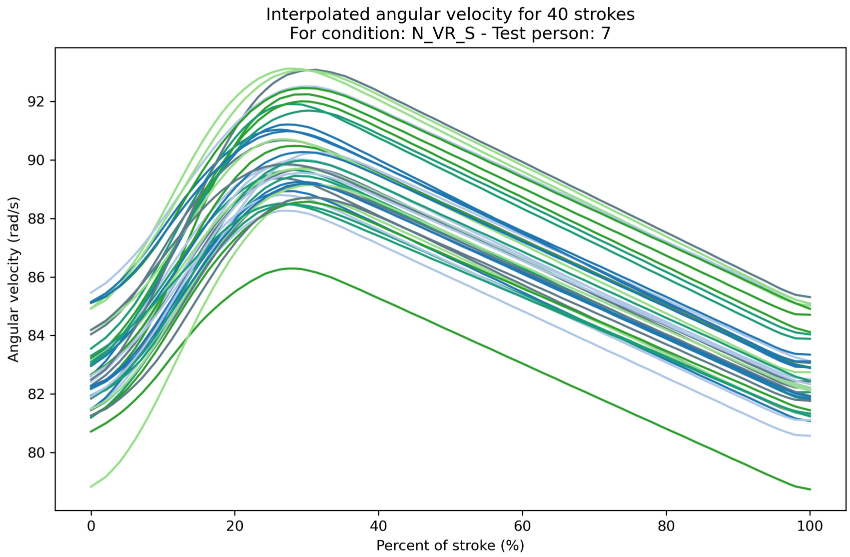

Figure 6.20: *Interpolated angular velocity mapped for 40 individual strokes independently for condition N_VR_S*

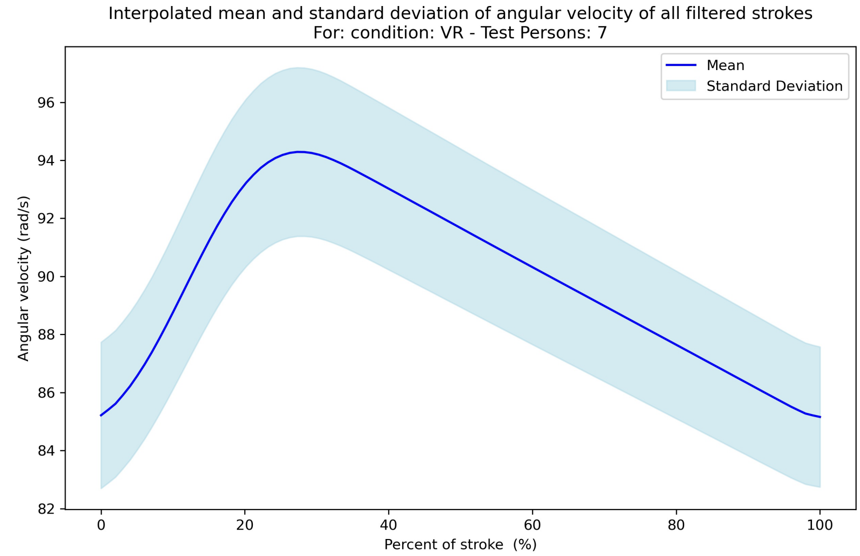

Figure 6.21: *Interpolated mean and standard deviation of all filtered stroke for condition VR*

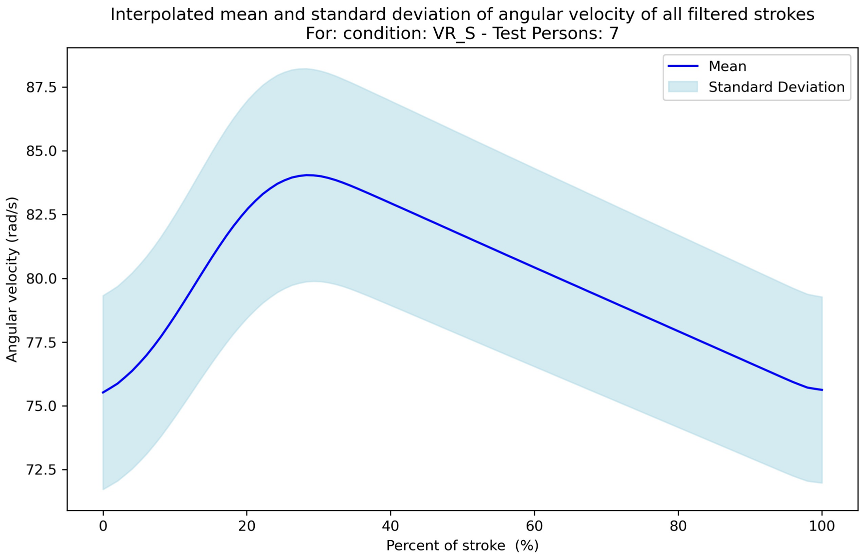

Figure 6.22: *Interpolated mean and standard deviation of all filtered stroke for condition VR_S*

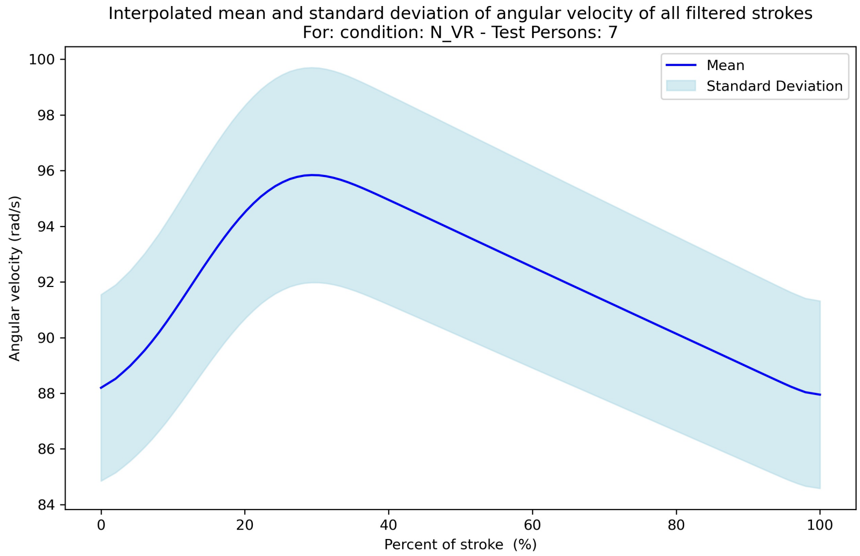

Figure 6.23: *Interpolated mean and standard deviation of all filtered stroke for condition N_ VR*

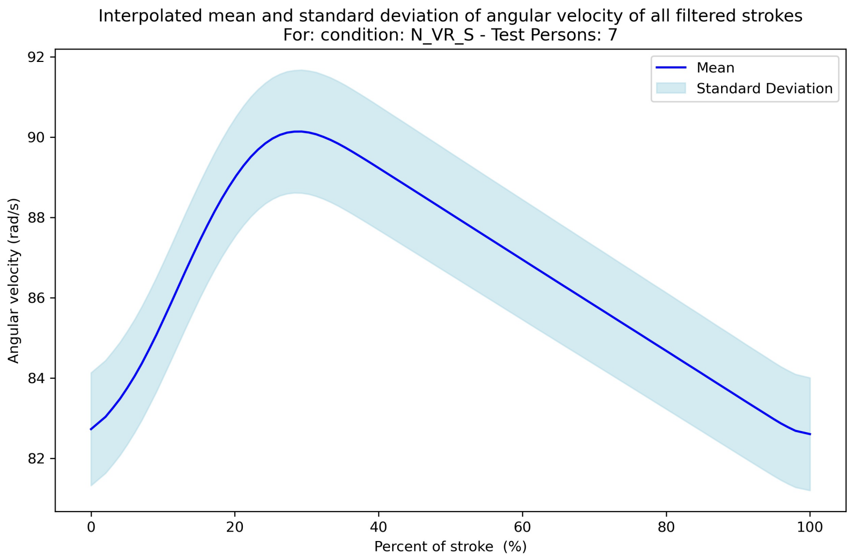

Figure 6.24: *Interpolated mean and standard deviation of all filtered stroke for condition N_ VR_ S*

Appendix C

This appendix presents various comparisons of conditions via ANOVA calculations which were performed during the evaluation phase.

```
ANOVA Test Results for x-axis values:
F-value: 3.0994
p-value: 0.0822
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 79

Additional Information:
Conditions Compared: VR_S + N_VR_S to VR + N_VR
X-axis Values (Group 1): [31.313131313131315, 33.333333333333336, 32.323232323232325, 33.333333333333336, 33.333333333333336, 3
4.343434343434346, 28.282828282828284, 30.303030303030305, 21.212121212121215, 19.191919191919194, 35.35353535353536, 32.3232323
23232325, 28.282828282828284, 29.292929292929294, 27.272727272727273, 30.303030303030305, 26.262626262626263, 27.27272727272727
3, 29.292929292929294, 31.313131313131315, 30.303030303030305, 32.323232323232325, 32.323232323232325, 35.35353535353536, 32.323
232323232325, 32.323232323232325, 28.282828282828284, 29.292929292929294, 32.323232323232325, 34.343434343434346, 31.31313131313
1315, 32.323232323232325, 24.242424242424242, 23.232323232323235, 20.202020202020204, 20.202020202020204, 30.303030303030305, 2
8.282828282828284, 25.252525252525253, 25.252525252525253]
X-axis Values (Group 2): [32.323232323232325, 33.333333333333336, 32.323232323232325, 33.333333333333336, 35.35353535353536, 39.
39393939393934, 31.313131313131315, 30.303030303030305, 27.272727272727273, 22.222222222222225, 34.343434343434346, 39.3939393939
394, 27.272727272727273, 29.292929292929294, 29.292929292929294, 29.292929292929294, 31.313131313131315, 32.323232323232325, 31.
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333336, 33.333333333333336, 27.272727272727273, 26.262626262626263, 34.343434343434346, 33.333333333333336, 33.333333333333336,
36.36363636363637, 27.272727272727273, 25.252525252525253, 21.212121212121215, 21.212121212121215, 33.333333333333336, 30.303030
303030305, 28.282828282828284, 30.303030303030305]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 1.0155
p-value: 0.3167
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 79

Additional Information:
Conditions Compared: VR_S + N_VR_S to VR + N_VR
Y-axis Values (Group 1): [106.49449234848487, 113.92898416666667, 83.51540767424243, 82.08070074999999, 85.80473583333335, 72.46
206202525251, 66.2546193228582, 61.3182917620651, 114.67941424242422, 113.48003512906844, 82.00109536868686, 98.5158545909091,
84.0445484621223, 90.13758453030303, 102.6838174318182, 109.30407356060603, 101.315497030303, 82.7065408754287, 112.8575455303
0301, 115.38090866161617, 98.02659407575757, 115.22378141414143, 106.17347121212121, 118.24134782828278, 92.77660927020199, 96.5
141995025252, 117.34719406565657, 114.616743030303, 114.6721868939394, 114.90639911616161, 76.22604944444446, 81.689218146464
4, 111.9753031818182, 126.5762917171717, 110.69862964646464, 106.03766555555558, 103.3029384469697, 99.58815629292926, 91.983744
96969697, 92.03304003030304]
Y-axis Values (Group 2): [111.10301946969696, 112.17861749999997, 80.31071150252527, 78.65812116666667, 81.04543886134067, 72.62
763871212123, 66.9731470291468, 71.05345995510663, 96.14623163636364, 108.06013249999998, 103.92413142676769, 96.696819280303,
94.28833081818185, 95.84026343686867, 101.01935125252524, 99.95923705050504, 93.67650736868686, 84.35395963636364, 99.9824102853
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5918983333332, 111.31762113636364, 112.22717729797982, 107.94464335858586, 110.58338916666669, 97.75590683333334, 88.09244079545
452, 99.4085806060606, 98.05723213243546, 109.10494363636363, 108.85990803030305, 90.83006216666666, 94.2454125, 83.671258532828
28, 74.99251269696968]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.25: *ANOVA calculations of the groups Sonification (VR_ S + N_ VR_ S) vs No Sonification (VR + N_ VR)*

```
ANOVA Test Results for x-axis values:
F-value: 0.9564
p-value: 0.3343
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: N_VR_S to N_VR
X-axis Values (Group 1): [33.333333333333336, 33.333333333333336, 34.343434343434346, 30.303030303030305, 19.191919191919194, 3
2.323232323232325, 29.292929292929294, 30.303030303030305, 27.272727272727273, 31.313131313131315, 32.323232323232325, 35.353535
35353536, 32.323232323232325, 29.292929292929294, 34.343434343434346, 32.323232323232325, 23.232323232323235, 20.2020202020202020
4, 28.282828282828284, 25.252525252525253]
X-axis Values (Group 2): [33.333333333333336, 33.333333333333336, 39.3939393939394, 30.303030303030305, 22.222222222222225, 39.3
939393939394, 29.292929292929294, 29.292929292929294, 32.323232323232325, 30.303030303030305, 32.323232323232325, 35.35353535353
536, 33.333333333333336, 26.262626262626263, 33.333333333333336, 36.36363636363637, 25.252525252525253, 21.21212121212121215, 30.3
03030303030305, 30.303030303030305]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 0.9457
p-value: 0.3370
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: N_VR_S to N_VR
Y-axis Values (Group 1): [113.92898416666667, 82.08070074999999, 72.46206202525251, 61.3182917620651, 113.48003512906844, 98.515
8545909091, 90.13758453030303, 109.30407356060603, 82.70654087542087, 115.38090866161617, 115.22378141414143, 118.2413478282827
8, 96.51419950252522, 114.616743030303, 114.90639911616161, 81.68921814646464, 126.5762917171717, 106.03766555555558, 99.5881562
9292926, 92.03304003030304]
Y-axis Values (Group 2): [112.17861749999997, 78.65812116666667, 72.62763871212123, 71.05345995510663, 108.06013249999998, 96.69
6819280303, 95.84026343686867, 99.95923705050504, 84.35395963636364, 108.57235113636361, 113.55487186868683, 109.2948649494949,
63.75918983333332, 112.22717729797982, 110.58338916666669, 88.09244079545452, 98.05723213243546, 108.85990803030305, 94.2454125,
74.99251269696968]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.26: *ANOVA calculations of the groups Sonification (N_ VR_ S) vs No Sonification (N_ VR)*

```
ANOVA Test Results for x-axis values:
F-value: 2.4578
p-value: 0.1252
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S to VR
X-axis Values (Group 1): [31.313131313131315, 32.323232323232325, 33.333333333333336, 28.282828282828284, 21.21212121212121215, 3
5.353535353535536, 28.282828282828284, 27.272727272727273, 26.262626262626263, 29.292929292929294, 30.303030303030305, 32.3232323
23232325, 32.323232323232325, 28.282828282828284, 32.323232323232325, 31.313131313131315, 24.242424242424242, 20.2020202020202020
4, 30.303030303030305, 25.252525252525253]
X-axis Values (Group 2): [32.323232323232325, 32.323232323232325, 35.353535353535536, 31.313131313131315, 27.272727272727273, 34.
343434343434346, 27.272727272727273, 29.292929292929294, 31.313131313131315, 31.313131313131315, 32.323232323232325, 34.34343434
3434346, 33.333333333333336, 27.272727272727273, 34.343434343434346, 33.333333333333336, 27.272727272727273, 21.21212121212121215,
33.333333333333336, 28.282828282828284]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 0.1541
p-value: 0.6969
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S to VR
Y-axis Values (Group 1): [106.49449234848487, 83.51540767424243, 85.80473583333335, 66.25461932285822, 114.67941424242422, 82.00
109536868686, 84.04454846212123, 102.6838174318182, 101.315497030303, 112.85754553030301, 98.02659407575757, 106.17347121212121,
92.77660927020199, 117.34719406565657, 114.6721868939394, 76.22604944444446, 111.9753031818182, 110.69862964646464, 103.30293844
69697, 91.98374496969697]
Y-axis Values (Group 2): [111.10301946969696, 80.31071150252527, 81.04543886134067, 66.97314702911468, 96.14623163636364, 103.92
413142676769, 94.28833081818185, 101.01935125252524, 93.67650736868686, 99.98241028535355, 104.38449533838381, 120.5633971212121
2, 74.27628766666668, 111.31762113636364, 107.94464335858586, 97.75590683333334, 99.4085806060606, 109.10494363636363, 90.830062
16666666, 83.67125853282828]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.27: *ANOVA calculations of the groups Sonification (VR_ S) vs No Sonification (VR)*

```
ANOVA Test Results for x-axis values:
F-value: 0.2687
p-value: 0.6072
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S + N_VR_S to VR_S + N_VR_S
X-axis Values (Group 1): [31.313131313131315, 33.333333333333336, 32.323232323232325, 33.333333333333336, 33.333333333333336, 3
4.343434343434346, 28.282828282828284, 30.303030303030305, 21.212121212121215, 19.191919191919194, 35.35353535353536, 32.3232323
23232325, 28.282828282828284, 29.292929292929294, 27.272727272727273, 30.303030303030305, 26.262626262626263, 27.27272727272727
3, 29.292929292929294, 31.313131313131315]
X-axis Values (Group 2): [30.303030303030305, 32.323232323232325, 32.323232323232325, 35.35353535353536, 32.323232323232325, 32.
323232323232325, 28.282828282828284, 29.292929292929294, 32.323232323232325, 34.343434343434346, 31.313131313131315, 32.32323232
3232325, 24.242424242424242, 23.232323232323235, 20.202020202020204, 20.202020202020204, 30.303030303030305, 28.282828282828284,
25.252525252525253, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 4.7267
p-value: 0.0360
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S + N_VR_S to VR_S + N_VR_S
Y-axis Values (Group 1): [106.49449234848487, 113.92898416666667, 83.51540767424243, 82.08070074999999, 85.80473583333335, 72.46
20620252525l, 66.25461932285822, 61.3182917620651, 114.67941424242422, 113.48003512906844, 82.00109536868686, 98.5158545909091,
84.04454846212123, 90.13758453030303, 102.6838174318182, 109.30407356060603, 101.315497030303, 82.70654087542087, 112.8575455303
0301, 115.38090866161617]
Y-axis Values (Group 2): [98.02659407575757, 115.22378141414143, 106.17347121212121, 118.24134782828278, 92.77660927020199, 96.5
1419950252522, 117.34719406565657, 114.616743030303, 114.6721868939394, 114.90639911616161, 76.22604944444446, 81.6892181464646
4, 111.9753031818182, 126.5762917171717, 110.69862964646464, 106.03766555555558, 103.3029384469697, 99.58815629292926, 91.983744
96969697, 92.03304003030304]
There is a significant difference between the two groups in terms of y-axis values.
```

Figure 6.28: *ANOVA calculations of the groups Sound 1 (VR_ S + N_ VR_ S and P = 1-10) vs Sound 2 (VR_ S + N_ VR_ S and P = 11-20)*

```
ANOVA Test Results for x-axis values:
F-value: 0.1093
p-value: 0.7447
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 19

Additional Information:
Conditions Compared: VR_S to VR_S
X-axis Values (Group 1): [31.313131313131315, 32.323232323232325, 33.333333333333336, 28.282828282828284, 21.212121212121215, 3
5.35353535353536, 28.282828282828284, 27.272727272727273, 26.262626262626263, 29.292929292929294]
X-axis Values (Group 2): [30.303030303030305, 32.323232323232325, 32.323232323232325, 28.282828282828284, 32.323232323232325, 3
1.313131313131315, 24.242424242424242, 20.202020202020204, 30.303030303030305, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 1.6912
p-value: 0.2098
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 19

Additional Information:
Conditions Compared: VR_S to VR_S
Y-axis Values (Group 1): [106.49449234848487, 83.51540767424243, 85.80473583333335, 66.25461932285822, 114.67941424242422, 82.00
109536868686, 84.04454846212123, 102.6838174318182, 101.315497030303, 112.85754553030301]
Y-axis Values (Group 2): [98.02659407575757, 106.17347121212121, 92.77660927020199, 117.34719406565657, 114.6721868939394, 76.22
604944444446, 111.9753031818182, 110.69862964646464, 103.3029384469697, 91.98374496969697]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.29: *ANOVA calculations of the groups Sound 1 (VR_ S and P = 1-10) vs Sound 2 (VR_ S and P = 11-20)*

```
ANOVA Test Results for x-axis values:
F-value: 0.1471
p-value: 0.7058
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 19

Additional Information:
Conditions Compared: N_VR_S to N_VR_S
X-axis Values (Group 1): [33.333333333333336, 33.333333333333336, 34.343434343434346, 30.303030303030305, 19.19191919191919194, 3
2.323232323232325, 29.292929292929294, 30.303030303030305, 27.272727272727273, 31.313131313131315]
X-axis Values (Group 2): [32.323232323232325, 35.35353535353536, 32.323232323232325, 29.292929292929294, 34.343434343434346, 32.
323232323232325, 23.232323232323235, 20.202020202020204, 28.282828282828284, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 2.8451
p-value: 0.1089
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 19

Additional Information:
Conditions Compared: N_VR_S to N_VR_S
Y-axis Values (Group 1): [113.92898416666667, 82.08070074999999, 72.46206202525251, 61.3182917620651, 113.48003512906844, 98.515
8545909091, 90.13758453030303, 109.30407356060603, 82.70654087542087, 115.38090866161617]
Y-axis Values (Group 2): [115.22378141414143, 118.24134782828278, 96.51419950252522, 114.616743030303, 114.90639911616161, 81.68
921814646464, 126.5762917171717, 106.03766555555558, 99.58815629292926, 92.03304003030304]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.30: *ANOVA calculations of the groups Sound 1 (N_ VR_ S and P = 1-10) vs Sound 2 (N_ VR_ S and P = 11-20)*

```
ANOVA Test Results for x-axis values:
F-value: 0.2747
p-value: 0.6017
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 79

Additional Information:
Conditions Compared: VR + VR_S to N_VR + N_VR_S
X-axis Values (Group 1): [32.323232323232325, 31.313131313131315, 32.323232323232325, 32.323232323232325, 35.35353535353536, 33.
333333333333336, 31.313131313131315, 28.282828282828284, 27.272727272727273, 21.21212121212121215, 34.343434343434346, 35.35353535
353536, 27.272727272727273, 28.282828282828284, 29.292929292929294, 27.272727272727273, 31.313131313131315, 26.262626262626263,
31.313131313131315, 29.292929292929294, 32.323232323232325, 30.303030303030305, 34.343434343434346, 32.323232323232325, 33.33333
3333333336, 32.323232323232325, 27.272727272727273, 28.282828282828284, 34.343434343434346, 32.323232323232325, 33.3333333333333
36, 31.313131313131315, 27.272727272727273, 24.242424242424242, 21.21212121212121215, 20.202020202020204, 33.333333333333336, 30.3
03030303030305, 28.282828282828284, 25.252525252525253]
X-axis Values (Group 2): [33.333333333333336, 33.333333333333336, 33.333333333333336, 33.333333333333336, 39.3939393939394, 34.3
43434343434346, 30.303030303030305, 30.303030303030305, 22.222222222222225, 19.19191919191919194, 39.3939393939394, 32.3232323232
2325, 29.292929292929294, 29.292929292929294, 29.292929292929294, 30.303030303030305, 32.323232323232325, 27.272727272727273, 3
0.303030303030305, 31.313131313131315, 32.323232323232325, 32.323232323232325, 35.35353535353536, 35.35353535353536, 33.33333333
3333336, 32.323232323232325, 26.262626262626263, 29.292929292929294, 33.333333333333336, 34.343434343434346, 36.36363636363637,
32.323232323232325, 25.252525252525253, 23.232323232323235, 21.21212121212121215, 20.202020202020204, 30.303030303030305, 28.28282
8282828284, 30.303030303030305, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 0.0132
p-value: 0.9089
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 79

Additional Information:
Conditions Compared: VR + VR_S to N_VR + N_VR_S
Y-axis Values (Group 1): [111.10301946969696, 106.49449234848487, 80.31071150252527, 83.51540767424243, 81.04543886134067, 85.80
473583333335, 66.9731470291468, 66.25461932285822, 96.14623163636364, 114.67941424242422, 103.92413142676769, 82.0010953686868
6, 94.28833081818185, 84.04454846212123, 101.01935125252524, 102.6838174318182, 93.67650736868686, 101.315497030303, 99.98241028
535355, 112.85754553030301, 104.38449533838381, 98.02659407575757, 120.56339712121212, 106.17347121212121, 74.27628766666668, 9
2.77660927020199, 111.31762113636364, 117.34719406565657, 107.94464335858586, 114.6721868939394, 97.75590683333334, 76.226049444
44446, 99.408580606060606, 111.9753031818182, 109.10494363636363, 110.69862964646464, 90.83006216666666, 103.3029384469697, 83.671
25853282828, 91.98374496969697]
Y-axis Values (Group 2): [112.17861749999997, 113.92898416666667, 78.65812116666667, 82.08070074999999, 72.62763871212123, 72.46
206202525251, 71.05345995510663, 61.3182917620651, 108.06013249999998, 113.48003512906844, 96.696819280303, 98.5158545909091, 9
5.84026343686867, 90.13758453030303, 99.95923705050504, 109.30407356060603, 84.35395963636364, 82.70654087542087, 108.5723511363
6361, 115.38090866161617, 113.55487186868683, 115.22378141414143, 109.2948649494949, 118.24134782828278, 63.75918983333332, 96.5
1419950252522, 112.22717729797982, 114.616743030303, 110.58338916666669, 114.90639911616161, 88.09244079545452, 81.689218146464
4, 98.05723213243546, 126.5762917171717, 108.85990803030305, 106.03766555555558, 94.2454125, 99.58815629292926, 74.992512696969
8, 92.03304003030304]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.31: *ANOVA calculations of the groups With VR (VR + VR_ S) vs Without VR (N_ VR + N_ VR_ S)*

```
ANOVA Test Results for x-axis values:
F-value: 0.2687
p-value: 0.6072
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S to N_VR_S
X-axis Values (Group 1): [31.313131313131315, 32.323232323232325, 33.333333333333336, 28.282828282828284, 21.212121212121215, 3
5.35353535353536, 28.282828282828284, 27.272727272727273, 26.262626262626263, 29.292929292929294, 30.303030303030305, 32.3232323
23232325, 32.323232323232325, 28.282828282828284, 32.323232323232325, 31.313131313131315, 24.242424242424242, 20.2020202020202020
4, 30.303030303030305, 25.252525252525253]
X-axis Values (Group 2): [33.333333333333336, 33.333333333333336, 34.343434343434346, 30.303030303030305, 19.191919191919194, 3
2.323232323232325, 29.292929292929294, 30.303030303030305, 27.272727272727273, 31.313131313131315, 32.323232323232325, 35.353535
35353536, 32.323232323232325, 29.292929292929294, 34.343434343434346, 32.323232323232325, 23.232323232323235, 20.2020202020202020
4, 28.282828282828284, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 0.1687
p-value: 0.6835
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR_S to N_VR_S
Y-axis Values (Group 1): [106.49449234848487, 83.51540767424243, 85.80473583333335, 66.25461932285822, 114.67941424242422, 82.00
109536868686, 84.04454846212123, 102.6838174318182, 101.315497030303, 112.85754553030301, 98.02659407575757, 106.17347121212121,
92.77660927020199, 117.34719406565657, 114.6721868939394, 76.22604944444446, 111.9753031818182, 110.69862964646464, 103.30293844
69697, 91.98374496969697]
Y-axis Values (Group 2): [113.92898416666667, 82.08070074999999, 72.46206202525251, 61.3182917620651, 113.48003512906844, 98.515
8545909091, 90.13758453030303, 109.30407356060603, 82.70654087542087, 115.38090866161617, 115.22378141414143, 118.2413478282827
8, 96.51419950252522, 114.616743030303, 114.90639911616161, 81.68921814646464, 126.5762917171717, 106.03766555555558, 99.5881562
9292926, 92.03304003030304]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.32: *ANOVA calculations of the groups With VR (VR_ S) vs Without VR (N_ VR_ S)*

```
ANOVA Test Results for x-axis values:
F-value: 0.0509
p-value: 0.8227
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR to N_VR
X-axis Values (Group 1): [32.323232323232325, 32.323232323232325, 35.35353535353536, 31.313131313131315, 27.272727272727273, 34.
343434343434346, 27.272727272727273, 29.292929292929294, 31.313131313131315, 31.313131313131315, 32.323232323232325, 34.34343434
3434346, 33.333333333333336, 27.272727272727273, 34.343434343434346, 33.333333333333336, 27.272727272727273, 21.212121212121215,
33.333333333333336, 28.282828282828284]
X-axis Values (Group 2): [33.333333333333336, 33.333333333333336, 39.3939393939394, 30.303030303030305, 22.222222222222225, 39.3
939393939394, 29.292929292929294, 29.292929292929294, 32.323232323232325, 30.303030303030305, 32.323232323232325, 35.35353535353
536, 33.333333333333336, 26.262626262626263, 33.333333333333336, 36.36363636363637, 25.252525252525253, 21.212121212121215, 30.3
03030303030305, 30.303030303030305]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 0.0769
p-value: 0.7830
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR to N_VR
Y-axis Values (Group 1): [111.10301946969696, 80.31071150252527, 81.04543886134067, 66.97314702911468, 96.14623163636364, 103.92
413142676769, 94.28833081818185, 101.01935125252524, 93.67650736868686, 99.98241028535355, 104.38449533838381, 120.5633971212121
2, 74.27628766666668, 111.31762113636364, 107.94464335858586, 97.75590683333334, 99.4085806060606, 109.10494363636363, 90.830062
16666666, 83.67125853282828]
Y-axis Values (Group 2): [112.17861749999997, 78.65812116666667, 72.62763871212123, 71.05345995510663, 108.06013249999998, 96.69
6819280303, 95.84026343686867, 99.95923705050504, 84.35395963636364, 108.57235113636361, 113.55487186868683, 109.2948649494949,
63.75918983333332, 112.22717729797982, 110.58338916666669, 88.09244079545452, 98.05723213243546, 108.85990803030305, 94.2454125,
74.99251269696968]
There is no significant difference between the two groups in terms of y-axis values.
```

Figure 6.33: *ANOVA calculations of the groups With VR (VR) vs Without VR (N_ VR)*

```
ANOVA Test Results for x-axis values:
F-value: 1.0699
p-value: 0.3075
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR + N_VR to VR_S + N_VR_S
X-axis Values (Group 1): [32.323232323232325, 32.323232323232325, 34.343434343434346, 35.35353535353536, 33.333333333333336, 33.
333333333333336, 27.272727272727273, 26.262626262626263, 34.343434343434346, 33.333333333333336, 33.333333333333336, 36.36363636
363637, 27.272727272727273, 25.252525252525253, 21.212121212121215, 21.212121212121215, 33.333333333333336, 30.303030303030305,
28.282828282828284, 30.303030303030305]
X-axis Values (Group 2): [30.303030303030305, 32.323232323232325, 32.323232323232325, 35.35353535353536, 32.323232323232325, 32.
323232323232325, 28.282828282828284, 29.292929292929294, 32.323232323232325, 34.343434343434346, 31.313131313131315, 32.32323232
3232325, 24.242424242424242, 23.232323232323235, 20.202020202020204, 20.202020202020204, 30.303030303030305, 28.282828282828284,
25.252525252525253, 25.252525252525253]
There is no significant difference between the two groups in terms of x-axis values.

ANOVA Test Results for y-axis values:
F-value: 1.6522
p-value: 0.2064
Degrees of Freedom (Groups): 1
Degrees of Freedom (Total): 39

Additional Information:
Conditions Compared: VR + N_VR to VR_S + N_VR_S
Y-axis Values (Group 1): [104.38449533838381, 113.55487186868683, 120.56339712121212, 109.2948649494949, 74.27628766666668, 63.7
5918983333332, 111.31762113636364, 112.22717729797982, 107.94464335858586, 110.58338916666669, 97.75590683333334, 88.09244079545
452, 99.4085806060606, 98.05723213243546, 109.10494363636363, 108.85990803030305, 90.83006216666666, 94.2454125, 83.671258532828
28, 74.99251269696968]
Y-axis Values (Group 2): [98.02659407575757, 115.22378141414143, 106.17347121212121, 118.24134782828278, 92.7766092702199, 96.5
1419950252522, 117.34719406565657, 114.616743030303, 114.6721868939394, 114.90639911616161, 76.22604944444446, 81.6892181464646
4, 111.9753031818182, 126.5762917171717, 110.69862964646464, 106.03766555555558, 103.3029384469697, 99.5881562929292 6, 91.983744
96969697, 92.03304003030304]
There is no significant difference between the two groups in terms of y-axis values.
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Figure 6.34: *ANOVA calculations of the groups Sonification (VR_S + N_VR_S P = 11-20) vs No Sonification (VR + N_VR P = 11-20)*