Bachelor's Thesis

Multimodal Virtual Rowing Coach

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ABSTRACT

Rowing can be enjoyed by people of all ages and abilities. However, because its entry level is so low many rowers lack proper technique, making injuries very common in the sport. Furthermore, rowing coaches often coach large groups where each rower is given a fraction of their time, and can have difficulties coaching a group with varying skill levels.

Therefore, a system was created using an indoor rowing machine and virtual reality technology which can provide augmented multimodal (visual, auditory, and haptic) feedback on a beginner's rowing technique. A motion tracking setup capable of estimating a rower's body position was realised in a narrow home environment using three motion tracking devices and the head-mounted display which also functions as a motion tracker. Then, to increase enjoyment of training, an accurate single scull rowing simulation was created accompanied by a virtual character.

The rowing skills hand trajectory and velocity, and back angle were chosen to address after interviews with four expert rowing coaches and a literature review. Subsequently, in all modalities, varieties of feedback on these rowing skills were designed based on related work. Through five qualitative tests on four beginning rowers all feedback varieties and several combinations of feedback were evaluated.

While the visual feedback was always observed to be most intuitive and effective, the also effective auditory and haptic feedback seem to have good potential to decrease the dependency on feedback, and avoid having to look in a direction while rowing. Additionally, when either auditory or haptic feedback is added to visual feedback it can point attention to details and allow the user to switch their focus between the two. Furthermore, preference for either a multimodal combination or a unimodal visual combination of feedback addressing different skills seems to heavily depend on the user.

The set up platform shows great potential for technique correction of beginning rowers using virtual reality. Now, it can be expanded using the results of this research, and by conducting quantitative research more conclusive results can be drawn.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor Robby van Delden for guiding me through this project and for always being available for discussing difficulties and for providing valuable feedback. I would also like to thank my second supervisor Dees Postma for often being available to pose the critical but important questions. Also, I am thankful to my critical observer Randy Klaassen for reading my work and giving additional feedback.

Then, I would especially like to show my gratitude to my family, who were always willing to participate in the experiments and provided many useful remarks. My gratitude is also extended to Annefie Tuinstra who helped me model a rowing boat and could always motivate me with her enthusiasm about this project. Furthermore, I want to compliment and thank Koen Vogel for creating the prototype this project continued with.

In addition, I am very thankful of the rowing coaches Thijs Rakels, Stefan van Haren, Arend Spaans and Leo van Adrichem for being available for extensive interviews, in which they provided very useful information.

I would also like to express my gratitude to RP3 Rowing for lending their rowing machines to the university and to the rowing club D.R.V. Euros, and I want to thank their CEO Jan Lammers for being available for two interview sessions and for showing great enthusiasm about this project. Additionally, I want to thank Abe Winters and Stijn Berendse for providing their feedback on the final version of the project, and for initiating the concept of Virtual Rowing at the university together with Jesse Rengers, Niels Sluiter and Remco Abraham.

I am extremely honoured to see the enthusiasm of Robby to continue mine and Koen's work further and would love to stay a part of it, even when I will be busy studying the violin.

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1 INTRODUCTION

1.1 BACKGROUND

In many sports the entry level is low. This is the case in rowing, where people of all ages and abilities can start to row on a rowing machine in the gym or step into a boat at the local rowing club. Partially as a result, injuries are very common in rowing. Specifically, 32 to 51 per cent of rowers experience strain in the lumbar spine [8]. Intense training schedules play a role, but the main cause of this problem seems to be incorrect technique of beginning rowers [9], as this can cause unnatural and unnecessary strain on the rower's body.

For beginners to learn the rowing technique, coaching is needed. However, rowing coaches often coach large groups and give each athlete a fraction of their time, while possibly becoming impaired by factors such as fatigue. Even experienced coaches cannot continuously focus on all aspects of technique of every individual and can be biased towards athletes they know well [1]. Furthermore, in training sessions for beginning rowers, there may be several complete beginners alongside the more experienced, which complicates the coaching process, as pointed out by the CEO of client RP3 Rowing (see section 2.3).

Additionally, training rowing on water is not always possible because of bad weather, low temperatures, or teammates availability. Thus, rowing indoors on a machine is an important part of the sport, not only because it presents more flexibility in training schedules, but also because it increases coaching possibilities as coaches can focus more on individuals [2].

Also, such an indoor rowing machine displays numbers and graphs which can be quite useful, if one knows how to read them. A beginning rower does not, and it is impossible for a coach to analyse every rower's data in real-time. Even for more experienced rowers it is hard to continuously be aware of all variables necessary to optimize the rowing stroke.

1.2 GOAL

To make it easier for beginners to optimize the rowing stroke and to attempt to solve the earlier mentioned coaching difficulties, one can record physical actions and translate it into intuitive feedback. Specifically, this can be done through motion tracking technology or physical effort on a machine. In addition, a suitable technology to provide this feedback is Virtual Reality (VR). VR technology has been increasing in popularity in recent years, especially immersive VR where a head-mounted display is used.

When applying VR to sport, the environment can be controlled and manipulated in specific and reproducible ways [55]. This makes it possible to assess performance, provide continuous feedback, and practice specific skills [3]. Additionally, the increasing availability of VR allows it to be used in local gyms and at home, without the need of technical expertise [55]. A great amount of academic work already exists on structuring feedback systems for rowing technique, of which two research projects cover non-immersive VR installations [14, 17].

Feedback during and after training is essential for athletes to know what good and bad technique feels like [1], and with VR this feedback can be given via extremely immersive visual channels, on top of auditory and wearable vibrotactile haptic channels. Therefore, the goal of this report is to use immersive VR and motion sensing technology in order to create an autonomous feedback system with the purpose of improving a beginner's rowing technique. Thereby it decreases the risk of injuries and provides unsupervised learning of rowing technique in the user's home environment using low-cost motion tracking. This project is building on the prototype of Koen Vogel whose main goal was to correct posture timing during the recovery phase of the rowing stroke [2].

1.3 Research questions

In order to structure a research project which could solve the above presented issues, the following research questions were established. These questions will be answered by interviews of experts, analysis of related work, and user testing of potential solutions.

Main question

How can rowing technique of a beginning rower be improved on an indoor rowing machine in an enjoyable virtual reality on-water rowing environment using autonomous visual, auditory, and haptic feedback?

Sub questions

What are the most common and important errors of beginning rowers to give feedback on?

How should augmented feedback on technique be designed per modality while considering the benefits from virtual reality?

Which varieties of these feedback designs are most effective?

What is the potential of combining feedback designs and modalities?

What is the feasibility of this project when situated in a home environment?

How can on-water rowing be simulated in order for increased enjoyment of rowing training with these feedback designs?

1.4 Overview

These research questions also give this thesis its structure. First, all knowledge about the current situation will be discussed, which entails the rowing technique, common errors of beginners, current state of coaching, commercial related work, and academic related work. Then, the method of research is explained, which had to be adapted to the COVID-19 pandemic. Afterwards, the entire physical setup of the project is shown, and how it improves on the setup of Koen Vogel [2] in multiple ways. In addition, all aspects of the virtual environment are shown and explained: the rowing machine and boat model, character, and environment.

Thereafter follow multiple design cycles of technique feedback. These cover the visual, auditory, and haptic modalities and are correcting three types of rowing errors, which were chosen based on the state of the art research. Specifically, trajectory and velocity of the hands in three modalities, and posture (back angle) in visual and auditory modalities are addressed. Additionally, after every design cycle follows an evaluation experiment with four family member participants.

Finally, after validation of two rowing coaches and the CEO of the main stakeholder, a discussion and conclusions to all research question are given, alongside several parts of ethical analysis. Subsequently, a multitude of recommendations to future research are made.

2 STATE OF THE ART

2.1 THE ROWING STROKE

First a universally acceptable model of the rowing stroke should be established which most beginners strive towards. Because this project focuses on the indoor rowing machine (ergometer), and rowing technique heavily differs between indoor rowing and on-water rowing, this section and the coming sections will concern the rowing technique as it is performed on the indoor machine. The following information is based on three years of personal experience as a competitive rower, and coaching manuals by the local rowing club [10] and by the national rowing association [5].

The rowing cycle is commonly divided into four phases:

1. Catch
2. Drive
3. Finish
4. Recovery

These are depicted below, demonstrated on the RP3 rowing machine[1] by Alistair Bond [4].

Figure 1 Rowing technique on the RP3 in four phases

During the drive, the boat, or in this case the flywheel of the ergometer is accelerated. It starts at the catch with a push on the legs, followed by a swing of the back, and finish by the arms. This order is important; however, they are not to be performed completely distinct from each other. The legs and back have an overlap, while the arms should actually come only when the back is finished. An extremely common misunderstanding is that the handle should be pulled with the arms [10], however this is only detrimental to stroke efficiency and quickly exhausts the relatively weak arm muscles (explained by a rowing coach during an interview, see section 2.2).

In the recovery the rower moves towards the next stroke, using the same order of execution but in reverse. At regular pace, it lasts twice as long as the drive. While being a relaxed movement, it is still necessary to carefully execute technique in order to smoothly prepare for the catch. In this phase, arms and back do have overlap, and overlap between back and legs is minimal (see figure 3). An important part of the recovery to get right, is finishing the incline of the back at half-way through recovery. This way the rower only has to bend their legs further and have a strong core and lower back at the catch.

[1] https://www.rp3rowing.com/

The recovery itself is commonly divided into four steps:

- 1. At the finish
- 2. Arms stretched
- 3. Back bent forward
- 4. Half-way on slides, knee angle 90 degrees

Three of these can be seen below as taken from [2]. Rowers frequently practice the recovery by stopping at one or a multiple of these points.

Figure 2 Steps 1, 2 and 3 in the recovery phase [2]

The entire movement structure of a rowing stroke can be seen below as visualized in a Gantt chart. The main points of attention are annotated. These are: the simultaneous finish of legs and back during the drive, the minimal overlap from back to arms during the drive, the more generous overlaps during the recovery versus the drive, and the double time duration of the recovery versus the drive.

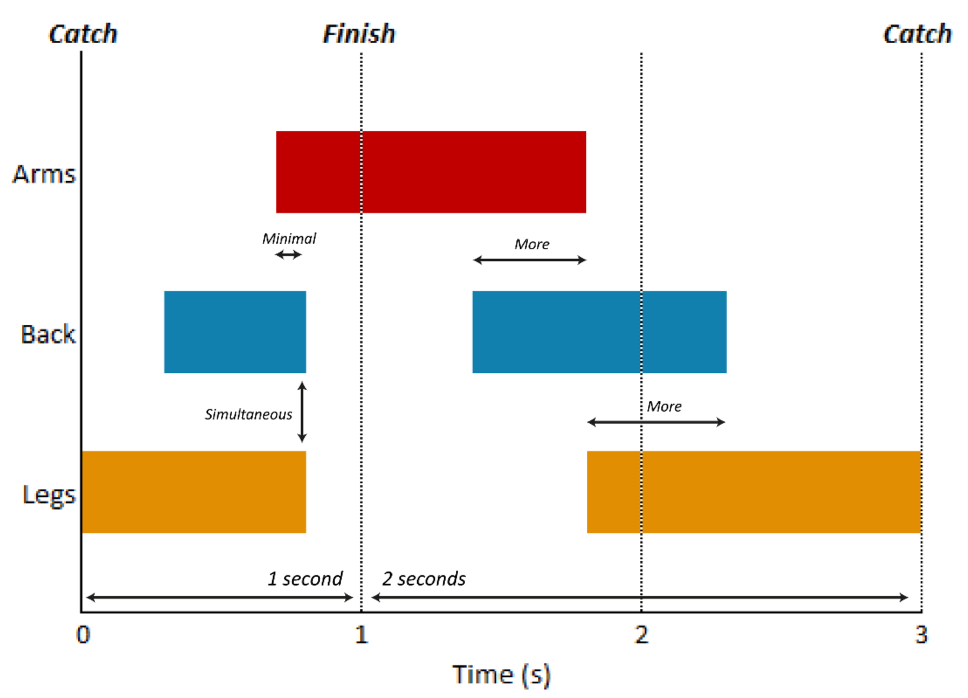

Figure 3 Muscle movements at stroke rate 20

This graph is created by analysing a video of Australian two-time World Champion, and three-time Olympic gold medallist Kim Crow [11]. Her rowing style proved to be more representative of how rowing is taught to beginners than the previous mentioned video ([4], figure 1); more segmented. Though, the drive-time-ratio of 1.1:1.9 was in this case rounded to 1:2 for simplicity. Do note that these muscle movements differ between rowing styles, but the execution order is always the same. Time stamps of this video can be found in Appendix D.

With every drive, a force curve appears on the monitor of the rowing machine. This line should be as smooth as possible in order to most efficiently transfer power into speed and can easily be used to identify disturbances in the drive. It can be seen below as displayed by the RP3 system. This display also shows the previous force curve, which is useful as feedback after each stroke and when training consistency.

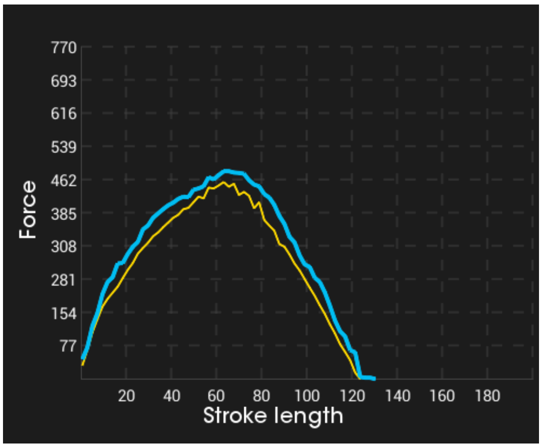

Figure 4 The force curve as displayed by RP3

Finally, the trajectory of the hands is important, especially during on-water rowing. It is necessary for efficiently moving the oar in and out of the water, and for achieving stability. When rowing indoors, trajectory is still important besides the practical use for transferring this skill to the boat, as the height of the handle is crucial at the catch and should be pulled in a straight line during the entire drive. This is important for power efficiency on an indoor rowing machine as then the handle is at the same height as the height that the chain is attached to the machine.

2.2 Current state of coaching beginning rowers

To obtain an accurate idea of the current state of coaching beginning rowers, the most common errors of beginners are discussed according to a guide of the Dutch national rowing association (KNRB) and via interviews with coaches of beginners from the rowing club D.R.V. Euros. These coaches also explained their current ways of giving feedback. While interviewing it became clear that the effectiveness of feedback heavily depends on the rower. Thus, this section also gives a brief overview of the four different types of practical learners. Finally, a conclusion is given on the common errors that would be plausible for this project to focus on.

2.2.1 Common beginners errors according to the KNRB

The Dutch national rowing association has published a guide which helps beginning coaches to learn all aspects of coaching rowers [5]. It provides a list of common improvement points of beginning rowers, their causes, and how to solve them. The information applicable to indoor rowing is summarized below in table 1.

Table 1 Common beginners errors, their causes, and solutions

Error	Causes	Solutions
Back tilts forward during catch	-Insufficient tilting of back -Rower wants a longer stroke -Is passive, mass goes forward -Braking before catch	-Faster in step 3, then slow -Less distance on slidings -Control the recovery speed -Control the recovery speed
Miss catch	-Tense arms and shoulders -Not prepared	-Relax muscles -Stretch arms earlier and relax
Back comes too early	-Focussed on upper body -Heavy push, too much length -Doesn't make stroke in steps	-More focus on legs -Lighter drag factor -Take more time for the stroke
Jumps off the seat	-Back can't transfer leg force	-Hang more on the handle
Finish too low	-Weak arms and shoulders -Wants to finish quickly	-Strengthen arms and shoulders -Take time

2.2.2 Interviews with coaches from D.R.V. Euros

Individual interviews through phone calling were conducted with four rowing coaches from the rowing club D.R.V. Euros. The amount of coaching experience of these coaches ranged from 3 to 8 years, of which at least 2 to 4 years were coaching beginners. Full details on years of experience can be seen in table 2, and full notes from the interviews can be found in Appendix C.1. Everyone agreed to be credited by full name.

Table 2 Interviewed coaches in order of interviewing, and their rowing and coaching experience in years

Coach	Rowing experience	Coaching experience	Coached first-years
Arend Spaans	7 years	8 years	4 years
Thijs Rakels	2 years	3 years	2 years
Stefan van Haren	4 years	3 years	2 years
Leo van Adrichem	8 years	6 years	4 years

They were asked what common mistakes of beginning rowers are when looking at indoor rowing, in what way they teach improvement of technique (visual, auditory, or haptic ways), and what way they think works best.

2.2.2.1 Common beginners errors

The most commonly mentioned error is not pushing only on the legs at the beginning of the drive, but immediately using the back. An important note was made about this: you should not say just to use legs at the catch because the rower also has to strengthen their core and lower back. Which brings us to the second most mentioned error, which is this lack of core and back strength at the catch. This causes the back to tilt forward during the catch because of forces of moving mass during the reversal of the body.

The wrong order of recovery execution is also a very common error, especially for complete beginners. Other errors include 'not going through step 3 of the recovery' (bending knees before back is tilted forward), 'pulling with the arms', 'not stretching arms before the catch', 'over-stretching arms during the catch' (stretching shoulder as well), 'not using enough power at the beginning of the drive', 'not taking the power to the end of the drive', and 'finishing with the handle too high'.

Furthermore, one coach nicely summarized four main groups of errors:

- Catch, legs and core not tightened
- Drive, not a straight handle trajectory
- Recovery, wrong order of execution
- Not achieving the ideal stroke length, back should be sufficiently inclined, arms should be stretched, and catch should be deployed when the shins are vertical.

2.2.2.2 Current feedback methods of coaches

Because this project will cover visual, auditory and haptic feedback, the coaches were asked in what ways they are already using these different senses when giving feedback on technique. These 'human' feedback methods could prove to be valuable inspiration when designing automated virtual feedback.

Visual

Demonstrating technique is the most popular type of visual feedback, however one coach did not consider himself to be a good example so he barely did it. Another coach explained that when demonstrating technique, it is effective when showing it a couple of times right and a couple of times wrong. Videos of themselves and of other (more experienced) rowers was also a common type of visual feedback. The mirror is also used, but there were several complaints about it. Firstly, when turning the head to look into a mirror on the side your body position changes significantly which is not representative of a usual stroke, a mirror diagonally in front or directly in front of the rower would be better. Secondly, a rower first needs knowledge of what they are doing before looking at themselves. Thirdly, some rowers look in the mirror too often.

Auditory

Aside from the usual verbal feedback, auditory feedback is not very popular by coaches. Sounds are usually used to improve synchronization, for example at the finish of the stroke, or the turning of the blade. But these are mostly only applicable in on-water rowing, where a lot of technique can be sensed through boat sound. As a side note, this was recently also addressed by a sound recorder of the Dutch news in a podcast about the sound of rowing.[2] One coach mentioned that noise made by the indoor rowing machine is a useful indication of correct acceleration, but the rower needs to be powerful enough and in most cases there are other rowing machines masking the sound.

Haptic

Touching the rower and nudging them into a correct position is a common form of feedback, this can be done during rowing or after telling the rower to freeze a certain position. Examples include pressing on the back to correct a rounded back or wrong angle, correcting the underarms to be horizontal at the finish, move the hands to the right catch height, and moving the shoulders down as they should be

[2] https://www.nporadio1.nl/podcasts/het-geluid-van-sport/125800-1-het-geluid-van-roeien

relaxed. However, one coach pointed out that eventually the rower needs to be able to perform the technique themselves, and guiding them by limiting movement would introduce a force which is not usually there and could make them dependent on the guide.

2.2.2.3 Most effective feedback

It is most important to make the rower understand and feel what good technique is like. Demonstrating the technique and doing it a couple of times right, and a couple of times wrong should be effective. As well as differential learning, where the rower tries to find both extremes of one aspect of technique, for example first catching very quick, then very slow, to find out what works. One coach is convinced that the freezing of the rower and putting them in a certain position is the most effective feedback to help feeling what good technique is like, while a different coach thinks introducing new forces does not help the rower to perform on its own.

In the end, most coaches agreed that the 'most effective feedback' cannot really exist as feedback methods needs to be alternated, otherwise they eventually are not effective anymore. Additionally, there are very different types of rowers which all learn most effectively in their own way.

2.2.2.4 Different types of rowers

One coach mentioned that according to the national rowing coach course there are different types of rowers for which feedback should be personalized in order to be most effective. These are Kolb's four learning styles [53] and go as follows:

- Doer, wants to experiment with different techniques
- Dreamer, wants to make connections between aspects of technique
- Thinker, wants to understand everything thoroughly
- Decider, just wants to be told how to do it

These four types of learners are very interesting to think about when designing feedback, however they do not seem to entirely apply to this project as not much verbal explanation, back-and-forth communication, or room for experimentation of technique will be provided. Therefore, it could be the focus of future research.

2.2.2.5 Conclusion

Many aspects of real coaching will be difficult to apply to this project and would make it too complicated. Instead, this project will mainly focus on giving simple, easy to interpret feedback in the three perceptual channels. Creating a virtual coach which can for example explain feedback in detail or freeze the rower and nudge them into a position would be out of scope for this project.

This project can however focus on the two most common beginners' errors, which is the incorrect back movement at the catch, and the wrong order of execution in the recovery by analysing the motion sensors in the chest, seat, and handle. The trajectory of the handle is also a very promising aspect of the rowing technique to give feedback on. This is because the position of the handle can be accurately measured and beginners very commonly do not prepare on time for the catch, do not pull the handle in a straight line during the drive, and finish too high or too low. Additionally, having a better velocity of the handle could avoid errors such as 'not using enough power at the catch', 'not taking the power to the end of the drive' (thus dividing power throughout the drive), 'not taking the time for the recovery', and 'braking before the catch'.

When designing the actual feedback, inspiration can be drawn from these current methods. Mainly, demonstration of technique is an effective visual method, as well as self-observation in a mirror. However, the mirror should not be to the side of the rower, as turning the head changes rowing technique. Luckily, in VR the side-view can be presented in front of the rower, and demonstration and self-observation can be combined into one display.

As the goal of this project is to improve the technique of an individual, currently used audio signals for synchronization will not work towards that goal. But audio can definitely be used for technique improvement, as natural sounds already play a big role in rowing on-water (especially in a single scull). Elite rowers can 'hear' their technique based on these sounds of the boat. However, it might not be as effective for beginners so more would have to be thought about how to make them understand it.

Finally, to be able to force the rower into a certain position would require high-level technology which is certainly out of scope for this project. Instead, the focus will be on low-cost mobile vibrotactile equipment.

2.3 INTERVIEW WITH CLIENT RP3

Mainly for the course Documentary Practice, Jan Lammers, the CEO of client RP3 Rowing[3] was interviewed. This company produces indoor rowing machines like the ones in the previous mentioned videos [4, 11]. The interview was conducted to explore possible themes for a documentary unrelated to this project and focused on how he considers 'recognition' in his life and work. However, after the meeting he gave rich insights into the problem situation, how much RP3 is interested in this project and what they are currently developing.

The main problem situation emphasised by Jan Lammers was the difference in skill levels during training sessions for beginning rowers which the company regularly arranges. In these trainings there will always be a number of complete beginners, and this heavily complicates the coaching process as they require more attention than others and do not understand many terms the other, slightly more experienced, rowers know. RP3 Rowing would thus be extremely interested in a virtual reality solution which they could simply just put on a person's head and have them learn the technique.

The company is currently developing an E-sports rowing platform, called E-racing, where rowers could compete against each other online, and which would allow for professionals to be able to earn money in the rowing world. Additionally, their plans for a gamification of rowing were explained, as a cooperation with BlueGoji[4]. This would be a game playable during rowing, controlled with your thumbs.

Finally, it was pointed out that it probably is not motivating enough to simulate the real world in virtual reality. Rather, it was suggested to add game elements to it, or present an experience totally different to rowing.

Figure 5 RP3 Rowing building located in Haaksbergen

[3] https://www.rp3rowing.com/
[4] https://www.bluegoji.com/

2.4 RELATED WORK

Knowing the common beginners errors and the current human ways of giving feedback there is already a relatively clear idea of what the focus of this thesis should be. However, it is good to be inspired by and learn from existing work. That is why a semi-structured web search was conducted with the search terms "rowing technique improvement system", "rowing technique virtual reality", and "sports technique improvement system". The sections below present the relevant commercial work that was found, all related to rowing technique measurement and feedback.

2.4.1 Quiske

The Quiske app [6] measures rowing technique and gives instant feedback. It uses two sensors, one on the ergometer which is a special Quiske pod, and a phone on the handle. Using only this, the app can measure five metrics

- Drive rhythm: ratio of drive time and full stroke time (depends on rate, smaller is usually better)
- Seat/Legs rhythm: percentage of time the seat is moved (same as previous)
- Legs speed: the maximum speed of leg push during the drive (in m/s, higher is better)
- Seat stopped: amount of time the seat is stopped as percentage of full stroke time
- Style: how segmented your rowing is

A preferred level of virtual coaching can be chosen before the start of a training. These parameters are shown during training in order to encourage improvement, and after the workout a technique score is calculated based on the measurements of all strokes. This score can be shared and viewed in more detail with an analytics subscription.

This is an extremely interesting product because of its relatively low cost, easy setup and ability to estimate a technique score via many parameters using only two motion sensors. However, it is not clear how accurate its technique measurements are.

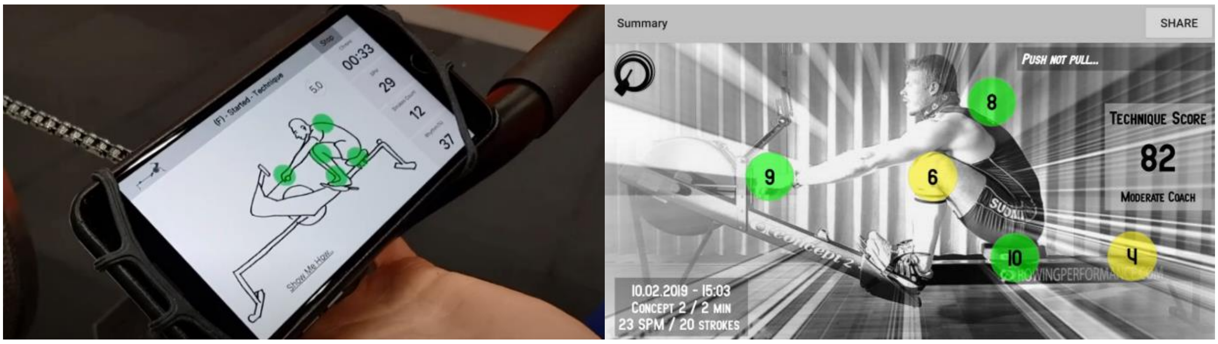

Figure 6 The Quiske app [6] showing the training result

2.4.2 Sofirow & Accrow

Sofirow [7] is an auditory feedback system used for elite on-water rowing. It measures the boat acceleration in real-time using their measurement and analysis system 'Accrow' (also found in [7]) and maps it onto pitch of a MIDI sound. It has been proven to increase mean boat velocity and other characteristics of the boat acceleration curve [41]. This 'sonification' enhances rowers' perception. Providing feedback about movement through the sense of hearing allows the improvement of otherwise invisible details. Sonification has also been shown to improve beginners' technique [36], however in a different form.

Figure 7 The acoustic feedback system Sofirow [7]

2.4.3 BioRowTech system for ergometer

This BioRowTech system for ergometer [12] helps correcting the "three most typical mistakes in rowing technique" with one-dimensional indicators and presents a graph display of body part velocity curves for more detailed technique analysis, all by using three spring-loaded string sensors.

The three mistakes which have the largest impact on performance according to BioRowTech, are:

1. "Opening up" of the trunk: the back comes too early. This makes the work for the quadriceps harder as it locks the knees at the sharpest angle, makes the drive less efficient due to increased velocity and inertial energy loss variation, and could be harmful for knee joints.
2. "Grabbing" the arms and shoulders: pulling the handle early in the drive. Using the smaller arm muscles limits acceleration of the rower's mass, and could overload and injure leg and arm muscles
3. "Throwing" the trunk: continuing to use the back after reversal of the handle. This excessive movement of the back is not utilised into the flywheel acceleration and causes the rower to use core strength to recover from this position. This overloads the core and upper-leg muscles and could lead to rib injuries at higher stroke rates.

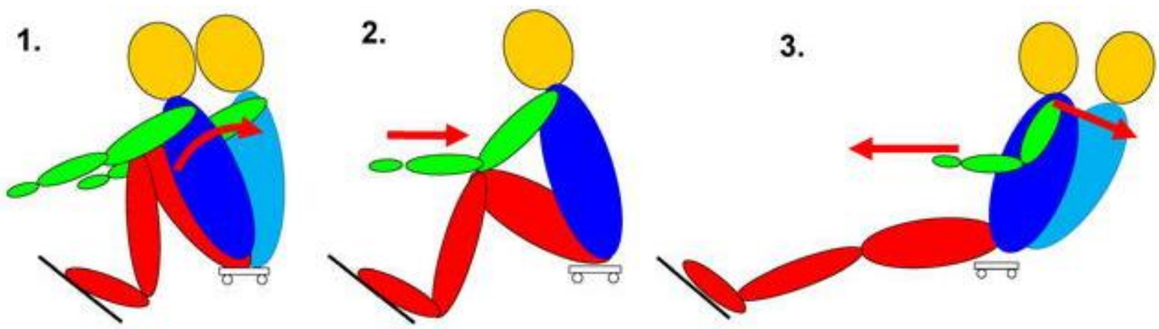

Figure 8 The three most typical mistakes which have the largest impact on performance, according to BioRowTech [12]

The BioRowTech software display consists of a graph of velocity curves of handle, legs, trunk, and arms on the right, and indicators based on the three mistakes on the left. The velocity curves on the right are displayed in a clockwise matter, where values above the horizontal axis are of the drive, and below of the recovery. Each rowing mistake has its own dedicated factor derived from the measured positions, consisting of a green zone where the specific technique is performed correctly and blue and red zones which indicate both erroneous extremes of the specific technique.

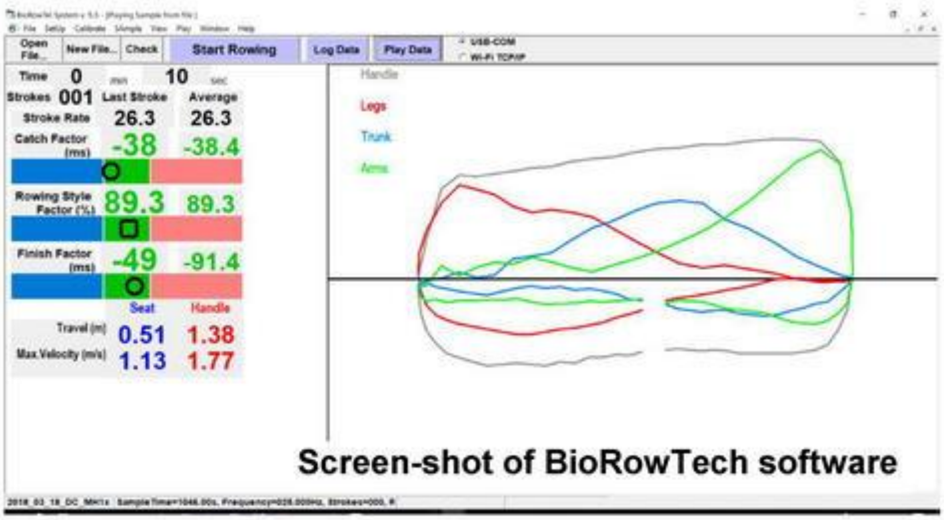

Figure 9 Screenshot of the BioRowTech software

The technique factor indicators of BioRowTech are in summary:

1. Catch factor: the time difference between reversal of the handle and reversal of the seat, at the catch (when initiating the drive). The optimal value for this is -25ms; when the legs push to change the seat direction, the handle should follow shortly after. Higher values indicate that the back is used before the legs, and lower values indicate that the seat is pushed away under the rower without taking the back with it as a result of a lack of core and lower back strength.
2. Rowing style factor: the ratio of seat distance to handle distance during the first 20 per cent of the drive length. The optimal value is 90 per cent, which means the main contribution to handle movement comes from the legs, and only 10 per cent from the upper body. Lower values indicate pulling of the handle or a too early opening of the back. Higher values indicate that the seat is faster than the handle due to a weaker back.
3. Finish factor: the time difference between reversal of the back and reversal of the handle, at the finish. The optimal value for this is -50ms; the back should stop and already slightly return before the handle is reversed almost instantly thereafter. Higher values indicate that the back is taken too far and reversed too late, and lower values indicate that the back is winded around the handle and back power is lost at the finish.

Figure 10 The three technique factor indicators of the BioRowTech software

2.5 Creating a virtual rowing coach: A literature review on effective technique-improving feedback

This literature review was written for the course Academic Writing of the graduation semester. A literature matrix which was constructed for this review can be found in Appendix G. Here, notes can be found on interesting but out-of-scope literature.

2.5.1 Introduction

A coach can provide a lot of feedback on technique, based on what they observe of a rower. However, human coaches are limited to sight and hearing, can only focus on one athlete at a time, and possibly become impaired by factors such as fatigue. That is why a great amount of research has already been carried out to explore the use of virtual coaches. These would be able to observe physiological and biomechanical variables, give more attention to every individual athlete, and have faster processing. Furthermore, human coaches are limited to demonstrating technique using only visual and verbal means, while motor behaviour is a multimodal phenomenon and motion can be observed by all senses [13].

The effectiveness of multimodal feedback on rowing related motor skill learning seems promising, however limited research has been done on synthesising a conclusion of all multimodal rowing feedback literature. Such a conclusion would help realise a system which could improve a rower's technique just as good, or maybe even better than a real coach. Therefore, this literature review is conducted with the following research question:

What makes augmented feedback in a rowing virtual environment effective at improving a rower's technique?

A surprising amount of research has been done in the field of motor skill learning of rowing related tasks using visual, audio, haptic, or multimodal (combined) feedback. Most notably, two CAVE (Cave Automated Virtual Environment) rowing installations have been constructed and thoroughly researched, and many related projects have been researched using a standard rowing machine. While not all covering virtual environments, all research on rowing technique feedback will be valuable.

First, an overview will be given of all relevant academic work. Then, the different methods of technique measurements of existing work are explained. Afterwards, an overview follows of all modality-specific advantages to consider when designing feedback. Subsequently, the effectiveness of feedback designs is presented and discussed, contributing to the conclusion of this literature review.

2.5.2 Cave automatic virtual environments

This literature review will mainly cover the following two CAVE systems due to their elaborate research in the field. However, several other systems are also reviewed.

SPRINT Rowing Training System

The rowing training system called SPRINT [14] is a multimodal platform aimed at studying the improvement of technique, energy management and team coordination of rowers. It can provide augmented visual, auditory, and haptic (vibrotactile) feedback for the purpose of technique optimization, and it allows training of sculling (two oars) and sweep rowing (one oar). Most commonly it uses an LCD screen as visual display, but it can also be reconfigured into an immersive setup where it is placed in a CAVE as shown below. This full setup simulates a real-task-like environment which enhances the effectiveness in conveying information to the user. Furthermore, it accurately estimates a rower's motion using VICON motion tracking. The system can be seen in action in a video [15].

Figure 11: The SPRINT rowing training system in immersive configuration [14, p. 2]

M^3 Rowing Simulator

M^3 means Multi-Modal Motion synthesis because the rower interacts using haptic oar movement and simultaneously perceives results visually and acoustically. This high fidelity simulator [16, 17] is able to provide technique-optimizing augmented feedback in these modalities and can adapt to the individual perception of the human athlete. Compared to SPRINT, this system fully surrounds the user, allowing the user to look to the side to observe their oars at the exact place they would be in the real environment. Also, for augmented haptic feedback the M^3 simulator uses force feedback as opposed to vibrotactile feedback in the SPRINT system. Furthermore, audio surrounds the user by using a ring of loudspeakers.

Figure 12: The M3 Rowing Simulator in sweep rowing setup [16]

2.5.3 Measurement of rowing technique

The trajectory of the hands "…turns out to be the most important factor influencing the overall performance" [32, p.2]. Consequently, in literature, the most common measurement of rowing technique is this trajectory [32, 33, 35, 36, 39]. This can be of the entire rowing stroke or only (trunk-)arm movement, to simplify the task. Generally, it is plotted in a two dimensional graph as seen below. However, do note that this trajectory shown below is of a simulation of on-water rowing where the legs are not used (trunk-arm rowing). Commonly, the velocity of the hands is addressed alongside trajectory. Furthermore, the M^3 rowing simulator divided this trajectory in four parts in order to address errors more specifically, and to measure its velocity profile [36, 37].

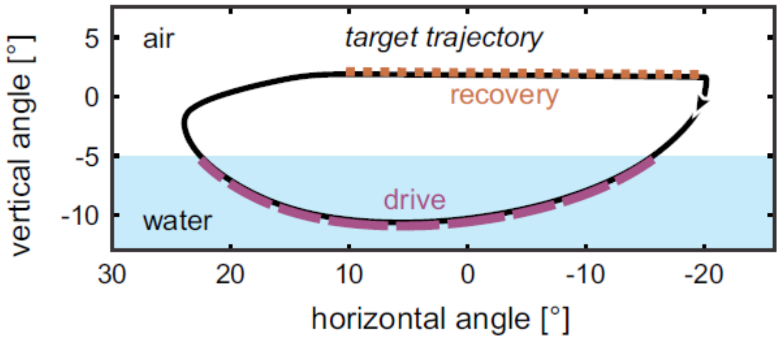

Figure 13 The rowing target trajectory as used in [35, p. 5]

The SPRINT rowing system measured the muscle onset timings of the back and arms during the drive phase [34]. According to literature and analysis [18, 19] this is an important feature of determining technique effectiveness.

A different approach to measuring technique is by using multiple movement parameters. In [38] the kinematic parameters stroke length, seat position, and dynamic parameters footrest force, and handle force are measured. Similar parameters are also used in [39], only in this study handle height and horizontal distance between seat and handle are used, together with the previously mentioned forces.

Also, a lower stroke rate and a longer stroke length are assumed to be beneficial for the overall rowing performance [20] according to [40]. This also partially matches with the aforementioned velocity of the hands, because when more time is taken for the recovery the stroke rate is lower.

2.5.4 General modality-specific advantages

Before discussing the effectiveness of existing feedback designs, a general overview will be given on modality-specific advantages. This will help understand the functioning of these three different senses of the human body, and already give an idea of which feedback would be effective for different tasks.

2.5.4.1 Visual

Vision can perceive spatial information more precisely than hearing [21]. Also, when permanently visualizing a movement trajectory, the user is able to anticipate and prepare their movements, instead of reacting on an auditory or haptic cue [37]. Additionally, visual feedback designs are very common and can be interpreted immediately [37].

2.5.4.2 Auditory

Hearing is effective for perceiving periodicity, regularity, and speed of motion [22]. Auditory feedback can help to keep focus on the task [23] or enhance perception of specific aspects of the movement [41]. This enhancement can be explained by the co-activation of auditory and motor brain regions, especially when the connection between the movement and the sound is understood [24]. This could also enhance memorization of the movement, as hearing is believed to contribute to motor planning [25].

2.5.4.3 Haptic

Haptic feedback can physically alter, disturb, or assist movements [35] and is suggested to be beneficial for teaching temporal aspects [26]. Rowing technique-improving literature discusses two types of haptic feedback: force and vibrotactile. In fact, vibrotactile feedback has proven to be more effective in training motor skills than haptic force feedback because it disturbs movement less [27].

2.5.4.4 Combining modalities

When distributing information to different modalities, it is processed better because of different cognitive resources [28]. This so-called multimodal feedback often produces better learning performance than unimodal feedback [29], but not always [30]. Additionally, augmented feedback provided in the same modalities may cognitively overload the learner or distract from perceiving intrinsic feedback [35]. Thus, the most effective feedback must be designed in such a way that it distributes information to modalities and exploits modality-specific advantages while not cognitively overloading the learner.

2.5.5 Effective feedback designs

There are many ways of giving feedback on trajectory. The SPRINT rowing system has researched the combination of visual and vibrotactile feedback, on an only-hands square trajectory [32], and on a full rowing stroke trajectory [33] as can be seen below. The visual feedback in the first study displayed a reference for the trajectory with four balls at the corners of the square, and a fifth displaying the current location of the hands. The visual feedback in the second study displayed balls over a normal rowing environment which had to be followed. In both, the user wore four vibrating motors, which gave correcting vibrotactile feedback depending on the deviation from the target trajectory.

Interestingly, the studies gave slightly different results. In the square trajectory study [32], the combination of visual and vibrotactile was more effective than either on its own, as the visual feedback allows the user to guess the forthcoming error and the haptic feedback improved concentration, but the visual feedback had a side effect of a slower execution because the user was trying to accurately follow the trajectory. While in the full rowing stroke study [33], vibrotactile showed the best improvement over visual or the combination of both, as it seemed that visual feedback introduced a dependency on the presence of technique.

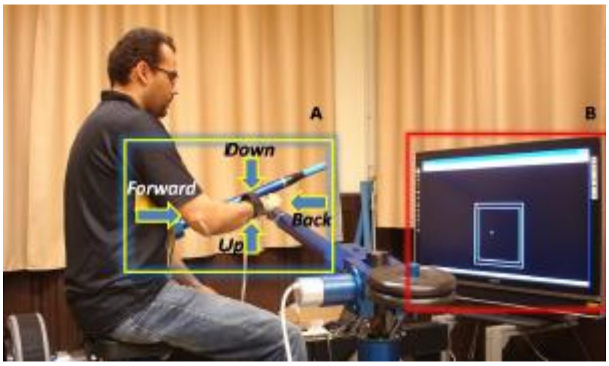

Figure 14 Training square trajectory [32, p. 3]

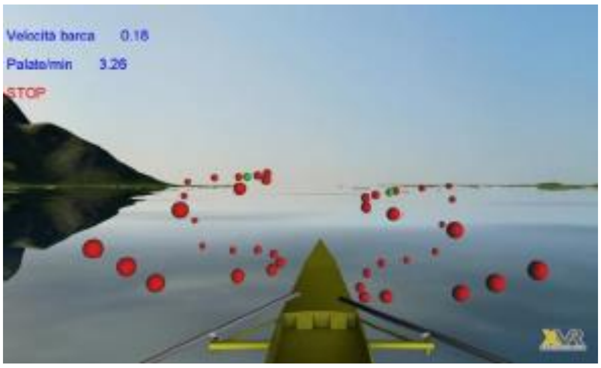

Figure 15 Training full stroke trajectory [33, p. 1]

The authors of the M^3 rowing system have conducted multiple studies on more complex feedback designs involving all modalities. Most notably, concurrent versus terminal feedback [37], about the added benefits from auditory sonification and haptic force feedback on visual feedback [35], and about automated selection of largest-error-specific feedback [36].

In [37] there is a discussion about which feedback on technique is more effective, and whether the feedback has to be concurrent (during the session) or terminal (after a session). All different modalities of feedback are tested in the M^3 virtual environment. The question was which feedback system resulted in the most similarity to a (perfect) target oar movement, and if there was a difference between concurrent or terminal feedback. It became visible that concurrent visual feedback worked the best when the participants tried to track the target movement pattern. This is in agreement with previous studies that covered the question whether visual feedback lead to more precise target tracking [31].

Visual feedback works the best for several reasons. Firstly, the target trajectory is always displayed, the participant is able to look ahead and prepare which makes timing easier. Secondly, it is easier to perceive spatial information like handle height using visuals, compared to audio or vibrations. Generally, visuals are mostly easy to interpret as they are more commonly designed. Both the concurrent and the terminal visual group in [37] scored similar.

Figure 16 Terminal visual feedback on trajectory [37, p. 5]

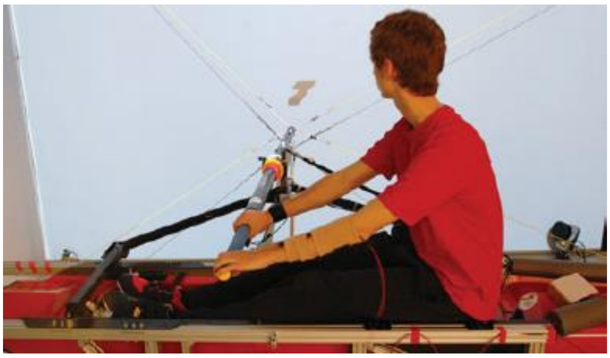

Figure 17 Haptic force feedback on trajectory [37, p. 4]

The other feedback modalities in [37] also gave interesting results. The auditory feedback was constructed similar to haptic feedback: both the volume of the audio and force on the oar increased with the deviation. This led to participants generally being able to move through the rowing movement, but less smoothly than in the visual case. Participants were observed to either react late or make a large correcting movement. These groups also had trouble with timing, like rotating the blade. Auditory feedback appeared to be the hardest to track the movement from. In the paper, it is assumed that visual feedback is less cognitively demanding, and therefore those kinds of feedback perform better compared to auditory or haptic feedback. Even though concurrent feedback may work very well, the outcome of the experiment proved that terminal feedback in the form of allowing the participant to visually observe their errors worked the best on internalizing motor skills.

The feedback design in [35] involves feedback which increased in intensity depending on the size of error, called bandwidth feedback. Visual feedback included an oar displayed to the right of the user, together with a target oar. Interestingly, based on the above mentioned study, concurrent and terminal feedback is combined in the form of a visual trace as can be seen below. Auditory feedback was presented in the form of sonification of oar movement, as the own oar can be heard on the right, while the target oar on the left. Finally, the haptic force feedback corrected the oar into the target trajectory,

Figure 18 Visual bandwidth feedback in the form of a trail, which combines concurrent and terminal feedback

also as bandwidth feedback, but with a dead zone around the target. Most importantly, all feedback mostly disappeared when the movement was performed correctly.

Sonification and haptic effects on trajectory performance were subtle, as the visual feedback alone was already effective. Concerning velocity, visual-auditory feedback performed the best, as well as causing a high transfer of skill to non-feedback conditions. This proves that not only expert rowers can profit from sonification [41], but also beginners [35], at least if it includes a reference sonification, and in this case is combined with visual feedback.

Recently, a study of the M^3 system covered automatic selection of feedback addressing the largest error of the rower [36]. Four segments of the recovery were measured, as well as the velocity ratio of above and below water. An appropriate feedback like the ones listed above was presented to any of these five errors. Specifically, the primary feedback for spatial errors (for a specific part in the trajectory) was visual (see figure 18) and the primary feedback for velocity errors was the aforementioned left-right sound. Then, when an error persisted, a haptic path control was added. This automated feedback selection strategy showed a significantly higher learning rate of the trajectory and velocity skill.

2.5.6 Conclusion

Many different approaches to rowing technique measurement and feedback designs were presented. In the end, it is impossible to conclude on one specific effective type of measurement or feedback as not enough comparison studies have been done, but it is possible to determine the aspects of effective feedback.

When a feedback system for a rowing machine is designed, a combination of different kinds of feedback can have great potential. It is suggested that visual and haptic concurrent feedback is useful for instructing the movement, whereas terminal visual feedback is useful for internalizing the motor skills of the stroke and making the user less dependent on the concurrent feedback. However, haptic feedback should not challenge the user or disturb smooth movements. A ‘sonification’ or sound additive is then useful for pointing attention to velocities or forces, which subtly enhances the perception of movement. Therefore, a combination of these kinds of feedback seems to have great potential for learning a complex motor skill like the rowing stroke.

Feedback should also “… not overload the learner and allow the learner to process intrinsic feedback when movement is performed correctly” [35, p. 13]. Thus, feedback should be provided in bandwidth form and mostly disappear when it is unnecessary. This also mostly avoids the dependency effect where technique can only be done correctly when feedback is present. Then, in order to improve effectiveness further, feedback would need to be adapted to the individual. Automatic feedback selection of the largest error would significantly contribute to this.

2.6 Conclusion on rowing errors

To be able to design feedback on technique, a number of rowing technique errors should be chosen. A great number of common beginner's errors have been found in chapters 2.2 and 2.3. However, the limitations of this project should be taken into account, which is mainly the small amount of motion trackers and their accuracy. That is why all mentioned errors have been narrowed down into a few common but feasible ones.

Consequently, errors which cause subtle movement changes, such as 'pulling the handle with the arms', 'not stretching arms completely', or 'over-stretching the arms' (also stretching the shoulders) were dismissed. On the other hand, the two most common errors according to the coach guides and the interviewed coaches, which are 'incorrect back movement at the catch', and 'wrong order of execution during the recovery' are feasible. This was also showed by Koen Vogel [2], who mainly focused on the timing of the recovery execution.

However, the literature review in chapter 2.4 concluded that the trajectory of the hands "…turns out to be the most important factor influencing the overall performance" [32, p.2]. Furthermore, there were a number of errors discussed in chapters 2.2 and 2.3, which in fact would be corrected with a better trajectory and velocity of the hands. Specifically, a better trajectory also implies the correction of errors such as 'missing the catch', 'not a straight line during the drive', 'finishing too high or too low', and 'not having the ideal stroke length'. In addition, a better velocity ratio implies the correction of errors such as 'not using enough power at the catch', 'not taking the power to the end of the drive' (thus dividing power throughout the drive), 'not taking the time for the recovery', and 'braking before the catch'. Improvement of the last error would also improve back movement at the catch, as one of the causes of the back tilting forward during the catch is actually 'being passive' and 'braking before the catch'.

A second reason to choose trajectory and velocity, is the fact that one of the goals of this project is to experiment with many varieties of feedback; several based on literature, and a number of original concepts of which several only possible using virtual reality. Due to literature mainly covering these two aspects of technique, it makes sense to build on that with the addition of virtual reality. Furthermore, trajectory and velocity can be trained separately, but also simultaneously in the same display, resulting in faster development of feedback varieties and a greater number of them.

A third reason would be because of the on-water rowing simulation this project will provide, where oar trajectory is even more important than on the indoor rowing machine.

For these reasons, it was decided to begin with the focus on trajectory and velocity, and afterwards address posture correction such as the back angle, which according to the rowing guidebooks [5, 10] and interviewed coaches also plays a big role in rowing technique and injury prevention.

3 METHOD

Due to the COVID-19 pandemic, this graduation project will follow a very different structure as opposed to the traditional process. Here, the standard Creative Technology Design Process will be explained, following with the impact the pandemic has on this project and how it will adapt in order to still execute the research in a way that would be useful and logical.

3.1 THE CREATIVE TECHNOLOGY DESIGN PROCESS

The Creative Technology Design Process [49] (CTDP) is a design process made for, and widely used by the bachelor study Creative Technology. It represents a combination of Divergence-Convergence models of design practice where the subject is richly explored after which it is narrowed down into a single solution, and Spiral models of design practice where steps are more interconnected and can be traversed in any order.

As can be seen to the right, the traditional design process consists of four phases: ideation, specification, realisation, and evaluation. In the ideation phase, the user's environment is observed, ideas are explored, and possible solutions are designed. In the specification phase, the best ideas are further thought out, by creating early prototypes and defining requirements, during which iteration and evaluating is taking place. In the realisation phase the chosen concept is created according to the specified requirements. Finally, this concept is evaluated, for example by means of user testing.

Summarized, the entire process consists of a multiple of comprehensible steps which all have their own diverging-converging aspect and cyclic aspect which allow for a structured process while maintaining the freedom of variety of paths, eventually leading to a final evaluation.

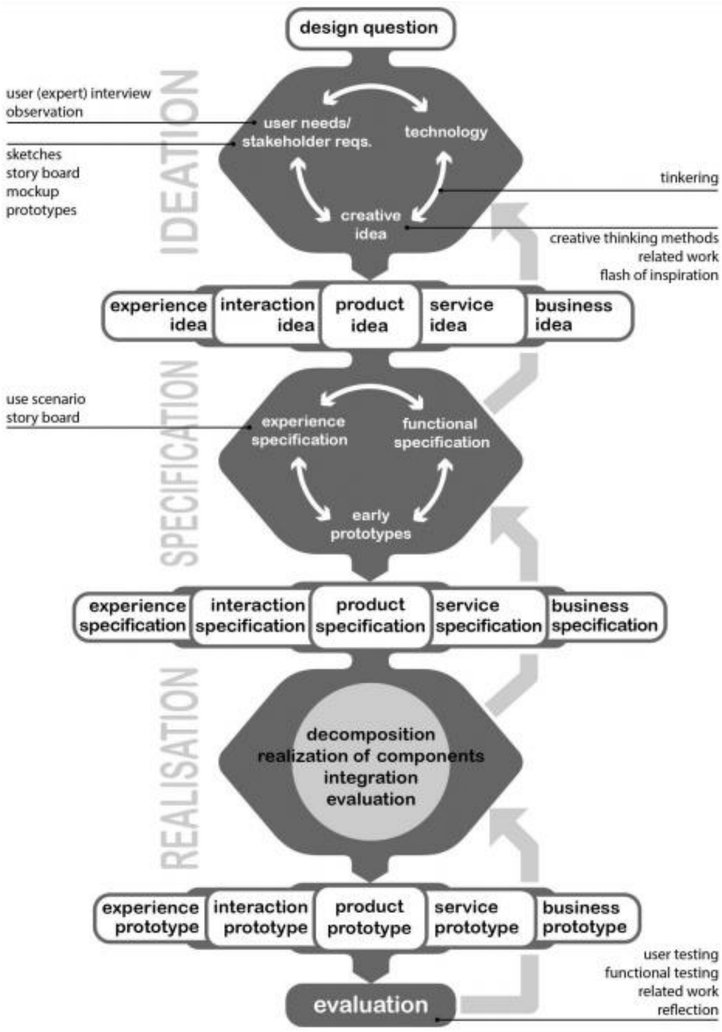

Figure 19 The Creative Technology Design Process

3.2 Implications of the COVID-19 pandemic

During this project, a novel virus named COVID-19 spread around the world. As a result, the university has closed, students have to work from home, and user testing will only be done on people living in the same house. This makes it unwise, and maybe even impossible to follow the CTDP in its original form. Practically speaking, a concept can be realised, but only evaluated by user testing on a handful of people which would make it impossible to draw any significant conclusion.

3.3 Adaptation

However, these implications open up two possibilities. First of all, user testing is made extremely easy as the participants live in the same house, are interested in my work, and like helping me out. Additionally, the concept can be developed and tested in a home environment, further advancing this project towards a universal product which could be placed anywhere.

Therefore, instead of working towards a final evaluation, there will be multiple shorter design cycles, all ending with a more informal evaluation on functionality and effectiveness. Furthermore, there will be less focus on specification, and more on creating a variety of concepts in order to compare between them in the evaluation. Then, at the end of the project, the best varieties of concepts can be integrated into several combinations which could be evaluated as well.

All tests will be done with the same participants, which will cause great bias in results. This is why no statistical analysis will be done. Rather, results will mainly be based on interviews and analysis of participants' behaviour.

In the upcoming chapters, first the physical and virtual setup of the project will be shown and how it is changed and improved from Koen Vogel's design [2]. Then, five feedback design cycles follow with their own ideation, realisation, and evaluation.

4 PHYSICAL SETUP

This chapter provides the entire physical setup of the project. This setup was derived from the work of Koen Vogel [2], but with several improvements. This was necessary, as Koen noted that "… the tracking accuracy was very inconsistent, with short periods of significant inaccuracy" [2, p. 27]. Accuracy, cost, and usability improvements were made, and the setup was adapted to the home environment. Another goal of this chapter is to make the setup reproducible for future research, that is why it is also shown how to use and calibrate the hardware.

4.1 ROWING MACHINE

The indoor rowing machine used for this project is the RP3 model S, it was lent to the local rowing club D.R.V. Euros[5] by the company RP3 Rowing[6]. It was coincidentally brought to my home by this rowing club to give me the opportunity to train on it. The rowing machine was placed in a narrow room, closely in-between a wall and a desk.

Compared to the more traditional rowing machines, like the widely used Concept2[7], the front part (the flywheel) is free to move just as the seat can. This allows for an experience closer to on-water rowing and decreases the chance of injuries. Furthermore, RP3 Rowing points out[5] that on this rowing machine, "good technique is rewarded and poor technique becomes apparent, can be felt and corrected in an early stage". Therefore, this rowing machine was found to be well suited for this project.

Figure 20 The RP3 Model S placed at home, mounted with motion trackers

4.2 MOTION TRACKING

The motion tracking hardware chosen by Koen Vogel are the HTC Vive[8] trackers, as these can easily be implemented alongside their virtual reality set, and because it is shown to be reasonably accurate for the purpose of scientific research [50]. However, the shape of the room made it difficult to create a setup with accurate motion tracking Nevertheless, this challenge contributed to the eventual expansion to a product which could be placed anywhere.

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[5] https://www.drv-euros.utwente.nl/en/
[6] https://www.rp3rowing.com/
[7] https://www.concept2.com/indoor-rowers
[8] https://www.vive.com/

The final and most reliable setup consists of three Vive trackers and a head-mounted display (HMD) which also functions as a tracker. These trackers are individually sold for around €125 at the time of writing. To actually track these motion trackers, the HTC Vive uses two infrared-emitting lighthouses. Their positions also had to be carefully considered because of the location.

As can be seen below there are multiple differences between Koen's and this setup. The next sections will explain why these choices are made and how they improve on the versatility, accuracy, usability, and cost of this setup.

Figure 21 The final setup

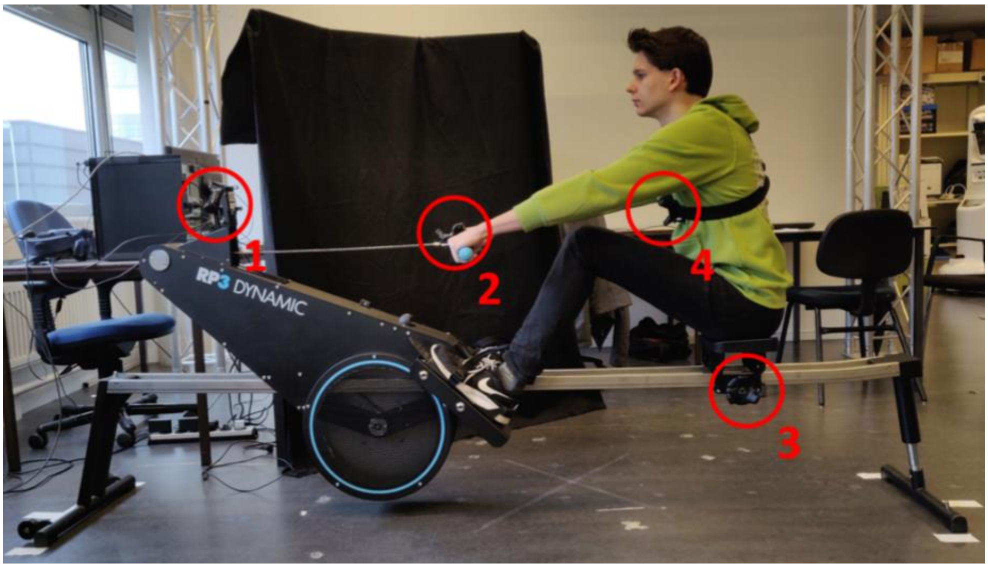

Figure 22 Setup of Koen Vogel [2, p. 27]

4.2.1 Flywheel tracker

The position of the tracker on the flywheel of the rowing machine stayed approximately the same. However, in this case the smartphone holder was tilted downwards, in order for the motion tracker to be placed on top. This way it has increased visibility for the lighthouses.

Figure 23 Flywheel motion tracker

4.2.2 Hand tracker

While testing out the tracking accuracy of the tracker attached onto the handle, it became clear that the rowing movement, especially during the drive, caused it to desync because of shaking.

This issue was solved by attaching the tracker onto a glove, which shakes considerably less during rowing, and thus leads to much smoother and accurate tracking. The final glove used for this project can be seen below. This glove also has other equipment integrated into it, in order to provide haptic feedback. More can be read about this further into this thesis, in section 6.3.2.

Figure 24 Final motion tracking glove, with integrated vibration motors (see section 6.3.2)

4.2.3 Seat tracker

To make the seat tracker visible to the lighthouses proved to be a lot more difficult. Under normal circumstances, this project would be developed in a larger design space. However, here we have to suffice with a narrow room. It quickly proved to be impossible to mount this tracker under the seat and still have accurate tracking. Even though a lighthouse placed at a lower level would have better sight of it, sight of the other trackers would then often be lost.

Therefore, a wooden plank was attached under the seat using cable ties, on which the tracker was mounted using double-sided tape. The tracker was also situated relatively far from the seat in order to avoid blocking sight of it during rowing.

Figure 25 Seat motion tracker mounted on a wooden plank connected to the seat

4.2.4 Head-mounted display tracker

During the project it became apparent that the HMD not only acts as a view into the virtual environment, but also as a motion tracker. Therefore, the motion tracker on the chest in Koen's setup is not used anymore, as the angle of the user's back can be reliably calculated via the HMD.

Specifically, from the HMD the centre of the head is found, from which point a back angle can be calculated. As a result, it is possible to turn the head and still have approximately the same back angle. This is illustrated in the pictures below. Having one less tracker in the setup of course greatly decreases the cost and increases the ease of use.

Figure 26 Calculation of the back angle target using the tracking of the HMD

4.3 LIGHTHOUSE LOCATIONS

The infrared tracking lighthouses are located high up and to the left of the rowing machine. This allows for a good overview and constant sight of the seat tracker and the left-hand glove. Moreover, they are connected with a syncing cable (regular 3.5mm jack cable) to further increase tracking accuracy.

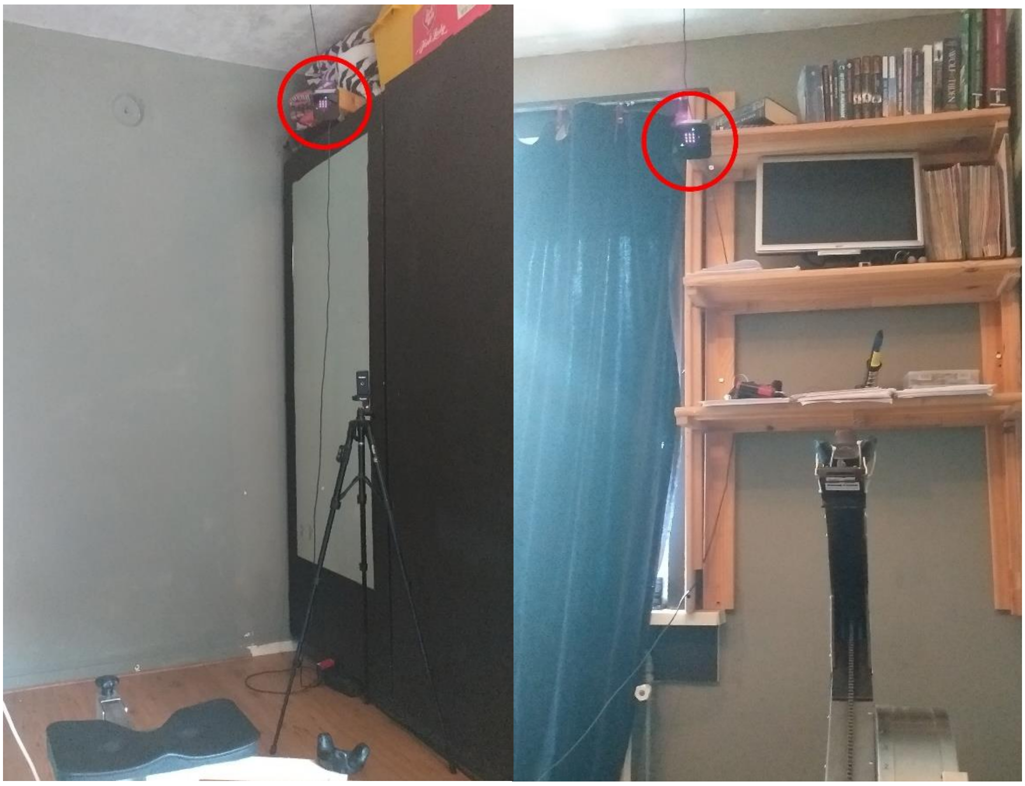

Figure 27 Rear and front lighthouse locations

4.4 SETTING UP AND CALIBRATION

To use the setup, the Vive trackers need to be paired in a specific order, for the software to know which tracker is which. This order is the same as the overview figure shown earlier, and goes as follows:

1. Flywheel tracker
2. Hand tracker
3. Seat tracker

Additionally, to set up or calibrate the room, a position on the sliding is marked. During calibration, the seat should be in this position with the HMD on top of it, facing forward. This procedure is illustrated below for clarity. Specifically, the front part of the seat is in this case positioned at 80.7 centimetres from the very backside of the rowing machine

Figure 28 Room calibration

4.5 PREVIOUS SETUPS

A multitude of other setups have been attempted before the above setup was found. This section will briefly explain what these entailed, and why their motion tracking was less accurate.

Firstly, it has already been discussed in section 4.2.3 that a lower location of the rear lighthouse would see the tracker under the seat better but would often lose sight of the other trackers. That is why the plank under the seat was used. However initially, this plank was mounted to the right of the seat in order to never get in the way when walking past the rowing machine. As a result, the lighthouses and the glove were also located on the right as can be seen below.

This setup was maintained throughout half of the project's lifetime and had a relatively high chance of moments of inaccuracy. It turned out that the seat tracker still could not be seen well enough, as it was too close to the user's body. Because it could not be moved farther away due to the wall, it was ultimately decided to move everything to the left of the rowing machine, resulting in far better results.

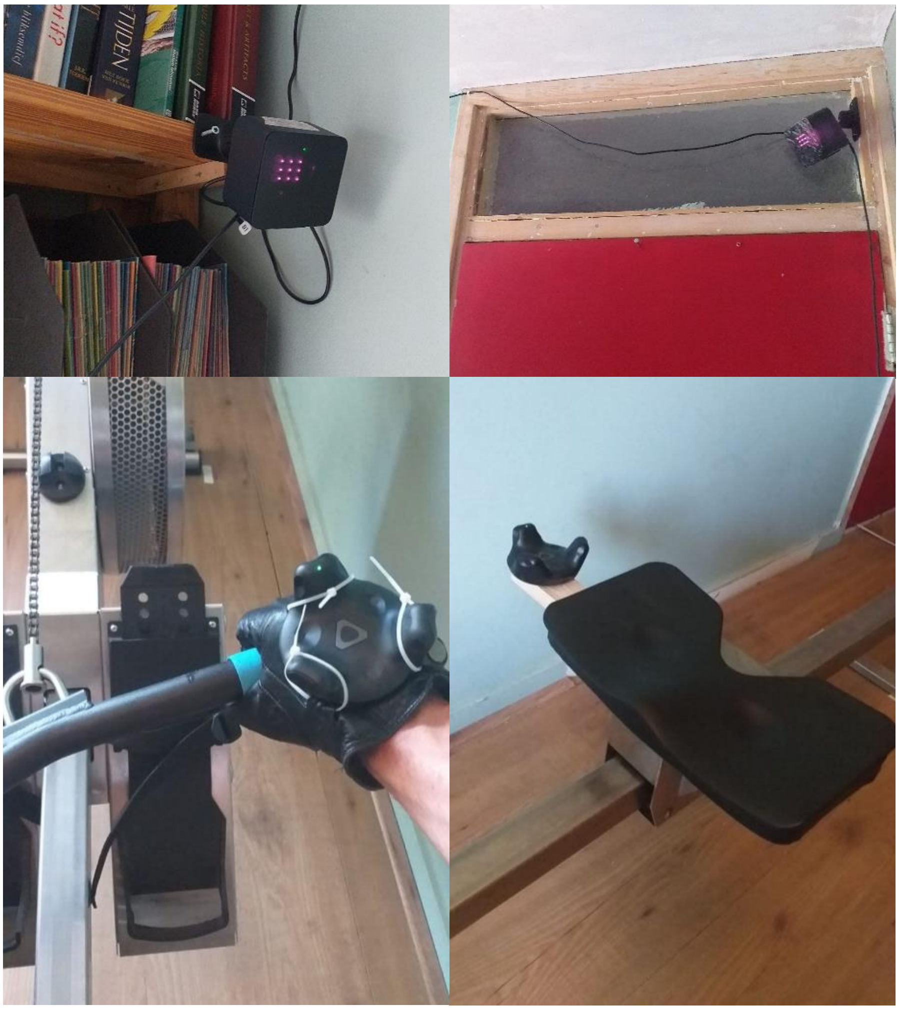

Figure 29 Right-sided setup

4.6 RECOMMENDATION

In order to further lower the cost of the setup, the two controllers that are bundled with the HTC Vive set could be used as flywheel and seat tracker instead. However, it was not done in this case, because they would be more difficult to mount due to their larger size, and because they were in use for debugging. Nevertheless, this could be a very promising solution, should this project ever develop into a commercial product.

5 VIRTUAL ENVIRONMENTS

The two virtual environments created by Koen Vogel [2] are used again and improved on. Mainly, a different indoor rowing machine model had to be created and a single scull (rowing boat) was modelled together with a fellow student, Annefie Tuinstra, and made functional inside this project. Furthermore, a more humanoid character was used, which rig was changed to have more natural back movement.

5.1 ROOM ENVIRONMENT

The room environment consists of just the rowing machine on a large floor. It is a simple environment meant for calibrating the setup and for development of concepts and mechanics. In this case, because a different version of RP3 (i.e. the RP3 Model S) was used, a new model had to be created. Additionally, a chain was added to the rowing machine, as well as a stroke rate display which can be used to instruct users to hold a certain stroke rate.

Because of the simplicity of this environment it can be used for testing feedback designs without distracting the user with anything else. Actually, this environment was used for the first two feedback designs as explained in the next chapter. However, when the more enjoyable river environment with simulated single scull was finished, testing was done in that environment to evaluate its benefits.

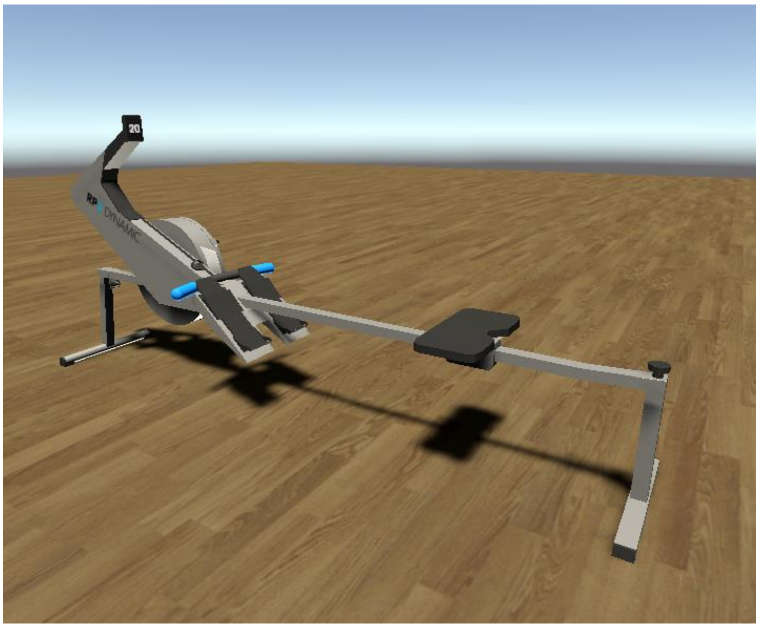

Figure 30 The room environment with the RP3 Model S

5.2 RIVER ENVIRONMENT

The river environment was already made by Koen Vogel [2]. However, with a less realistic single scull and character. The only change in this environment was the lowering of the waves, to simulate the more tranquil water found in a canal.

Because of time constraints and limited skill in 3D modelling, the single scull and oars were modelled together with Annefie Tuinstra, a fellow student who is also a member of the rowing club D.R.V. Euros. This model was then analysed for correct proportions and prepared for implementation in the project. The entire boat was connected to the physical flywheel of the RP3, and by using several 'aim constraints' to positions connected to the handle the oars and oarlocks were made functional.

A showcase video of the final version of the on-water rowing simulation, as well as all final visual feedback designs can be found in Appendix A.2.

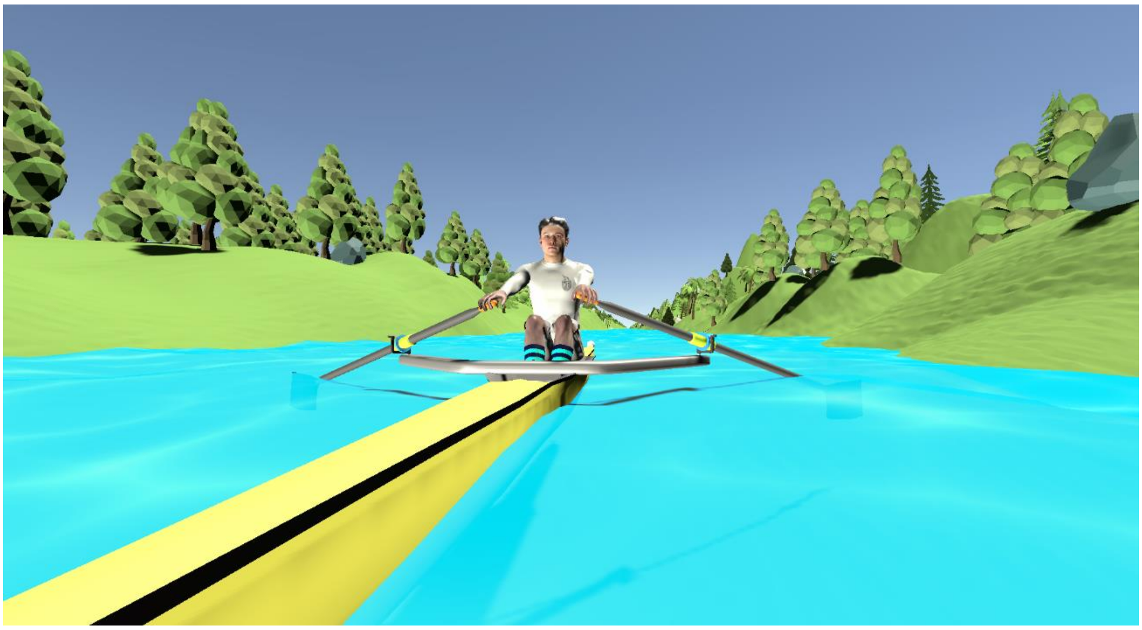

Figure 31 The river environment with single scull and character

5.3 CHARACTER

The robot-like character from Koen Vogel [2] was dismissed in favour of a more humanoid character, to make the rowing movement better visible. Due to time constraints this character was also downloaded from Mixamo[9], however with an improvement in its rig setup.

Namely, to represent the rowing movement more accurately, an extra joint just above the hip and close to the back was added. Otherwise, the character would rotate his back starting from the belly. In fact, the actual hip joint could not be used for back rotation because it is the root of all joints. This change was accompanied with skin binding of the mesh to this joint.

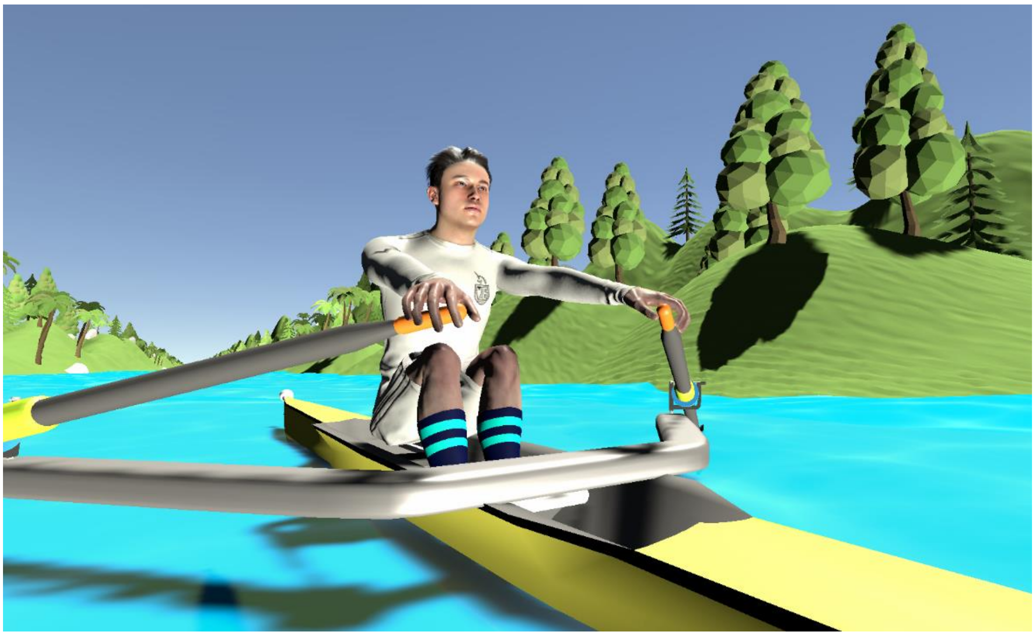

Figure 32 The character rowing in the single scull in the river environment

[9] https://www.mixamo.com/#/

Furthermore, the Animation Rigging package[10] was used again for movement of the character using inverse kinematic and other calculations, but with a more reliable setup where one rig object was used instead of multiple, and with a correct order of execution of body part calculations. Namely, first the back with a 'multi-aim constraint', then the legs and arms with 'two-bone IK constraints', and then the head with a 'multi-rotation constraint'. Moreover, because the back movement was too sensitive when targeting the HMD, the target for the back constraint was positioned half a meter above the HMD and slightly backwards by trail and error.

Finally, the character was set up for both RP3 rowing (see below) and single scull rowing (figure 32), and due to time constraints a large and medium sized character were created, which best fitted the participants. However, stretching of the model caused the feet and hands to stay at their target with slight inaccuracy.

Figure 33 The character rowing on the RP3 Model S in the room environment

[10] https://docs.unity3d.com/Packages/com.unity.animation.rigging@0.2/manual/index.html

6 FEEDBACK DESIGN CYCLES

This chapter covers all cycles of feedback design. As explained in chapter 3, every cycle consists of an ideation, realisation, and evaluation phase. This way, many varieties of feedback are designed in the different modalities while testing the benefits of virtual reality, fitting the second and third sub research questions established in chapter 1:

- *How should augmented feedback on technique be designed per modality while considering the benefits from virtual reality?*
- *What varieties of these feedback designs are effective?*

As explained in section 2.6, the hand trajectory (handle height) and velocity (horizontal handle velocity) will first be addressed and afterwards the back angle. All feedback designs will be based on effective concepts of literature and expanded with new ideas.

6.1 VISUAL TRAJECTORY AND VELOCITY

This section explains the entire visual trajectory and velocity feedback design cycle. Visual feedback is explored first in order to introduce the participants to the movement before presenting more abstract feedback, and because the visual domain benefits the most from virtual reality.

6.1.1 Ideation

Concluding from the conducted literature review in chapter 2.5, based on [36, 37] the most effective design of visual feedback on trajectory is a combination of concurrent and terminal feedback in the form of a trail, overlaying a target trajectory. Furthermore, feedback given in bandwidth form shows the most potential to transfer the technique to a non-feedback situation, because in that case the feedback entirely disappears when technique is performed correctly.

To add to this concept and to experiment with the benefits of virtual reality, it was chosen to create varieties of visual feedbacks at different locations and for different trainings, because trajectory and velocity can be trained separately but also simultaneously in the same display. For the evaluation of this design cycle, it was decided to test in the room environment without a character, in order to have full attention to the feedback.

6.1.1.1 Location

The largest benefit from virtual reality is the expansion of possibilities in the visual domain. Therefore, four locations of visual displays were selected, of which multiple are largely specific to virtual reality. Moreover, in the work of Koen Vogel only a side-view display in front was used in order “to attract the most attention,” [2, p. 31] without consideration of other locations.

Side display
Here, the visual feedback is displayed on the right side of the user, where the display corresponds with the actual handle position. This is technically possible outside of virtual reality by the use of a monitor, although this display would not be able to be placed as close to the user.

Immersive display
In this case, the visual feedback is displayed at the location where the movement is occurring. Thus, the virtual handle will be moving inside the display. This is a possibility that virtual reality technology, but also augmented reality technology, provides.

Head-up display

Feedback can also be visually displayed in such a way that it is always visible, regardless of the view direction. This is called a head-up display (HUD). In this case, the feedback can simply be attached in front of the point of view of the HMD.

Side-view display

To give a clear overview of the entire situation, it was also decided to create a side-view of the RP3 which will be displayed in front of the user. This is more similar to existing methods of visual feedback, for example in [40] and [32].

6.1.1.2 Training

In all found cases of similar work, either trajectory alone is trained or trajectory and velocity together [31, 32, 33, 35, 36, 37]. This is why feedback was designed which specifically targets velocity without regard to the trajectory. As a result, there are three different types of trainings.

Trajectory

Here, only the height of the handle is trained. This will be done by showing a target trajectory once the user deviates from it. Additionally, a red trail can be seen at significant deviation from the target. This way, it is possible to see where errors were made, even a few seconds after their occurrence (realisation in figure 34-36).

Velocity

Here, the velocity ratio between the drive and recovery is trained. This training will also display a target position when the user is deviating from it, but this time it is represented by an animated trail which will perform the desired handle velocity. Also here, a red trail can be seen from significant deviation (realisation in figure 37).

Trajectory and velocity

These two can also be combined into a single display, where both can be trained. This is done by showing a target trajectory with an animated ball. Of course, here a red trail can also be seen from significant deviation, and all feedback will turn transparent when done correctly (realisation in figure 38).

6.1.2 Realisation

6.1.2.1 Feedback design

The target trajectory is created by careful analysis of my own rowing. Due to three years of personal experience as a competitive rower, it was decided that this would be good target technique for beginners. The final version can be seen below.

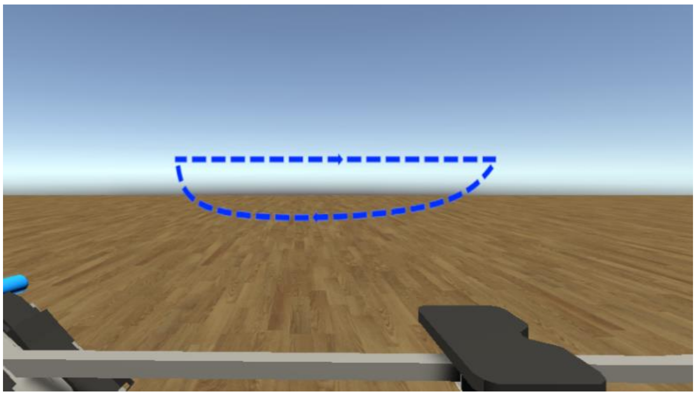

Figure 34 Target trajectory

As mentioned earlier, one of the main principles of these feedback designs is the fact that it completely disappears when technique is performed correctly. On top of that, a red trail should appear when deviation is significant. To achieve this, some deviation thresholds were set:

- Minimal vertical deviation = 3 cm. From this deviation the feedback will start to be displayed, lower values mean the feedback is not visible.
- Maximum vertical deviation = 9 cm. At this point the feedback is fully displayed.
- Trail threshold = 1.5 times max deviation. From this point on the red trail will leave a trace

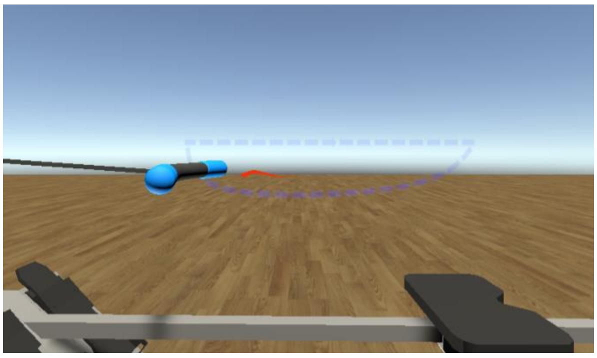

Figure 35 Fading feedback

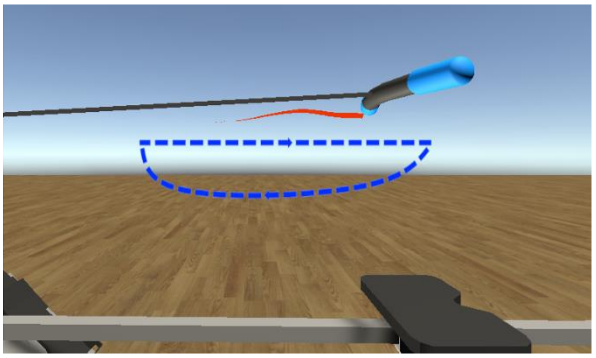

Figure 36 Deviation trail

For the velocity and the combined feedback, an animation had to be created. This was made specifically for stroke rate 20 which is a common stroke rate for standard intensity rowing. Coincidentally, at this stroke rate the drive usually lasts 1 second and the recovery 2 seconds. Due to the nature of the moving flywheel of the RP3, the handle stays relatively in the same place for the first few moments of the drive. This was taken into account in the animation. Additionally, a parameter was created in order to set a target stroke rate, which controls the speed of this animation, should stroke rate 20 not fit beginning rowers.

The feedback designs for velocity and combined feedback can be seen below. The light blue object represents the target position, which is controlled by an animation. In the case of velocity feedback, the target and deviation (current) trail is expanded into a line, and two boundary markers are placed in order to indicate the points of reversal.

Furthermore, it was decided to have different, more generous deviation thresholds for horizontal deviation, due to the fact that a rowing trajectory has a lot more horizontal movement than vertical movement. These are:

- Minimal horizontal deviation = 9 cm.
- Maximum horizontal deviation = 27 cm.
- Trail threshold = 1.5 times bounds of maximum deviations

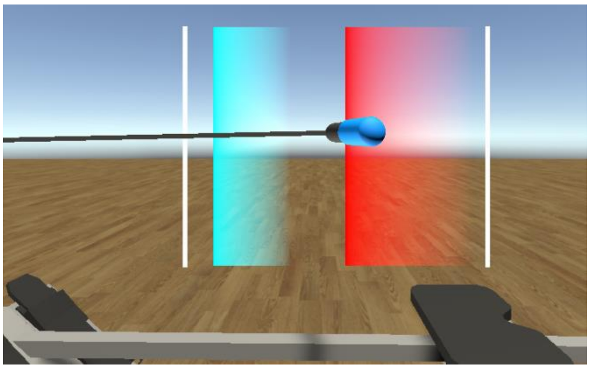

Figure 37 Velocity feedback

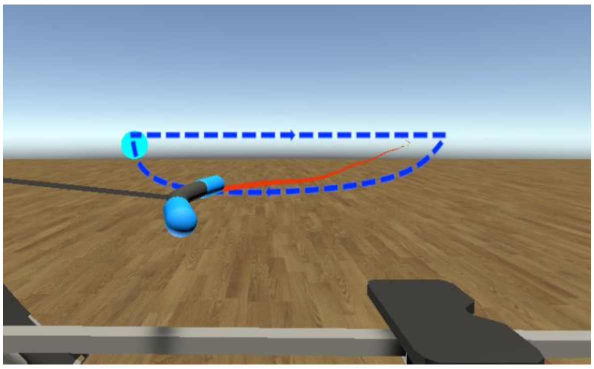

Figure 38 Trajectory and velocity feedback

6.1.2.2 Locations

In this section, the implemented locations of feedback are explained. Additionally, it is shown how feedback designs are adjusted to the immersive display. Also, due to having a total of 12 different varieties, only a selection of displays is shown.

<u>Side display</u>

The side display is located directly to the right of the handle. A view of its combined trajectory and velocity feedback can be seen below. All varieties of the side display have already been shown in the previous figures.

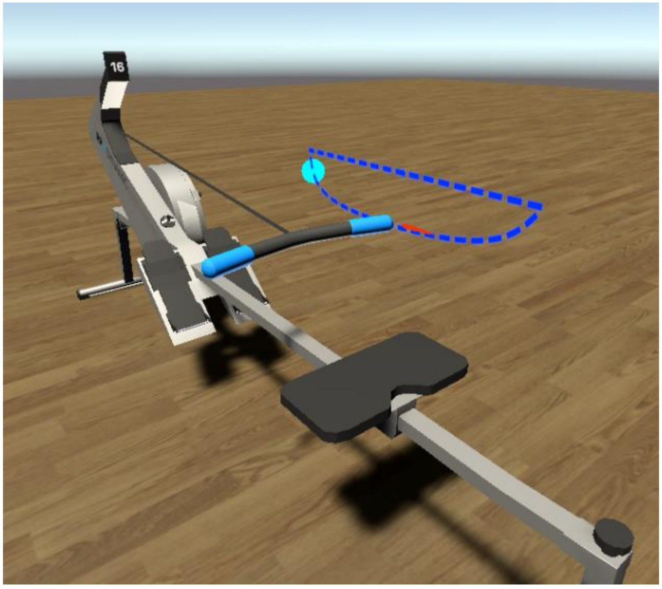

Figure 39 Side display of combined feedback

Immersive display

To be implemented in the immersive display, the trajectory image and the velocity trails had to be adapted. First, a 3D model of the target trajectory was created in two parts, a drive and recovery model which turned visible depending on the state of the stroke. Then, the velocity feedback was transformed to be visible under the handle.

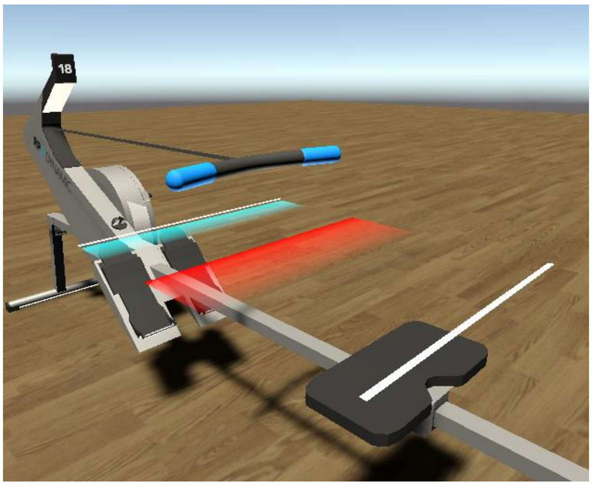

Figure 41 Immersive velocity feedback

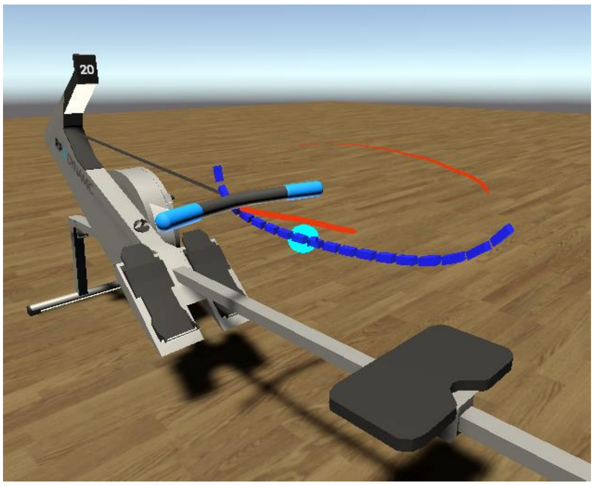

Figure 40 Immersive combined feedback

Head-up display

For the head-up display, a live updating texture from a side camera was put in front of the HMD. It was positioned in such a way that it always stayed in the centre of the view.

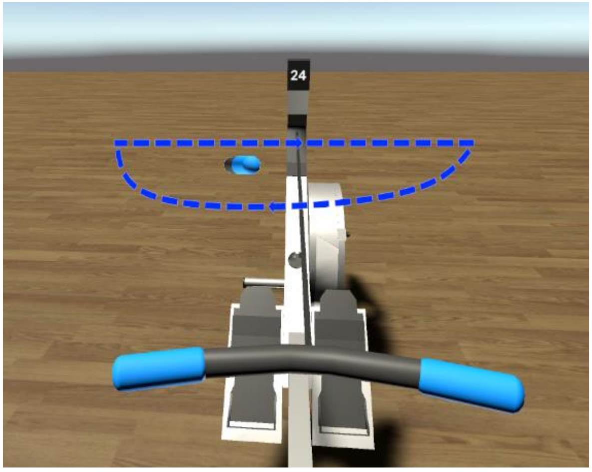

Figure 42 Head-up display

Side-view display

The side-view display also involves a live updating texture from a side camera, only now showing the RP3 as well. This display is located to the front of the user.

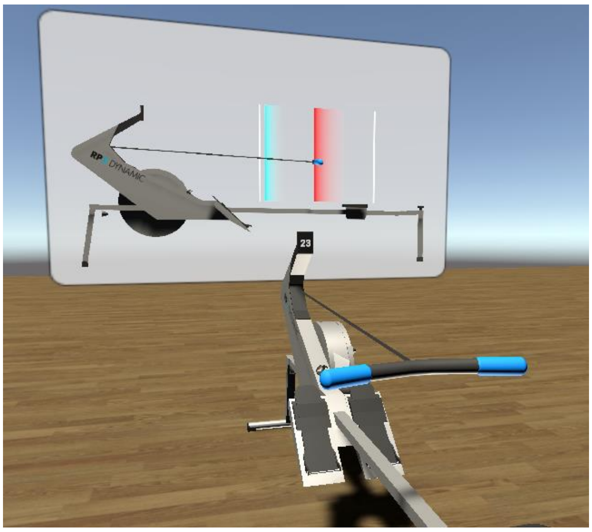

Figure 43 Side-view display

6.1.2.3 Technical details

These feedback designs are integrated in such a way that all varieties can easily be turned on with the use of two switches for the trainings and four switches for the different displays. Additionally, a master trajectory object was created far out of sight of the user. This object can be used to calibrate the trajectory's scale and position based on the reach of a user as all other displays are controlled by it, and provides the visual feedback in the case of the head-up and the side-view display.

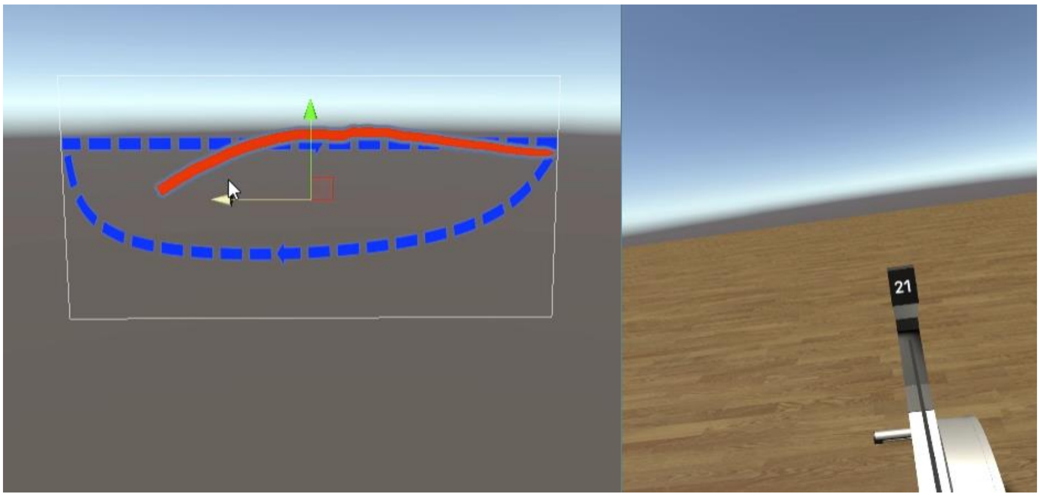

Figure 44 Calibrating the master trajectory

Finally, to calculate the vertical deviation during the recovery in the case of only-trajectory training, a thin and without-gaps 3D model was made of the recovery trajectory. Then, with a ray casted from the handle onto this invisible model the vertical deviation can be calculated. During the drive, it was possible to calculate the vertical deviation from a certain y-position. Also, for the velocity and combined training this deviation was simply calculated from the animated target ball.

6.1.3 Evaluation

To examine out how beginning rowers react to these visual feedback varieties, a test was conducted with family members living in the same house. Several aspects of the feedback varieties were evaluated by means of interviews and analysis of video recordings.

6.1.3.1 Method

For all user testing of this research, approval of the EC of the faculty of EEMCS of University of Twente was received under the number RP 2020- 42. All ethical documents can be found in Appendix B.

The test was done on four family members. Three of the participants have already rowed one time with instructions. Experience with VR was varied; two participants had moderate experience, one participant had little experience, and one participant experienced VR only once.

The participants were first introduced to the rowing machine and were asked to row on it for one minute. Then the motion trackers were equipped, and the virtual reality environment was introduced, in which they also rowed for 1 minute. Then it was asked to hold stroke rate 20 for one minute in order to get used to this tempo. Meanwhile, the scale and position of the master trajectory object was calibrated to the participant's reach.

Before the actual test started, the participants were informed that they would be experiencing feedback on their rowing technique for three blocks, each consisting of 4 times 30 seconds of feedback and 30 seconds of no feedback. They were also asked to try to hold stroke rate 20 at all times and row at a medium intensity. In order to test intuitiveness, the feedback designs were not explained beforehand. Only when a question was posed, a hint was provided.

All participants experienced all feedback varieties for short periods of 30 seconds. Only, for every participant the first two trainings were switched, and the display order was randomized[11]. The order of feedback varieties per participant can be seen in the table below.

Table 3 Visual feedback order per participant. T = trajectory, V = velocity, TV = trajectory and velocity, 1 = side display, 2 = head-up display, 3 = immersive display, 4 = side-view display

Participant	Training order	Display order (random)
1	T, V, TV	2, 3, 4, 1
2	V, T, TV	3, 2, 4, 1
3	T, V, TV	1, 4, 3, 2
4	V, T, TV	4, 3, 2, 1

After each training block, the participant was instructed to take off the HMD and answer a number of questions:

- What did you see?
- What did you try?
- Was it clear?
- Was it difficult?
- Was it annoying?
- Which display worked the best for you and why?

After the entire session, several other questions were asked:

- Did you find it fun?
- Were you nervous?
- Do you think you are good at it now?

[11] https://www.random.org/lists/

- Would you be able to perform the technique now without virtual reality?
- What do you think of using such an installation to train technique?

6.1.3.2 Results

Based on observations during the test, analysis of video recordings, and answers to the questions, the following results were gathered. These are grouped into several sections in order to compare between participants and feedback types most clearly.

<u>Enjoyment</u>

Generally, the participants really liked training their rowing technique using this installation. One even noted that it was really motivating, as it made them focus on a pattern. Another participant found it very helpful to immediately see clear visual feedback as opposed to having a coach say something to them.

Additionally, the participants found the structure of the test pleasant, as the 30 seconds of no feedback in between gave a break and allowed for a reflection on what was happening.

While most participants found it very fun to row in virtual reality, even in this dull environment, one participant mentioned they were overwhelmed by VR and found it hard to correct their body movements because they could not see themselves anymore. Moreover, this participant rated the trajectory feedback (their first block) annoying, while others never found anything annoying.

<u>Unintended behaviour</u>

There were several difficulties with technique and unintended behaviour observed during the test. All participants had trouble with holding the target stroke rate 20 and were almost always rowing at a much higher tempo. This was due to the fact that not enough time was taken for the recovery, even though this skill was being trained during this test. The participants usually solved this issue by using less power during rowing, which is not the proper way to achieve a lower stroke rate.

In velocity training, two participants believed they had to pull the handle with their arms in order to achieve a fast drive, which is unintended behaviour and a very common misunderstanding. The trajectory feedback also caused unintended behaviour, as the participant with no rowing experience believed the handle had to pass between the knees during the recovery in order to achieve the target trajectory.

However, this recovery trajectory did remind one participant with a bit of rowing experience to incline their back before riding up the slides, as to not hit the knees when moving the handle forward. Furthermore, one participant even remarked that the trajectory alone reminded them to divide their power and have more of a flow during the movement.

<u>Uncertainties and difficulties</u>

There were also a number of uncertainties about the feedback designs, which the participants luckily almost always eventually solved on their own. Usually in the first feedback block, there were some doubts about how to perform the desired technique. Two participants did not understand what was supposed to be done during the trajectory training; one took the lower trajectory during the drive and the higher trajectory for the recovery, and one stayed at the top line of the trajectory.

Additionally, while most participants understood the function of the deviation trail and found that it really helped, one participant could not figure out for the entire first block (velocity training) whether they were controlling the red or blue trail. The concept of bandwidth feedback was also relatively difficult to understand during the first block. One participant remarked that when they perform the technique correctly, the feedback disappears which quickly caused them to fall back into wrong technique again.

However, it should not go unmentioned that many times the feedback designs were found clear, and fun to train with. In fact, the opinions were quite divided, and because no questionnaire was done, no objective conclusion can be derived. What can be concluded, is how the different locations made the feedback designs clearer, and this is elaborated in the next subsection.

Other inconveniences included: sweating in the HMD, especially among two of the participants, and decreased focus near the end of test due to it taking a long time.

Feedback location preferences

There were two feedback locations which were disliked. Firstly, the immersive trajectory 3D model was pointed out by three participants to be unclear and not make sense because height could not be estimated well when looking down on it. Secondly, the head-up display in general was found annoying by two participants because it came too close. However, one participant preferred the head-up display over all other displays for every feedback design, because it was simple and allows for free head movement while always seeing the feedback.

Most of the participants found the side-view display in front of them extremely useful to understand the feedback, as it showed the complete picture of what was happening. Though, after understanding the feedback, most participants preferred a different display in order to train with more precision. For trajectory and combined feedback, the side display next to the participant was most useful because it directly corresponds to the position of the handle. Moreover, the slight rotation of the head for the side display was not deemed as technique-changing as a display further away (like a mirror), which was pointed out by an interviewed rowing coach. Next, for velocity training the immersive display under the participant was most clear because it also corresponds to the position of the handle and is in a position easily visible without looking into a specific direction.

6.1.3.3 Conclusion and discussion

The used trajectory image is not entirely self-explanatory, as two participants followed the trajectory in an unintended matter upon first seeing it. Moreover, it was not immediately clear that it should be followed in a cycle, and which part of the trajectory should be taken when. Though after a small remark it was quickly understood.

It turns out that providing feedback on trajectory and velocity without any explanation of rowing technique can remind a slightly experienced rower of a proper muscle execution order during the recovery, but also cause very unintended behaviour when presented to a complete beginner; in this case, moving the handle between the knees.

As for feedback location, the side view in front was most useful to understand technique, but usually a different location was preferred for training with more precision. Namely, the side display for trajectory and combined training, and the immersive display for velocity training. Opinions on the head-up display were varied, one participant preferred it every time, and two other participants were always annoyed by it. Also, the amount of VR experience could play a role, as the participant with the least VR experience was overwhelmed by the technology and pointed out to have difficulty with coordinating their own body. Hopefully, the implementation of an embodied character solves this issue.

There are four things which will be changed based on the results of this test. Firstly, due to the difficulty of beginners to row at stroke rate 20, the target animations will adapt to the stroke rate of the user. Secondly, to improve on the intuitiveness of the concept of bandwidth feedback, feedback should never entirely disappear, in order to never completely lose sight of the target visual. Thirdly, While the great number of varieties resulted in rich results, it did cause fatigue to play a role near the end of the test. Therefore, in the next cycle the evaluation test should consist of less varieties. Lastly, in order to reduce sweating, the room will be well ventilated using an open window and a fan.

6.2 AUDITORY TRAJECTORY AND VELOCITY

6.2.1 Ideation

In this cycle, the focus is on creating auditory feedback on trajectory and velocity, which is similar to the situation of the M^3 Rowing Simulator [35, 36, 37]. Hence, inspiration will be drawn from there. However, in order to not simply imitate their feedback design, multiple other parameters of sound will be considered. Also, the concept of surrounding spatial sound, a benefit of VR, is integrated.

6.2.1.1 Sound parameters

<u>Pitch</u>

The pitch of a note is inherently associated with height [51]. This was also the reason for the authors of M^3 to choose it to represent the vertical position of the oar [35, 36, 37]. And so, it also seems like a good decision to use it for the height of the handle. Additionally, it could be used to represent velocity, but this has not been found to be done before, so it is unknown how intuitive this would be.

<u>Stereo balance</u>

This parameter stands for the volume ratio between audio played to the left or right ear. M^3 used this in [37] to represent horizontal deviation from the target oar, while the user was continuously looking to the right. As mentioned by an interviewed coach in chapter 2.2, turning the head changes rowing technique significantly, so this would not be a good idea. Luckily, VR allows for immersive spatial sound, which could possibly be used instead. This is further elaborated in the next subsection. Additionally, stereo balance could be used to play different sounds to each ear. Specifically, in [35] the target position sound was played to the left ear and the users position sound to the right.

<u>Loudness</u>

The loudness of sound seems to correlate with distance and speed [51], thus in this case it could be worthwhile to use it to represent horizontal velocity. However, a possibly much clearer implementation was used by M^3 where it controlled the amount of feedback given based on the deviation [37], as this allows for a realisation of bandwidth feedback.

<u>Timbre</u>

The timbre or ‘tone colour’ is the most complex characteristic of sound and depends on the shape of its sound wave [51]. For example, a note played on the piano sounds different than the same note on a guitar. This parameter is not significantly correlated with any spatial variable and is, by nature, not continuous, thus it would not make sense to map it to for example handle height. However, it could be used to represent a switching variable, as in the case with M^3, where it was mapped to oar rotation. In this case, no such variables are used.

<u>Distortion</u>

Sound can also be distorted, which means a corruption of the signal. This could also be used as a deviation indicator such as mentioned earlier with loudness. However, this parameter could cause discomfort, which would decrease the user friendliness of the installation.

<u>Tremolo</u>

This parameter controls a repeating volume pattern, where the sound is essentially quickly turned on and off. At first glance, this parameter could only be used to strengthen feedback (similar to volume) due to the difficulty of recognizing a specific rhythm. But, at lower rhythms it might actually be useful for indicating how long the drive and recovery last.

6.2.1.2 Spatial sound simulation

One of the benefits of VR is the possibility of having spatial sound. It can be used to improve immersion, where the user has a higher belief of being in the virtual world. Though, in this case it could be an extension to the stereo balance concept used by M^3 [37].

However, in order to be able to distinguish from front and rear sound without any other reference, the sound design should be considered carefully. Due to not having advanced recording technology, it was decided to simulate this front and rear sound with subtle sound effects. Specifically, with a low-pass filter and reverb effect to the rear sound. This technique was found on a forum[12].

6.2.1.3 Direction of deviation sound

When mapping deviation to sound, it should be considered what direction of relation the deviation has to the sound parameter. For example, when the handle is too high, should the sound be high-pitched or low-pitched? Ultimately, it was decided to follow the conclusion of [52], where direction-indicative sound was found to be more practical.

[12] https://forum.unity.com/threads/3d-audio-positioning-front-rear.44697/

6.2.2 Realisation

Based on the evaluation test from the visual feedback, less feedback varieties will be created in this cycle in order to have less effect on fatigue. Therefore, four varieties were chosen to develop. These will be explained in detail in this section. Recordings of all final versions of the auditory feedback varieties can be found in Appendix A.1.

6.2.2.1 Sound design

The sound used as a basis for all the feedback varieties is a pleasant, slightly vibrating sound derived from a synth preset (CH Chordionator FN) found in the TAL NoiseMaker plugin for the audio production software REAPER[13]. Its second oscillator was turned off, and all filter sliders were turned off as well. The note value to represent the handle height during the drive was chosen to be 440 Hz; the common tuning note A4. All higher and lower notes were played as distinct notes following the major scale of A4. This way, pitches would be easier to distinguish from another, and there would be a dead zone around the target position. Sound parameters were controlled in real-time via FMOD[14].

Figure 45 Synth settings for the feedback sound clip

6.2.2.2 Feedback varieties

Out of all mentioned sound parameters, it was ultimately decided to use the ones that would have the highest chance of being intuitive, which are; pitch for vertical movement, spatial position (with simulating effects) for horizontal movement, and volume for deviation.

Trajectory left-right sound

According to the note value map seen in figure 46, the target and own handle position were turned into a note. The target note is then played to the left ear, and the current note to the right ear.

Trajectory deviation sound

Here, the deviation from the target note is played on its own. A position too high results in a low note, and vice versa. Essentially, the sound signals to the user where they should be; direction-indicative.

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[13] https://www.reaper.fm/
[14] https://www.fmod.com/

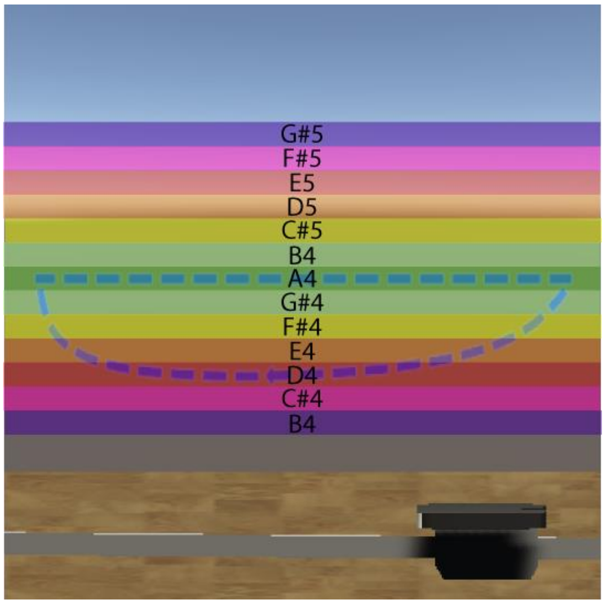

Figure 46 Note values per handle height

<u>Velocity spatial sound</u>
The spatial sound for velocity was implemented in an audio emitter object which changes its position on the z axis depending on the deviation from the target velocity position. In addition, when the emitter is behind the user, the A4 note gets a slight low-pass filter and reverb effect. This is implemented by using two audio tracks and fading between them. As a result, it should be possible to differentiate from front and rear sound even without turning the head. These FMOD parameters for the rear sound can be seen below.

Figure 47 Rear sound parameters

<u>Trajectory and velocity spatial deviation sound</u>
For the combined feedback, the deviation trajectory sound was combined with the spatial velocity sound. And so, the direction-indicative pitch is emitted behind or in front of the user with simulating effects to the rear sound.

6.2.2.3 Remarks

With the evaluation test in mind, two varieties were not created. These were: a left-right velocity training sound where horizontal movement would be mapped onto pitch, and an inversed deviation pitch sound. These were dismissed because of the limited duration of the test, and because they would likely confuse the participant as the sound parameters would be used for different purposes.

6.2.3 Evaluation

6.2.3.1 Method

These four feedback varieties were tested with the same four participants as in the previous test. This test also had a similar structure where every participant experiences all feedback varieties, except for a smaller amount of them. As a result, the participants were given some more time for every variety.

The participants were told before the test that the velocity animation would now be based on their stroke rate, and that they should stay between 20 and 26 strokes per minute. The test was conducted in the same virtual environment; the empty room with the RP3, to not distract the participant.

In order to test intuitiveness again, the feedback was not explained except for whether it targets trajectory or velocity. First, participants rowed for 45 seconds with the feedback sound, after which they were asked if they understood it. Then, after an explanation, they rowed for another 45 seconds, to really try to correct their technique using it. The order of feedback varieties per participant can be seen in the table below.

Table 4 Auditory feedback order per participant. lrT = left-right trajectory sound, dT = deviation trajectory sound, sV = spatial velocity sound, sTV = spatial deviation trajectory and velocity sound

Participant	Auditory feedback order
1	lrT, dT, sV, sTV
2	dT, lrT, sV, sTV
3	lrT, dT, sV, sTV
4	dT, lrT, sV, sTV

After each feedback variety the participant was asked the same questions as in the visual evaluation test. In addition, because sound memorization can improve movement memorization [25], they were asked afterwards whether they could remember the feedback sound when rowing without it.

After the test, a small introduction to the character on the RP3, and to the river environment with the single scull was done in order to observe how they react to it and to not surprise them when it is shown in the next evaluation test. Meanwhile, they were asked how it felt to be controlling a virtual character, and whether it was strange that in the on-water environment the arms cross each other.

6.2.3.2 Results

The following results were gathered based on observations during the test, analysis of video recordings, and answers to the questions. These are grouped into several sections in order to compare between participants and feedback types most clearly.

<u>Intuitiveness</u>

Almost all participants did not understand the feedback designs for the first moments they rowed with them. However, near the end of the first 45 seconds, and especially after an explanation, the feedback was understood, and technique could be corrected relatively accurate.

In fact, during the lrT sound all participants did not know what to do with the sound playing in either ear for the whole first 45 seconds, and one did not even know that two different sounds were playing. Interestingly, one participant remarked at the end of the left-right trajectory block that they thought they did it “pretty good”. What helped this participant in particular was the single note during the drive.

All participants also did not understand the dT sound for most of the time rowing with it, although two participants did note that the volume change was a useful indication of wrong technique.

In contrast, the sV sound was understood much better. It was observed that the velocity ratio was clearly being improved, and that generally the participants reacted appropriately to the feedback. This feedback was pointed out as being “very straightforward”. Additionally, one participant even remarked that the illusion of spatial sound was working. Although, another participant did not notice much change in the sound, but this was due to them performing the technique quite well.

Finally, the sTV sound was not clear for two participants, and overwhelmed one of these two participants. However, another participant finally understood the deviation sound, and the other participant pointed out that it was pleasant to try to always have the same note playing.

Unintended behaviour

There was some negative but also positive unintended behaviour observed. Namely, one participant thought that with a louder sound in the drive during the velocity training, they had to pull harder with the arms, which is a misunderstanding of rowing technique as explained previously (section 2.1) and was also observed in the visual evaluation test. However, another participant actually used the changing pitch of the trajectory sound to memorize a rhythm which they would be able to follow. This was the same participant who did not notice the spatial velocity sound because the technique was performed correctly. Finally, all participants occasionally stopped to enjoy playing different melodies by moving their hands, which is unintended behaviour but also allows for a better understanding of the heights of specific notes

Enjoyment

Even though the feedback designs were not always understood, it was pointed out by three participants to be a very enjoyable experience. Occasionally, the ‘composing’ of music by raising the handle was enjoyed as mentioned above, but also the actual training of technique. It was even mentioned that the sound helped to stay focused at all times. In contrast, one participant did not find it enjoyable and rated the sounds as annoying.

Reaction to character and single scull

Most participants reacted very positive to the rowing character and single scull environment to which they were introduced to after the test. However, one participant was immediately repelled by the character. After a few seconds of trying the character out, this participant wanted to stop the test and never wanted to row with such a character again. This was presumably because of little experience with VR.

6.2.3.3 Conclusion and discussion

It can be concluded that auditory feedback in these forms definitely have potential, but they should first be well understood before being able to correct technique with them. Usually, an explanation was necessary, but also plenty of times the participant figured out the feedback on their own.

It seems that the trajectory sounds have the most potential to teach rowers the straight drive trajectory, as then the note could be trained to stay the same. Additionally, the spatial sound was well understood and was effective, but this likely is not due to its spatial aspect but because it was a simpler form of sound. Namely, it only plays one note which changes in volume, and distinguishing between front and rear sound was relatively easy with the low-pass filter and reverb effect added to the rear sound.

Finally, it was a good decision to introduce the participants to the character and single scull environment at the end of this test. This made clear that the inaccuracies and uncanny realism of the character could be repelling for users who have little VR experience. Therefore in future tests, at request, this participant will not be shown an embodied character anymore.

6.3 HAPTIC TRAJECTORY AND VELOCITY

6.3.1 Ideation

Creating augmented haptic feedback on trajectory and velocity has been done by both CAVE installations [32, 33, 35, 36, 37]. Two types of haptic feedback have been discussed already in this thesis:

- Force, where a user is forced into a specific movement
- Vibrotactile, where vibrations are provided in order to suggest a movement.

Interestingly, it has been proven by [27] that vibrotactile feedback is more effective when training motor skills than force feedback, as it disturbs the movement less. Also, the SPRINT system has found that vibrotactile in combination with visual feedback is more effective than either alone [32], but also that vibrotactile alone is more effective than visual feedback or their combination [33] as the visual feedback introduced a dependency in that case.

Due to these findings and the scope of the project, vibrotactile haptic feedback was chosen. Even though no VR-specific benefit can be implemented in this case, it is still important to address this modality for three reasons. Firstly, there are definitely varieties of feedback which have not yet been explored in this scenario. Secondly, it can eventually be used in combination with the other modalities. Thirdly, when developed, it could potentially be adapted to function as posture feedback.

<u>Pushing vibration versus pulling deviation vibration</u>

The SPRINT system [32, 33] uses four vibration motors: on top and below the wrist, on the middle finger, and on the elbow. They correct spatial errors of the user by vibrating on the side which is reaching a 'boundary'. For convenience, we can call that pushing vibration. In fact, it is not explained by the SPRINT system in both studies whether pushing vibration is the most intuitive vibrotactile feedback. That is why it was decided to create a similar setup with varieties which provide both pushing and pulling vibration on trajectory and velocity.

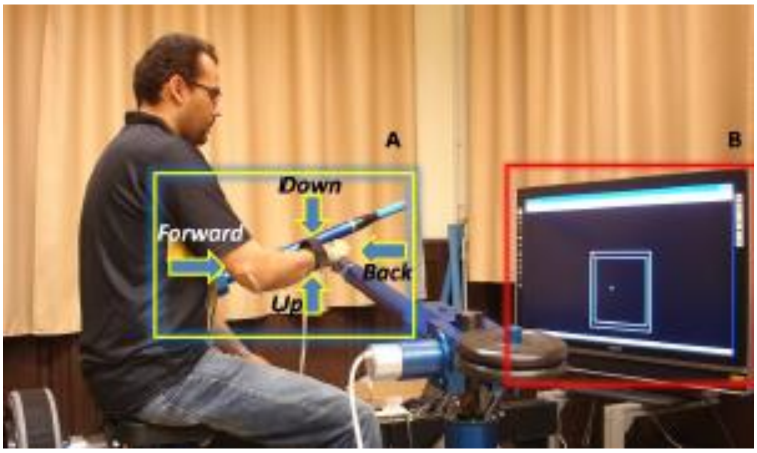

Figure 48 Vibrotactile feedback in the SPRINT system as seen in [32, p. 3]

<u>Rhythmic vibration</u>

As mentioned in chapter 6.2, the tremolo parameter of sound might be useful or indicating how long the drive and recovery last. This was reconsidered for this design cycle, and it was ultimately decided to create a feedback design using rhythmic vibrations with the goal to improve the rhythm of the drive and recovery or enhance perception of their durations. In fact, it has been shown by a study covering a haptic drum kit [55] that haptic stimuli can be used to learn a variety of rhythms, is generally just as effective as sound, and that novices in particular benefit from it.

6.3.2 Realisation

6.3.2.1 Wiring and soldering

Two vibration motors[15] were connected to a switching transistor circuit controlled by an ESP32 board[16] with Wi-Fi and Bluetooth functionality. Because the ESP32 does not deliver enough current on its own and for increased battery life, two coin batteries (figure 49, wrapped in duct tape) are used to directly power the vibration motors. Otherwise, without batteries, a more complicated circuit had to be created with rectifier diodes[17].

Using pulse-width modulation, the ESP32 controls two transistors which connect the ground paths of the vibration motors, turning them on. This allows for different vibration intensities, making bandwidth feedback possible. The module with transistors and resistors, and both vibration motors are put on their own printed circuit board, and everything is soldered together. Though, because batteries are dangerous to solder on, their wires are connected with duct tape.

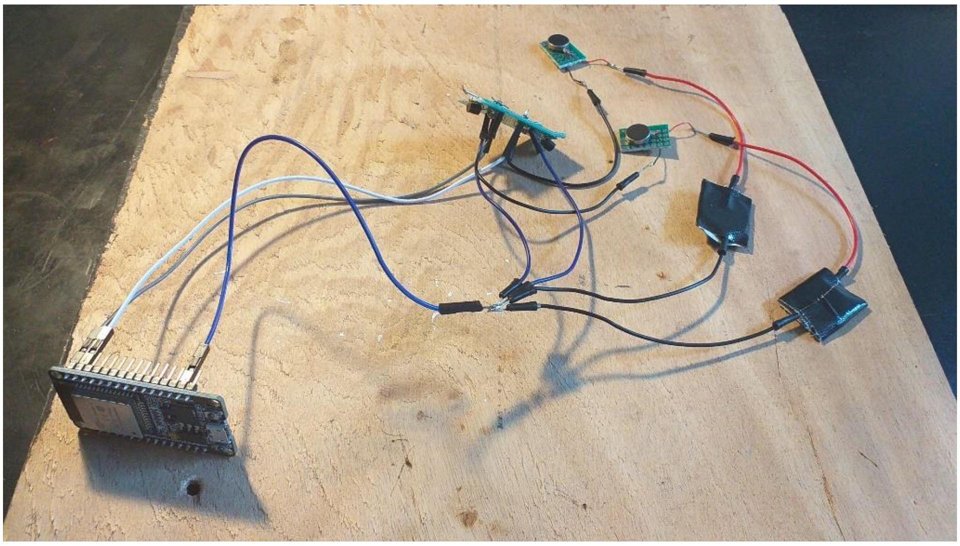

Figure 49 The final soldered circuit

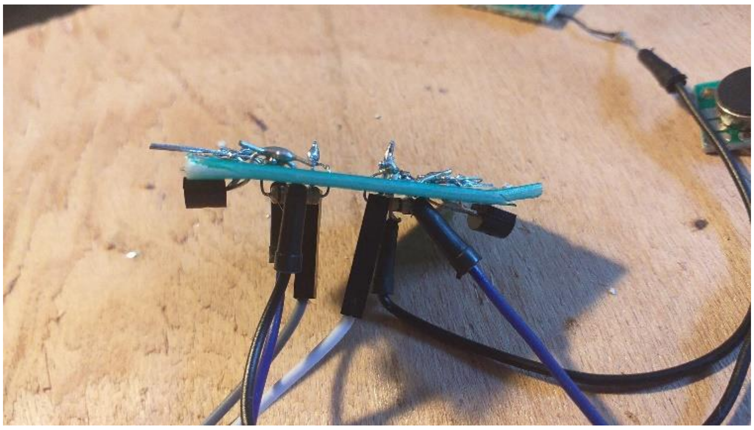

Figure 50 The transistor module

15 https://www.tinytronics.nl/shop/nl/robotica/motoren/motor/kleine-tril-vibratie-dc-motor-2.5-4v
16 https://www.tinytronics.nl/shop/nl/communicatie/bluetooth/esp32-wifi-en-bluetooth-board-cp2102
17 https://www.circuito.io/app?components=513,8449,360217

6.3.2.2 Glove integration

This soldered circuit was then integrated into the glove which was already used for motion tracking. The vibration motors were placed above and below the wrist, separated from the skin with one layer of cloth. Additionally, the transistor module was positioned and covered inside the left of the glove (figure 51), and the ESP32 and power source on top of the glove next to the motion tracker (figure 52).

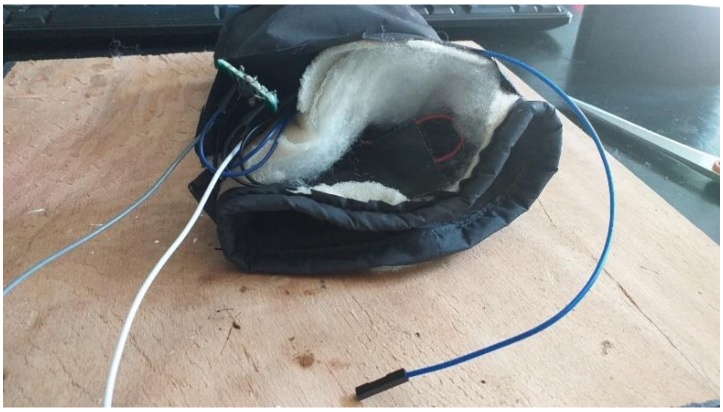

Figure 51 Integration of the circuit inside the glove

For powering the ESP32, a power bank is very inefficient due to multiple voltage conversions. That is why first, two AA batteries were used. However, these batteries ran out quite quickly, so the power bank proved to be a better option because it had a longer battery life and could be recharged.

Figure 52 Two powering options: battery and power bank. The final version used a power bank.

Furthermore, to realise intuitive vibrations during velocity training, the bottom vibration motor was put inside a ring which could be placed on a user’s ring- or middle finger. This ring could then also be flattened and put back into the bottom of the glove for simple switching between the two trainings.

Figure 53 Velocity training setup with vibration ring

6.3.2.3 Feedback design

A script for the ESP32 was written inside the Arduino IDE[18] to allow for controlling the intensity and rhythm of both vibration motors via simple Bluetooth commands. These commands are sent by using the free version of the plugin Serial Port Utility Pro[19]. This section will explain the exact functioning of the vibration motors during the haptic feedback.

Intensity vibration

The intensity of vibration is divided in ten levels, from no vibration to full intensity vibration. These vibration levels are controlled in bandwidth form around the target position, where a deviation of either 10 centimetres from the trajectory target or 20 centimetres from the velocity target corresponds with full intensity of the vibration motor.

Rhythmic vibration

To explore rhythmic vibrations, a simple and a complex rhythmic feedback design was created. These rhythms are divided in ten levels around 240 beats per minute (BPM). During the simple variety, both motors would vibrate four times during the drive (at 240 BPM) and four times during the recovery (at 120 BPM) to enhance perception of their duration. During the complex variety, the bottom motor would vibrate like in the simple variety, and the top motor would vibrate in the tempo of the user. This meant that at deviations behind the velocity target the top vibration motor would have a lower BPM, and at deviations in front a higher BPM.

Unfortunately, after development of this feedback design it was quickly observed that the rhythmic vibrations are not noticeable enough during rowing. This is because the vibration motors cannot vibrate at a high intensity when constantly turned on and off, even when the BPM values were halved. Therefore, these rhythmic feedback designs were abandoned and not evaluated with the participants. Though, this concept could have potential with stronger vibration motors or as auditory feedback.

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[18] https://www.arduino.cc/en/main/software
[19] https://portutility.com/

6.3.3 Evaluation

6.3.3.1 Method

These haptic trajectory and velocity feedback designs were tested with the same four participants as in the previous test. Both were tested as pushing and pulling vibration, which resulted in four varieties. The main goal of this test was to get an idea of which direction of vibration is more intuitive per training. Therefore, the order of feedback was different for every participant, in order to reduce bias. The order of feedback varieties per participant can be seen in the table below.

Table 5 Haptic feedback order per participant. pushT = pushing trajectory vibration, pullT = pulling trajectory vibration, pushV = pushing velocity vibration, pullV = pulling vibration vibration.

Participant	Haptic feedback order
1	pushT, pullT, pushV, pullV
2	pullT, pushT, pullV, pushV
3	pushT, pullT, pullV, pushV
4	pullT, pushT, pushV, pullV

Similar to the auditory evaluation test, every feedback was experienced twice for 45 seconds. Before every block, the training (either trajectory or velocity) was mentioned, but not whether it would be pushing or pulling. After the first 45 seconds the feedback was explained if it was not already clear. After the second 45 seconds, questions were asked similar to previous tests, after which it was explained that the vibration will be inverted for the following block. Then, after both directions of vibrations, it was asked which type of vibrations was more intuitive.

This test was done in the river environment with the single scull and character, in order to test enjoyment and potential distraction by the environment. The participant who felt repelled by the character was not shown the embodied character, at their request.

6.3.3.2 Results

The following results were gathered based on observations during the test, analysis of video recordings, and answers to the questions. These are grouped into several sections in order to compare between participants and feedback types most clearly.

<u>Intuitiveness</u>

For the trajectory vibrations, opinions were split. Half of participants preferred pushing, and the other half pulling vibrations. This was also not just a preference for the first option, as half of participants preferred the second experienced option. Usually, this preference was accompanied with a certainty that it was more logical, but no other explanation was provided. One participant even mentioned that the pulling vibration caused an almost automatic reaction.

Despite all participants finding the trajectory training intuitive, one participant stayed at the top line (handle height of the drive) during almost the entire first 45 seconds. However, eventually this participant remembered the visual trajectory and quickly got better at correcting their handle height with the vibrations. This was the same participant who stayed at the top line in the beginning of the visual trajectory feedback in the first evaluation test.

The velocity vibrations were less intuitive. It seemed that the participants were confused about which vibration meant which direction, even after explaining it. This could be a result of the many reversals of vibrations during the test. One participant even continuously kept thinking out loud and asking questions.

Even when velocity vibrations were understood well, two of the participants barely corrected their recovery speed. It was only after a remark was made addressing this fact, that it got improved. In the end, only one participant had a real preference, which was for the pushing vibrations.

Difficulty
Accordingly, the trajectory training was generally rated easy, and the velocity training hard. It was harder to react to the velocity vibrations because they were less intuitive, and corrections would disturb the movement. This could also explain why two of the participants did not change their recovery speed much, even after understanding the feedback.

Additionally, three participants remarked that the vibrations were not noticeable enough, especially during velocity training. While the hand of one participant was actually a little too small for the glove, it could be that there just was not enough deviation from the target in order to receive a vibration which would be noticeable. Also, as mentioned in section 6.3.2.3 the shaking of the rowing machine played a role in making the vibrations less noticeable. Therefore, one participant suggested to place the vibration motors on bare skin.

There was also difficulty in remembering previous trained skills, as the velocity training of previous times was observed to be completely disregarded when training trajectory during this test. Furthermore, during the velocity training of this test, the previously attained trajectory skill was also not transferred, possibly because of the difficulty of velocity training, or of a lack of focus.

Unintended behaviour
Similar unintended behaviour to the previous tests was observed. Mainly, the pulling of the handle when the velocity vibration signalled a faster drive. Furthermore, two participants believed they had to use more power in general during the drive of velocity training, which is a good assumption, but then performed the recovery faster as well. Nevertheless, both participants eventually performed a reasonably good velocity ratio near the end of the training.

Enjoyment
Only one remark was made at the very beginning of the test that the vibrations are a little annoying. Otherwise, the haptic feedback was not found annoying by any other participant.

The river environment was enjoyed a lot and was not found to be distracting. Rather, three participants said that it made the test more fun, and two participants said that it was relaxing. Additionally, the idea of haptic feedback was found fun by two participants, and one of these two participants even liked it more than the visual or auditory as it helped them concentrate.

In contrast, one participant preferred auditory velocity training over haptic, because sound is more noticeable than vibrations. This participant also remarked that visual feedback is generally more rewarding than haptic, as it is then clearer how to correct a movement.

Sweating
Finally, sweating was still an issue with an open window and ventilator. This can be explained by the new haptic glove, which is a thicker glove with wool. Unfortunately, no other suitable left-hand glove could be found.

6.3.3.3 Conclusion and discussion
No conclusion can be drawn on which direction of vibration is more intuitive. Namely, during trajectory feedback, both pushing and pulling vibration were equally preferred, and during velocity feedback most participants did not have a preference. This is partially explained by the low noticeability of vibrations, which could be because of the more subtle vibrations at little deviation from the target. That is why the concept of bandwidth feedback possibly should be disregarded from haptic feedback (except for the

dead zone around the target). Another option would be to decrease the deviation necessary for full vibration power, in order to make deviations noticeable more quickly.

Additionally, it has been shown that pushing vibrations as used by the SPRINT system [32, 33] might not be as intuitive. However, the comparison between these two directions of vibration might have been detrimental to intuitiveness, because the constant switching caused confusion. Nevertheless, it does indicate that intuitiveness of direction differs a lot between people, so in the future users should potentially be given an option between the two. In fact, in the combination test in section 6.5, every participant is given their preferred vibration direction.

This direction of feedback could also be tested with sound in a similar manner to this test, as in the auditory feedback test it was assumed from [52] that direction-indicative sound is more practical. Actually, sound was mentioned to be more noticeable than vibrations, thus such a test would likely produce better results.

It has also been observed that when given haptic feedback, beginning rowers correct trajectory faster than velocity, even when both are well understood. This is possibly because in order to correct velocity, the speed of the whole rowing movement has to changed (or stopped) upon reaction, whereas with trajectory feedback only the hands have to be corrected. Also, it could be that a slower recovery speed requires more control of the movement, which a beginner is lacking.

Finally, it is interesting that one participant prefers haptic over visual feedback, due to increased concentration. In contrast, another participant finds visual feedback more rewarding, and also finds auditory feedback more noticeable than haptic feedback. However, because of the observed technique corrections and a generally positive reaction, the haptic feedback could still prove to be an effective feedback method. Especially for trajectory feedback due to less disturbance of movement than velocity feedback, and when the noticeability issue is solved.

6.4 VISUAL AND AUDITORY POSTURE

6.4.1 Ideation

As mentioned in section 2.6, after hand trajectory and velocity the focus would be on the back angle (here also called: posture) because the most common errors are associated with it. Therefore, in this design cycle, feedback designs addressing wrong back movement will be created and evaluated.

Koen Vogel [2] created a feedback design for the muscle execution order during the recovery, which also partially addressed back movement. Though, his Gantt chart feedback design on the different muscle timings (similar to figure 3 in section 2.1) was remarked by some of his participants to be complex and did not yield better results than human coaching.

However, [40] implements a feedback design which shows more potential. Their feedback design taught beginning rowers the rowing movement by combining self-observation with real-time expert modelling in the same display (see figure 54). Both the experimental and control group completed seven intervention sessions over the course of seven weeks consisting of traditional coaching methods, but the experimental group always rowed with this feedback design. Significant improvements in technique (higher stroke length and lower stroke rate) and rowing outcome (more average distance and average power) were found in the experimental group, whereas the control group only significantly improved in technique. Furthermore, their choice for this feedback design was based on results of many earlier studies indicating the effectiveness of real-time expert modelling.

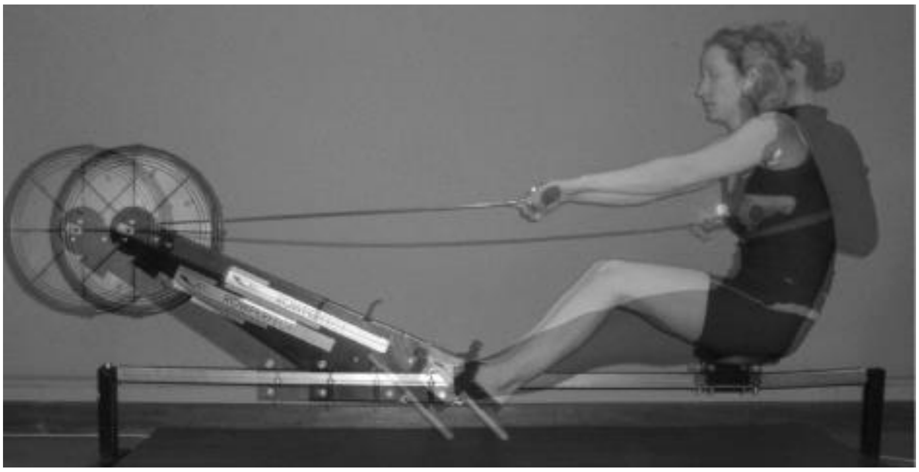

Figure 54 Visual feedback which combines self-observation and expert modelling [40, p. 6]

Because of the success of this feedback design, it will be used as inspiration. Though, for it to address only the back angle, it has to be simplified. This can be done by matching the seat position of the expert model with that of the user, and by only showing a body or maybe even only a shape which resembles the expert's back. Additionally, the concept of bandwidth feedback can be applied with transparency to attempt to improve the retention of skill.

Due to time constraints, auditory feedback on posture will also be created during this cycle. However, the immediate comparison between the visual and auditory posture feedback in the evaluation test might give interesting results.

6.4.2 Realisation

6.4.2.1 Visual posture feedback

This design cycle focussed on the river environment again to further evaluate its benefits and to make the evaluation test more enjoyable. However, this visual posture feedback was ultimately also made functional in the room environment.

First of all, the previously constructed side-view had to be made functional in the river environment. This was then used as a display of feedback similar to [40]. A display closely to the side of the user was also created but quickly rejected because of the difficulty of observing it.

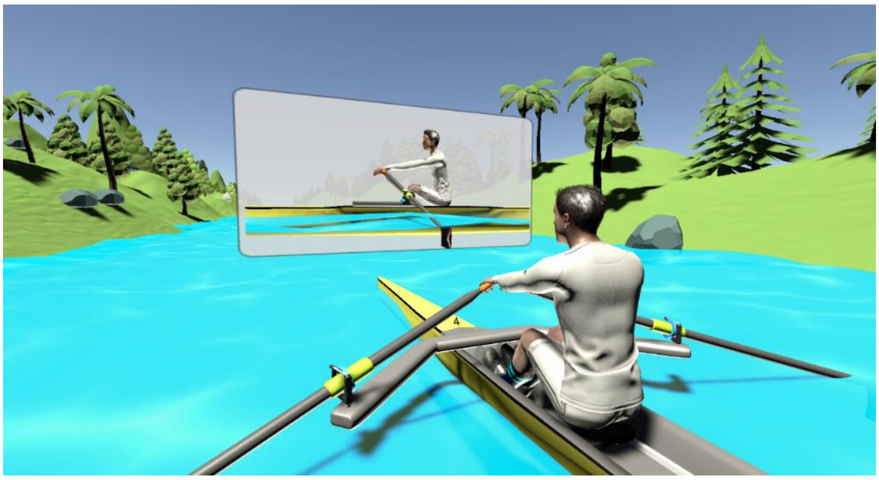

Figure 55 Side-view display in the river environment

Then, a target rower was animated using the analysis of Kim Crow [11] (figure 3). This target rower received a red outfit and blonde hair, to stand out next to the embodied character. Additionally, the target rower animation was added as an overlay in the side-view and its seat position was connected to the seat position of the user. The latter had to be done because the seat can be anywhere on the slides during rowing on the RP3, and in order to only display a back angle with no unnecessary information.

Moreover, the concept of bandwidth feedback was applied by controlling the transparency of this target rower. Specifically, at a back angle deviation of less than 8 degrees he cannot be seen, and at a deviation of 30 degrees he is fully visible. Furthermore, at every catch the target rower animation resets and adapts its speed to the stroke rate of the user.

<u>Body and boat display</u>

The most complex variety shows the target rower and his oars. The blades of these oars were also made red for better visibility.

Figure 56 Body and boat visual posture feedback

Only body display

A variety was also created with just the body displayed, because the oars might distract users from the primary focus of this feedback, the back angle.

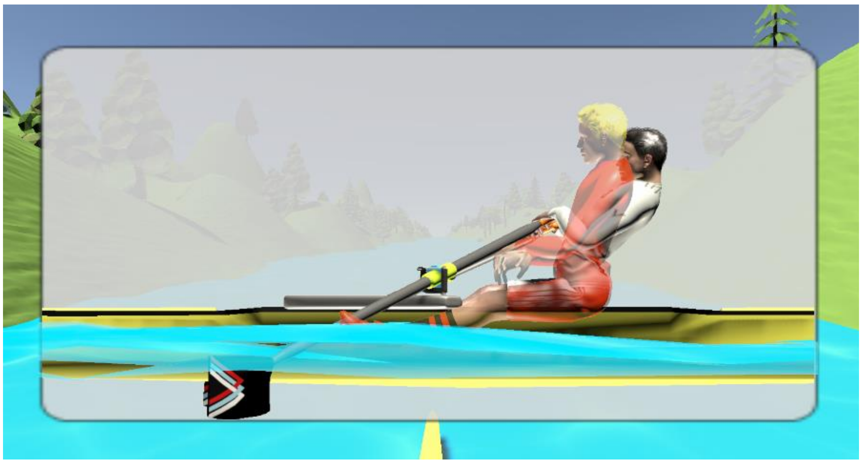

Figure 57 Only body visual posture feedback

Capsule display

In addition, a simplified variety was created with a capsule representing the back of the target rower. When the hands of the only-body display would be distracting, this display can provide the back angle feedback in its most basic form.

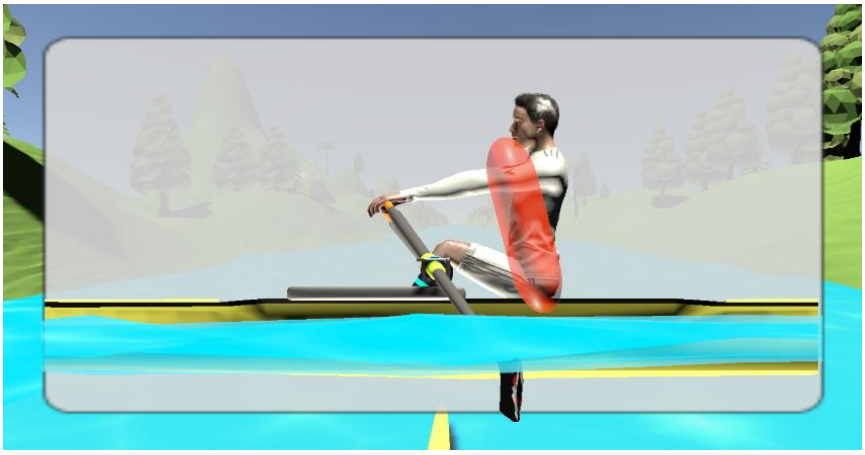

Figure 58 Capsule visual posture feedback

6.4.2.2 Auditory posture feedback

For the auditory posture feedback, similar concepts of the auditory trajectory and velocity feedback were used again, as well as the controlling of volume to realise bandwidth feedback. Moreover, at deviations less than 5 degrees the sound is played at 40 per cent volume and at a deviation of 30 it is played at maximum volume.

Left-right sound

Here, the user hears the target rower's back angle in pitch in their left ear, and their own back angle in pitch in their right ear. In this case, every 6 degrees of back movement represents a different note in the A4 major scale.

Spatial sound

Additionally, the same concept of spatial sound was used to signal whether the back of the target is in front of behind the users own back.

6.4.3 Evaluation

6.4.3.1 Method

These three visual and two auditory feedback varieties on posture were tested in the same manner as in the previous tests. However, because one participant was not available anymore, the test had to be done with three participants. The order of feedback varieties per participant can be seen in the table below.

Table 6 Visual and auditory posture feedback order per participant. C = capsule, B = body only, W = whole; body and boat, S = spatial sound, LR = left-right sound.

Participant	Visual feedback order	Auditory feedback order
1	C, B, W	S, LR
2	W, B, C	LR, S
3	C, B, W	LR, S

As mentioned in the realisation section, the river environment was chosen for this evaluation. After a warming-up of around one minute, the side-view in front of the user was introduced where the movement of their character could be seen. Then, the visual feedback varieties were shown, each lasting one minute. In between, some questions were asked similar to previous tests. After the final visual variety, the participant was asked for a preference, and whether they could still mainly focus on the angle of the back when an entire target character and oar was shown. The auditory feedback varieties were played twice for a minute, in order to properly understand them. Then it was asked how clear and useful these were, how they compare to the visual feedback, and whether sound works better for the back angle than trajectory or velocity.

6.4.3.2 Results

The following results were gathered based on observations during the test, analysis of video recordings, and answers to the questions. These are grouped into several sections in order to compare between participants and feedback types most clearly.

Visual posture feedback

All varieties of the visual posture feedback were immediately remarked to be clear and very intuitive. It worked well according to all participants, and one participant even said that it is pleasant feedback and found it a fun little game. Another participant also quickly noticed they had been performing the back movement wrong for all of the previous tests. The other participant found this feedback more enjoyable than trajectory and velocity, as it requires less focus due to only having to move the back forwards or backwards. Accordingly, based on observations, all participants considerably improved their back angle technique, and it was also retained relatively well in the time between where no feedback was shown.

When a body was shown instead of a capsule, the back angle was still the clearest aspect of the feedback. Also, the target oar did not distract much from the back angle, and one participant did not even notice it. Two participants preferred seeing a body perform the movement, as it makes it clearer to see the exact back angle. One of these participants mentioned that with a body displayed they could synchronize the entire body, thus also focusing on the hands. The other participant preferred the capsule because it was simpler but did not have a strong preference.

It was even remarked by one participant that they could now maybe row in a real boat, but they quickly realised that with their current handle trajectory they would likely capsize.

Auditory posture feedback

For all participants it took some time to understand the LR sound, and it usually required slow movement and some experimentation. When understood, it was mentioned to be effective by two participants, but not as well as the visual feedback. One of these participants found it hard to correct their movements as it was not immediately clear in which direction to correct when the two notes did not synchronize, and mainly focused on the memory of visual feedback. The other participant could correct their movements relatively well, but not as detailed as in the visual feedback. Thus, it appears that the visual feedback points out deviations more precisely than the auditory feedback.

The S sound was perceived to work slightly better, as it made it clearer which direction the back should be corrected. With this sound the back movement could be performed quite well, but possibly because it was already being trained for some time. However, the visual feedback was still mentioned by all participants to work much better. Also, two participants mentioned that sound works better for the velocity of the hands.

<u>Technique focus</u>
As observed in previous tests as well, when the focus is on a certain aspect of technique (here, a novel one), other aspects would be almost completely disregarded. In this case, it was observed that two participants did not focus on trajectory and velocity at all during the posture feedback.

<u>Unintended behaviour</u>
The visual target rower animation has a downside when shown to beginners. Usually, beginning rowers have a much shorter stroke length than they are capable of (also mentioned by a coach in section 2.2.2.1), which causes a higher stroke rate. This, in turn causes the target rower animation, who does row at full stroke length, to row faster. As a result, the target accelerates, and the participants in this case attempt to follow this incorrect fast back movement, which is especially noticeable in the first part of the recovery. This also led to two participants using only half of the arms, in order to better synchronize with the faster example rower in the recovery. However, this only increased the stroke rate further.

When this occurred during the test, the participant was told to focus on long strokes and to realise that the example rower is based on their own stroke rate. This always corrected the issue.

6.4.3.3 Conclusion and discussion
This feedback proved to be intuitive and effective at correcting the back angle, which covers the most common beginners' errors. Especially the visual feedback was found to be clear and enjoyable. It was also good for the participants to experience this feedback, as the participant who always had incorrect back movement at the catch immediately noticed it.

It seems that the body display is most effective because it makes it clearer to see the back angle instead of a capsule. Also, with a body displayed, the back angle is still the clearest aspect, and the user can focus on the hands as well if they want to. However, because the body was always the second presented variety the results might be biased. The added target oar was not really noticed, and it was also mentioned that it was never used for correction, probably because it is moving into opposite directions of the hands.

Auditory feedback is effective, but less than visual feedback because it makes it difficult to understand how to correct a movement, and because in this case it pointed out deviations starting from higher values (wider bandwidth). If auditory feedback is to be used, the spatial sound would be more effective, not because of its spatial aspect, but because it is simpler and makes the direction of correction clearer. However, auditory feedback still seems to be most useful as velocity feedback.

To avoid the issue of a shorter stroke length causing a faster moving target rower, two solutions are suggested. Firstly, the participant could be informed that they should row with full legs (ride up the entire slide) in order to have a longer stroke length. Secondly, a calibration option similar to the visual trajectory and velocity training could be implemented to adapt the rowing animation to the user's reach. The latter would be a more universal option, as not every beginner is able to ride up the entire slide due to inflexibility of the hamstrings.

6.5 COMBINATIONS OF FEEDBACK

This final feedback design cycle will explore the potential of combining all previous feedback designs. In order to choose a set of combinations for the evaluation test, all results from literature regarding feedback combinations will first shortly be analysed and compared again. Additionally, while all previous feedback designs are created in such a way that every combination is possible, several had to be adapted to the river environment first.

6.5.1 Ideation

First of all, the feedback designs are narrowed down into their best varieties. Because of a limited duration of the evaluation test, the auditory and haptic feedback were narrowed down into the training in which they were most effective. Also, the posture feedback was chosen to only be in its most effective visual form. Based on all previous results, these are:

- Visual trajectory in the side display
- Visual velocity in the immersive display
- Auditory velocity spatial sound
- Haptic trajectory with preferred direction of vibration
- Visual posture feedback with body only

Same training

Two feedback modalities with the same purpose can be given to a learner, in order to give more extreme feedback, or to enhance the perception of feedback. The SPRINT system has experimented twice with visual-haptic trajectory training, with simple (square) [32] and complex (balls in virtual environment) [33] visual feedback. In the first study, the visual caused more precise but slow execution and the visual-haptic combination showed the best results [32]. In the second study, the unimodal haptic feedback showed the best results in the retention test, because the visual feedback seemingly introduced a dependency [33].

Additionally, the M^3 simulator has shown that visual feedback causes more precise movements [31], and also that visual feedback is less cognitively demanding [37]. Moreover, they pointed out that visual feedback has "… potential to instruct complex movements, and haptic guidance to teach temporal aspects of a movement" [37, p. 18]. M^3 also experimented with combining visual feedback and a haptic path guide in [36], where the path guide was turned on if a specific error persisted, which was a successful method of accelerating learning.

M^3 also experimented with adding auditory and haptic feedback to visual feedback in [35], but because their visual feedback was already effective, the added feedback had subtle effects. However, their visual-auditory auditory did indicate a high transfer of the trained velocity to non-feedback situations. Furthermore, such a combination allowed users to switch from one feedback to another.

Different training

Even though information distributed to different modalities can actually be processed better because of different cognitive resources [28], no study has been found that uses different modalities for different purposes. In contrast, when combining two trainings in the same modality the learner might be overloaded or distracted from perceiving intrinsic feedback [35]. Therefore, it would be interesting to explore such multimodal combinations, and possibly compare them with unimodal combinations.

Conclusion

Keeping in mind the limited duration of the evaluation test, a setup of five combination was created in which almost every combination could be compared with the previous. The full setup can be seen in table 7 in the evaluation section. Mainly, similar combinations to successful ones from SPRINT and M^3 are tested but with slightly different feedback designs, and the cognitive load of multimodal feedback for different trainings is explored and it is compared to an entirely-visual combination in the side-view.

6.5.2 Realisation

The river environment was chosen again in order to develop all previous work into a prototype for showcasing, and to explore the trajectory and velocity feedback in the single scull. Therefore, the side trajectory, immersive (below) velocity, and side-view feedback designs had to be adapted.

<u>Trajectory feedback</u>

Because rowing is done with oars in the single scull as opposed to a handle on the RP3, the side display could not simply show a flat trajectory image. Therefore, using the plugin Unity UI Extensions[20] a curved trajectory was created with dimensions corresponding to the previous trajectory image.

Also, the trajectory display now had to move together with the single scull due to its curvature around the oarlock. As a result, the trail did not function properly anymore because trail renderers in this game engine always emit their trail in world space. Luckily, a local trail renderer script made by Eric Hodgson was found online[21] and was implemented.

Additionally, a new (invisible) model of the recovery trajectory had to be created for calculation of deviation during the recovery.

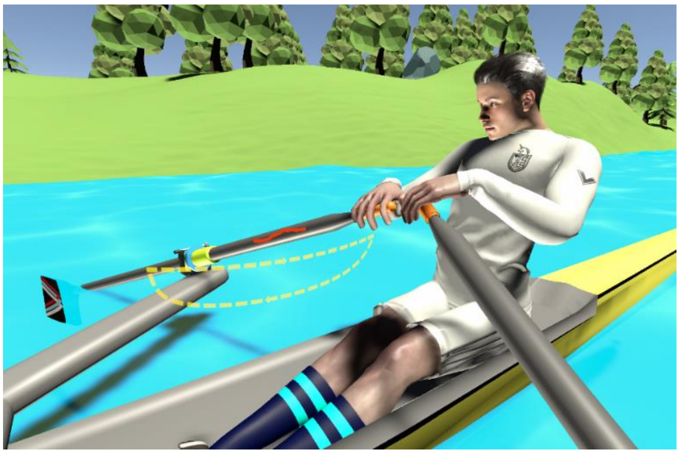

Figure 59 Visual trajectory feedback in the single scull

<u>Velocity feedback</u>

The velocity feedback had to be made slightly larger to fit the range of movement of the oar handles. This display was also connected to the boat, but the local trail script was not implemented because it does not allow for transparency. However, it was deemed to not be as necessary in this case.

Figure 60 Visual velocity feedback in the single scull

<u>Side-view display</u>

Because the trajectory of the oar handles has different proportions than the RP3 handle, a new master trajectory object had to be created for this side-view display. To the right, feedback on trajectory and velocity (ball) can be seen. Similar to the above feedback, this display also moves with the single scull.

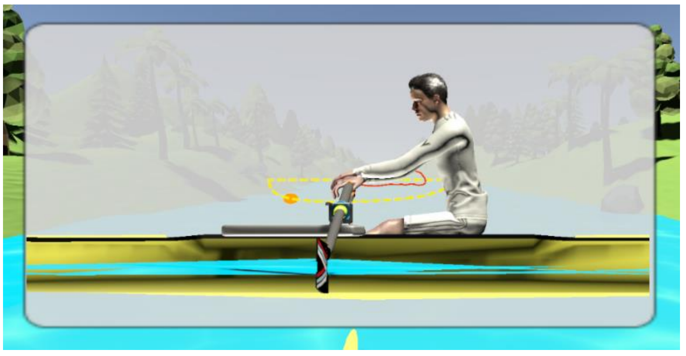

Figure 61 Side-view of the single scull

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[20] https://bitbucket.org/UnityUIExtensions/unity-ui-extensions/src/master/

[21] https://forum.unity.com/threads/trail-renderer-local-space.97756/

6.5.3 Evaluation

6.5.3.1 Method

These five combinations of feedback were tested with the same three participants as in the previous test. The setup of the test can be seen in the table below. In order to not cognitively overload the participant, no varieties of feedback were simultaneously switched on.

Table 7 Feedback combinations order. T = trajectory, V = velocity, P = posture (back angle)

Duration	Feedback	Main questions
30s	Visual T	
90s	Visual T + Haptic T	
break		Is trajectory training enhanced?
30s	Visual V	
90s	Visual V + Auditory V	
break		Is velocity training enhanced?
30s	Auditory V	
90s	Auditory V + Haptic T	
break		Can you focus on two trainings? Is the feedback understandable without anything visually?
90s	Auditory V + Haptic T + Visual P	
break		Can you focus on three trainings? Which aspect of technique has the most focus?
90s	Visual P + Visual T & V	
end		Is everything visual better than everything in a different channel?

The entire test was done in the river environment. Along with the main questions as listed in the table, several questions were asked similar to previous tests. As can be seen in the table as well, the feedback modalities were built up during the test. Furthermore, a relevant comparison can be made between every feedback combination and its previous.

6.5.3.2 Results

The following results were gathered based on observations during the test, analysis of video recordings, and answers to the questions. These are grouped per feedback combination in order to compare between participants most clearly.

<u>Visual-haptic trajectory training</u>

An issue with the single scull trajectory display was immediately noticed. People with shorter legs could not follow the trajectory entirely to the finish because the trajectory was designed roughly to personal body proportions and because the display moved with the single scull which was moved with the legs.

One participant noted that the trajectory was not always very noticeable, but this was intended, as with good technique the feedback becomes less apparent. Though another participant found that it had to be observed from the side to really see at which height the oar should be.

Two participants found that the addition of haptic feedback enhanced the trajectory training. One of these participants mentioned that the vibrations really helped when the visual display was not easily visible, which was half-way between finish and catch, and to provide more detailed feedback. The other of these participants mentioned that the added haptic feedback helped, but they would not be able to perform the trajectory with only haptic feedback. Additionally, the remaining participant found that the haptic feedback did not add much to the training because it was more vague feedback, and it was hard to notice which motor was vibrating during rowing.

Visual-auditory velocity training

The visual velocity training was found pleasant and clear to follow. All participants performed the velocity ratio quite well with only the visual feedback. Thus, the added auditory feedback did not make much difference. One participant stated that the sound might be more useful if it would be already noticeable at slightly smaller deviations. In contrast, another participant did not understand the sound at all and solely focused on the visual feedback.

Haptic trajectory and auditory velocity training

In between the last combination and this combination, the participants trained with only auditory velocity feedback for some time. This was to allow the participants to understand the sound better, which would be necessary to provide a good result when combining it with haptic trajectory feedback.

The addition of a different modality for a different purpose, namely haptic trajectory added to auditory velocity, was difficult for the participants at first, but eventually the feedback turned out to work relatively well, mainly for two participants. Interestingly, one of these participants found the vibrations effective and the sound a bit unclear, whereas the other participant found sound to work well and the vibrations sometimes unnoticeable.

The latter participant also mentioned that while it is slightly harder to correct velocity using auditory feedback, it might actually be better than visual for two reasons. First, following visual feedback does not require much attention and is easy, while during auditory feedback the skill has to be thoughtfully performed leading to less dependency on feedback. Second, visual feedback requires looking in a specific direction, while with auditory feedback the view direction does not matter which also leads to more concentration.

The remaining participant, who also did not understand the sound in the previous test and mentioned they would not be able to perform the trajectory with only haptic feedback, said that they could not correct their technique at all with this feedback combination. Therefore, it was chosen to not have this participant experience the next feedback combination.

All trainings in best modality

Focussing on all three technique aspects in different modalities went surprisingly well for these two participants. One participant even managed to perform all skills within their dead zones and said they could focus well on all feedback. The other participant focussed mainly on the visual posture and auditory velocity feedback and mentioned to have slight trouble with also focussing on the haptic trajectory feedback.

All trainings visually

The participant who performed very well during the previous feedback combination mentioned that training everything visually also worked, but less effectively, as you need to look at multiple things simultaneously. In contrast, the other participant who experienced the previous feedback combination preferred this entirely-visual feedback combination. The remaining participant found these visual feedback designs much clearer than the auditory and haptic varieties.

It was difficult to simultaneously focus on all aspects of visual feedback. Namely, every participant mentioned that velocity was the hardest to focus on, partly because the target velocity ball moved behind the character at the finish of the stroke. Also, the velocity of the hands of the target character could not be seen because its transparency was controlled with the back angle. As a result, mainly back angle and trajectory was trained, while correction of velocity was occasionally ignored.

6.5.3.3 Conclusion and discussion

The three participants all reacted very differently to the feedback combinations. Specifically, one participant found the haptic feedback effective and the auditory not as much and preferred the complete feedback combination to be entirely visual. Another participant found the haptic feedback to not be very noticeable and the auditory feedback effective and preferred a complete multimodal combination of feedback over an entirely visual one. The remaining participant could not entirely understand the nonvisual feedback and their combination. This person has also been observed multiple times before to not like VR as much, so motivation for participating might be lacking.

When combining two modalities on the same aspect of technique, visual-haptic trajectory feedback could prove to be an effective combination. In such a case, the visual feedback shows the movement clearly, and the haptic feedback can point attention to details and give feedback during moments where the visual display is not in view.

The visual-auditory velocity feedback shows less potential as a combination because the visual feedback is already very effective. This confirms [35] where it was also shown that an added modality to visual feedback only subtly improved it. However, [35] also showed that visual-auditory feedback indicates a high transfer of the velocity skill, so this combination could still have potential for decreasing dependency. Additionally, when the dead zone of the auditory feedback is made smaller, it could possibly point out details similar to the haptic feedback in the visual-haptic trajectory feedback.

Interestingly, it was mentioned by one participant that unimodal auditory or haptic feedback might actually be better than unimodal visual feedback for two reasons; (i) they demand more attention which possibly leads to less dependency on feedback, and (ii) they do not require to look in a certain direction. Actually, a similar theory was suggested by the SPRINT system in [33] where the haptic trajectory feedback showed the best results in the retention test because the visual feedback introduced a dependency. The participant suggested that first, visual feedback should be shown to teach the general skill, and then an auditory or haptic feedback should be used to actually make someone remember the movement.

The visual feedback design here could also be improved, as two issues were noticed during the test. Firstly, the visual trajectory display was not reachable for every participant at the finish of the stroke due to the shorter legs of participant as opposed to the creator of the feedback. This could be solved with a calibration functionality similar to the feedback in the RP3 environment, which was not done in this case because the curved trajectory made it difficult to implement. Secondly, during the entirely-visual feedback combination, the trajectory and velocity training were covered by the embodied and target character. This could be solved by overlaying this visual feedback over the characters.

In addition, the posture feedback could be improved to show only the back when the back angle is incorrect and the hands (and oar) when the velocity is incorrect. Because in this case, the participants could never focus on the hands of the example rower when the back was performed correctly.

When more combination could be tested, it would be interesting to turn on both visual skiff displays: side trajectory and immersive velocity. This combination was suggested during the test and might be effective, as the two could be seen simultaneously relatively well.

7 VALIDATION

The final version of this project was showcased via video calling to two student coaches of D.R.V. Euros and to the CEO of RP3 Rowing for validation and feedback. They were shown a demonstration of the river environment with the single scull and character, along with several visual feedback varieties. Auditory and haptic feedback varieties were explained as well.

7.1 STUDENT ROWING COACHES FROM D.R.V. EUROS

The two student rowing coaches from D.R.V. Euros, named Abe Winters and Stijn Berendse, were part of the group which initiated the concept of Virtual Rowing two years ago. They had previously given feedback to the final version of Koen Vogel [2], so now they can compare between Koen's and this project. Furthermore, both have at least one year of competitive rowing experience and one year of coaching experience.

The reaction was very positive; they mentioned that it is clearly visible that an experienced rower created this project. Additionally, the rowing movement of the character was found to be accurate, as well as the behaviour and look of the single scull.

The feedback was also perceived to be much more intuitive. Especially the visual feedback on posture was found clear, and Abe even mentioned that this was even one of the ideas they had, where a ghost would perform the target movement. A feedback location of Koen was mentioned where the feedback was displayed to the right of the user, which caused Stijn to rotate his head very uncomfortably. In contrast, the side-view in this case presented directly in front of the rower was mentioned to be "really nice". Moreover, they mentioned there was an "information overload" by the many UI elements of Koen's feedback design, whereas this feedback is simpler and more understandable.

7.2 CEO OF RP3 ROWING

The project was also showcased to Jan Lammers, the CEO of RP3 Rowing, which is the main stakeholder of this project. The company provided a rowing machine to the university for the project of Koen [2], and previously lent rowing machines to D.R.V. Euros, of which one is now located at my home.

The reaction of Jan Lammers was also very positive, as the project entailed more than he expected. This step towards virtual reality rowing training was well received. The focus on trajectory, velocity (which he called "drive-time ratio"), and posture was mentioned to be a good choice. Specifically, with trajectory training, the rough movement of hands can actually be trained on the RP3, which would be very useful for beginning rowers, even though the feeling of moving oars is quite different than moving an ergometer handle. While the visual feedback designs on trajectory and velocity were not entirely noticeable, the visual feedback on posture was perceived to be really intuitive and clear.

Showing moving objects such as a trail or an example rower was deemed to be much clearer to beginners than numbers or graphs. Also, the auditory feedback, while not demonstrated but explained, was mentioned to have good potential for beginners.

The entertainment value of the project was also complimented. It was said that in general a sport is more enjoyed with better technique, and in the case of rowing it is more enjoyable for beginners to row on water with prior knowledge of technique. This could then be facilitated by this project. Furthermore, the implemented on-water rowing simulation could make training technique on the ergometer more fun and effective, and make beginners more enthusiastic about rowing. Thus, the improvement of the project's enjoyment value in the future was mentioned to be very interesting.

A realistic on-water simulation is already something RP3 Rowing is working towards. For example, they are developing (i) a seat which can tilt sideways in order to simulate the rolling of the boat (imbalance), (ii) a frame which can simulate the pitch of the boat (front or back more submerged in water), and (iii) a rowing machine which could change the drag factor when the handle is too high, to simulate a rowing crab (full stop of boat velocity). The constructed virtual reality rowing environment could definitely be combined with these technologies to enhance rowing simulation even further.

In fact, simulating on-water rowing has a relevant benefit; it improves retention of the on-water rowing technique. Recently, due to the COVID-19 pandemic, it was not allowed to row anymore. Jan Lammers mentioned that during that time, the rowers that trained on the RP3 showed an easier adaption to rowing on-water again, whereas the rowers that trained on the static ergometer (the Concept2[22]) had more trouble with injuries and deteriorated technique. Such a period of no on-water rowing actually occurs every winter, and with a higher quality of on-water rowing simulation, injuries could be prevented, and retention of technique could be improved. As a matter of fact, a sports training simulation probably has a lot of potential, as in the Formula 1 sport the high-level racer Max Verstappen already regularly trains in a simulator[23].

Also, the scenario of a training session for many beginning rowers, which RP3 Rowing regularly hosts, was mentioned again. For such a scenario, the company is interested in a VR system where they would simply have to put the head-mounted display on a rower for them to start learning technique on their own. Certainly, the removal of the chest motion tracker and the adaptation to a home environment brings this project a huge step forward to that goal.

Finally, it was suggested to develop a recording function to the feedback system, which could be used to analyse the training afterwards by a coach or possibly the rower themselves. Such a function would also allow for objective selection of rowers to clubs or teams, or to notice rowing talent in beginners.

[22] https://www.concept2.com/
[23] https://www.teamredline.co.uk/work/max-verstappen/

8 DISCUSSION

This chapter will present the interpretations of all important findings, along with comparisons to related work. Then, the limitations of this study will be explained. And afterwards, several excerpts from an ethical analysis on this project are highlighted.

8.1 FINDINGS

The sections below follow roughly the same order as the research questions established in chapter 1. Because all findings have already been discussed after every evaluation, they will not be explained in as much detail.

8.1.1 Rowing errors

The chosen aspects of rowing technique to design feedback for were hand trajectory and velocity, and back angle. While the back angle covers the two most common rowing errors according to the interviewed coaches, feedback for the hand trajectory and velocity was first explored because of five reasons. Namely: (i) trajectory of the hands (including velocity) "… turns out to be the most important factor influencing the overall performance" [32, p.2], (ii) many common errors mentioned by the interviewed coaches are corrected by better trajectory and velocity (see section 2.6), (iii) feedback designs from related work can be explored further using virtual reality, (iv) feedback on trajectory and velocity seem to have more possibilities for variation and can be trained in the same display, and (v) on-water rowing is simulated, where trajectory is even more important.

It can be said that during all evaluation tests, correction of the errors covered by these rowing technique aspects was observed. During trajectory training, especially the straight line during the drive was trained, while achieving the ideal stroke length was more difficult due to inflexibility. During velocity training, most participants realized that the entire drive requires power and to take time in the recovery, but pulling of the arms could not be avoided.

Because of posture (back angle) training, participants who always performed incorrect back technique finally corrected it. Especially the early onset of the back at the catch or the insufficient incline of the back during the recovery were corrected.

However, because of the small scope of the experiment no real conclusions can be drawn. Also, these visual improvements in rowing technique might not necessarily cause improvements in rowing outcome as pointed out [40]. Therefore, rowing effort should also be measured. Additionally, it is uncertain how much of these obtained skills are retained to later non-feedback conditions.

8.1.2 Unimodal feedback varieties

<u>Visual trajectory and velocity</u>

The visual feedback usually required a short explanation when first seeing it. Namely, the trajectory image was followed incorrectly twice, and the concept of bandwidth feedback demanded some time to be understood. Nevertheless, it was found intuitive by all participants.

The side-view in front was found useful in order to understand the feedback. But, in order to really train the technique a different location was preferred where the handle correlated with the display. Specifically, a trajectory feedback in the side display, and velocity feedback in the immersive display (below handle). These best locations for visual feedback require a slight turning of the head, but it was not believed to change technique as much as an interviewed coach mentioned looking into a side mirror to be. Then, the head-up display was always preferred by one participant, but two other participants always found it annoying.

On the other hand, because the visual feedback derived from side-view thinking, a different location could be preferred once the feedback design is different. Possibly, an immersive trajectory display with arrows displayed on top and below the handle as seen in a video of SPRINT [15] would be effective, but it would be challenging to integrate the trail, bandwidth and target position concepts in other visual feedback designs.

Auditory trajectory and velocity

The auditory feedback has potential, but first needs to be understood with an explanation. Moreover, the trajectory sounds using pitch is only really effective during the drive, where only one note is heard when done correctly. The spatial velocity sound was effective and understood, but likely not due to its spatial aspect but because it was a simpler sound with only a rear-sound simulation effect and volume changes. Then, the combined auditory feedback caused a cognitive overload for most participants, so combining trainings in the more abstract auditory modality does not show potential.

Surprisingly, one participant used the changing pitch of the trajectory sound to remember the durations of drive and recovery. This shows how effective rhythmic auditory feedback could be, and therefore is a relevant option for future work.

Occasionally, a low noticeability of sound was mentioned. However, this was likely an effect of bandwidth feedback where the sound is played at lower volume when technique is performed (nearly) correctly. However, this caused participants to question whether they are either not hearing the sound well enough or performing the technique correctly. This issue could possibly be solved with more drastic volume changes. Namely, no volume when inside the dead zone, and noticeable volume when outside the dead zone.

Haptic trajectory and velocity

The haptic feedback also shows potential, even though it was occasionally slightly unnoticeable. Though, haptic trajectory feedback was observed to more intuitive and effective than haptic velocity feedback. This was likely due to corrections of velocity causing more disturbance of rowing movement, and velocity being harder to correct for beginners. Additionally, one participant found haptic feedback to work better than visual because of increased concentration.

No majority of preference for a vibration direction was found. For haptic trajectory training the opinions were split and this was not because of a preference for the first presented option. For haptic velocity training only one participant had a preference, which was for pushing vibrations. This suggests that the vibration direction chosen by the SPRINT system [32, 33] might not be as intuitive. However, the constant switching of vibration directions could have led to poor results.

Also, because of the occasionally low noticeability of haptic feedback, sound was preferred for velocity training. To solve this noticeability issue, bandwidth could possibly be disregarded from the haptic feedback, or the vibration motors could be placed on bare skin.

Visual and auditory posture

The visual posture feedback was very intuitive and worked well. With a full-body target rower the back was still the clearest aspect and it could be estimated better than when a simple capsule was shown. Also, a target oar was not found distracting, but because the oar moved in the opposite direction, the only-body was still preferred.

Auditory posture feedback was also effective, but this could be influenced by the memory of the visual feedback. The left-right sound was found difficult to follow, whereas the spatial sound worked better because of its simplicity. One participant pointed out that the sound worked, but it did not specify the back angle with as much detail as the visual, so possibly its bandwidth size should be reduced. However, the visual feedback was still found to be a lot more effective.

Comparisons

Based on observations and participants' responses, visual feedback seems to be most effective at correcting technique during the session. However, it is still uncertain how much this skill would transfer to later non-feedback conditions. Because of this, auditory and haptic feedback might be better, as they require more memorization of movement. This was also pointed out by a participant who mentioned that visual feedback does not require much thinking, whereas with auditory feedback you really have to do it yourself. Furthermore, non-visual feedback does not require to rotate the head to look in a certain direction, which would improve rowing technique (section 2.2.2.2).

In fact, this dependency on visual feedback has been shown to exist [33], as well as the slow [32] but more precise [31, 32] movements it causes, which was also observed in this research. However, [37] has shown that visual feedback scores well and is less cognitively demanding. But, this research suggests that haptic and auditory feedback could improve concentration and therefore also memorization.

It was also observed that participants performed a previously trained technique aspect considerably worse when focusing on another technique aspect during the same session. For example, trajectory was almost disregarded when training velocity. Also, between sessions, previously trained skills were observed to be diminished. This could be explained by either (i) the difficulty of training, (ii) a lack of focus, (iii) a guidance effect, or (iv) the novelty of feedback.

Intuitiveness

Especially the visual and haptic feedback designs have been shown to be intuitive to beginning rowers. The auditory feedback always needed a good explanation, but eventually could be used relatively well to correct technique. Furthermore, it could be argued that these feedback designs are more intuitive than those from Quiske [6] (section 2.4.1) and BioRowTech [12] (section 2.4.3), but these feedback designs provide less detailed feedback. However, detailed feedback might not be useful and effective for beginners.

8.1.3 Multimodal feedback combinations

Same training

When combining two feedback modalities on one training, a visual-haptic trajectory combination shows potential. Specifically, the haptic trajectory feedback gave attention to details and could give feedback during moments that the visual feedback was not in view. On the other hand, the auditory velocity feedback did not improve the visual feedback because it was already effective. However, when the dead zone of the velocity sound is made smaller it could possibly point attention to details similar to the visual-haptic trajectory combination. This combination should have more potential, because a visual-auditory velocity combination was shown to be effective and cause a high skill transfer in [35], although with slightly different feedback designs.

Different training

Training trajectory with haptic and velocity with auditory feedback was difficult at first, but after some time worked well for most participants. Though, the vibrations were occasionally unnoticeable and the sound unclear. Also, the person with the least amount of VR experience could not handle a training without visuals, but this could also be explained by their lack of motivation.

Surprisingly, a combination of three feedback designs in different modalities was effective for two participants. One of these participants could even focus on everything and stay within all dead zones, whereas the second participant only had slight trouble with focussing on the haptic trajectory feedback.

Then, the previously mentioned participant who was observed to have low motivation found the entirely-visual combination of the three feedback designs much clearer than the nonvisual feedback. Also, the participant which had slight trouble during the multimodal combination preferred the visual as well. However, the participant who performed very well during the multimodal combination found that combination to work better. The issue pointed out by this last participant was that you cannot look at multiple feedback designs simultaneously very well (even in the same display), but you can see, hear, and feel different feedback. In fact, during the visual combination all participants had trouble following the target velocity ball. However, there was an issue observed of feedback disappearing behind the character, this could have contributed to the difficulty of following the target velocity ball.

8.1.4 On-water rowing simulation

Two rowing coach experts mentioned that the movement of the character and single scull in the river environment was very accurate to real rowing. The participants also reacted very positive to the on-water rowing simulation and commonly found it relaxing and fun. Additionally, even the empty room environment was enjoyed. This suggests that training with the feedback on its own is already enjoyable.

However, one participant was heavily disturbed by the embodied character and preferred not to row with it. This means that there is a good chance this character could cause feelings of discomfort for future participants in any follow-up research. Therefore, participants should be informed of this issue and possibly be presented an option regarding the character. Though, the other participants found the difference in actual arm movement and virtual arm movement never uncanny.

8.1.5 Feasibility of home environment setup

While situated in a narrow room as opposed to a large design space, this project still acquired better tracking results than the work of Koen Vogel [2]. This was due to several improvements to the setup. Firstly, a wooden plank was connected to the seat for its motion tracker to be visible at all times. Secondly, the motion tracker on the handle was moved to a glove for smoother tracking. Thirdly, through trial and error the best locations of lighthouses were achieved.

Also, the head-mounted display is now used for calculation of the back instead of the previously used motion tracker for improved usability. However, the currently used glove is not user friendly as it causes sweating and is difficult to take off. Therefore, it should be replaced by a thinner glove or a wristband.

Nevertheless, these improvements on accuracy and usability show a high potential for this project to be placed at any location. Furthermore, the use of immersive virtual reality greatly reduces the necessary space and increases immersion as compared to the two Cave Virtual Environments: SPRINT Rowing Training System [14, 15], and M^3 Rowing Simulator [16, 17]. But the indoor rowing machine is less comparable to on-water rowing than their simulations.

8.1.6 Value of virtual reality

The preferred locations for visual feedback, a display under for velocity and a display closely to the side for trajectory, could in theory be realised with augmented reality as well. But, compared to standard monitors and the two CAVE's, virtual reality definitely adds value to feedback designs on rowing technique. Furthermore, in the M^3 Rowing Simulator [16, 17] participants commonly had to look to the side, which is not optimal for rowing technique. In this case, a smaller rotation of the head is necessary to observe the feedback under and to the side. However, the implemented spatial sound can certainly be created without virtual reality because the spatial position aspect was not what caused its effectiveness.

It was also found that virtual reality indeed allows for control of the environment in specific and reproducible ways, and for practicing specific skills with continuous feedback as stated in [3]. Also, because of the previously mentioned accuracy and usability improvements, virtual reality has shown to have more value than was found in [2].

Besides, virtual reality also allows for immersion into the virtual environment, which leads to enjoyment and relaxation as mentioned by all participants in this study and also found in [2]. Furthermore, these effects could lead to increased enjoyment of technique correction, and thus also enhance effectiveness of feedback.

8.2 LIMITATIONS

The main limitations of this research were due to the COVID-19 pandemic, but also a lot of possibilities were created because of it. Other limitations were a result of time constraints or limited skills.

User-testing

Only four family member participants could be recruited for user testing, which decreased the significance of results, but also allowed for a broader qualitative study. Unfortunately, three of the four participants had rowed once before with instructions, but this likely only introduced a bias to the results of the first test. Also, every test was done with the same participants, and every participant experienced all feedback. This introduced a great bias in evaluating feedback, but it also allowed for making many comparisons between feedback designs.

Simplicity of setup

The simple setup with four tracking points, while increasing usability and versatility, limited the scope of rowing errors that could be addressed. For example, no detailed feedback could be given on back posture, or on something else like elbow position. Also, no feedback could be given on the activation of more specific muscle groups.

Vibration motors

The effectiveness of the haptic feedback was limited by the use of standard vibration motors. Also, these vibration motors were separated from the skin with one layer of cloth, and the varying sizes of participants' wrists could not be taken into account.

Character

Because of time constraints, only two characters were made: a tall and a medium-sized one. The movement of these characters was not always accurate, due to having to stretch the model. This could be solved by using the more advanced Final IK plugin[24]. Furthermore, this character had to be downloaded from the website Mixamo[25], and its look does not exactly represent a rower. Also, because of being uncanny, it heavily disturbed one participant. When a more cartoonish character is used, this issue could potentially be solved.

Single scull feedback calibration

Additionally, the feedback in the single scull did not have a calibration option because of the implementation of a curved trajectory display. Therefore, some participants were unable to follow the entire trajectory. With more knowledge of the Unity UI Extensions plugin[26], calibration could be added.

Sweating

Both the HMD and glove were observed to cause sweating. The sweating in the HMD was worse than in the glove, and likely harder to solve. Though, the sweating in the glove could be solved by using a wristband instead. However, more expertise is necessary to integrate both the haptic hardware and motion tracker into a smaller wristband.

[24] https://assetstore.unity.com/packages/tools/animation/final-ik-14290
[25] https://www.mixamo.com/#/
[26] https://bitbucket.org/UnityUIExtensions/unity-ui-extensions/src/master/

8.3 ETHICAL ANALYSIS HIGHLIGHTS

An ethical analysis was written as the final assignment for the course Reflection of the graduation semester, and follows the seven step guide of [45]. Moreover, the ethical analysis of Koen Vogel [2] was used for insights and inspiration. In this section, several excerpts of this analysis are highlighted. The full analysis can be read in Appendix E.

8.3.1 Ethical risk sweeping

Ethical risk sweeping is an essential tool for good design and engineering practice, it consists of a broad analysis of any possible ethical risks [45]. Thereby answering the question: "Which design choices could possibly cause significant harm to persons or other entities with a moral status, or cause acute moral controversy?" Below, five of the eleven analysed risks are discussed.

Motion sickness

Virtual reality is known to evoke motion sickness. The most important cause of this is the dissociation between feeling and sight and occurs more often when physical activity or fast movements are involved. The presented system requires physical activity, but never displays very fast movements, unless the user decides to. Mainly in the on-water rowing scenario motion sickness should be considered a significant risk as there the hands of the virtual character move over each other as opposed to besides each other, and the user is surrounded by a large moving environment.

Sensory deprivation

When a user is immersed into the Virtual Rowing Coach, many senses are blocked from the outside world. A virtual reality head mounted display on its own already visually presents a whole other world. On top of that, many VR experiences include sound as well, including this project. Also, the haptic sense is distracted because of the rowing movement and of vibrating motors in the glove.

Generally, blocking out all these senses could lead to great physical accidents. But luckily in this case, the user is seated and partially constrained to a single movement, which means that chance is small. However, this chance still does exist and thus is covered in the next section. Other significant risks caused by sensory deprivation could include home invasions, leaving the stove on, or not hearing an important phone call.

Overestimation of capabilities

Realistic virtual task environments could make individuals believe that they are able to do the same in the real world. This is especially dangerous in a rowing scenario, as it is extremely common for beginners to fall into the water when attempting to row in a single scull. On top of that, hand movement is very different (cross each other) and rowing will feel different. It is in general quite hard for a complete beginner to row in a single scull, and the individual should thus be carefully guided in the case they want to row on the water. Interestingly, a participant actually mentioned in the combination test that they could probably row in a rowing boat, but luckily realised that they would likely capsize.

Coach feels unneeded

When an experienced rower uses the eventual final version of this project, their coach might feel unneeded. This would especially be the case if the system is able to detect technique very detailed and give personally optimized feedback. However, the aim of this project is not to replace a coach entirely, but rather, to give simple feedback to beginning rowers which could be used besides the normal trainings with a coach.

Inability to perform target technique

This project presents a universally agreed upon target technique which most beginners should strive towards. However, it does not consider the limited movements of people of older age, overweight people, or disabled people. The inability to perform the target technique could amplify the awareness of having limited movement and leads to misery because of body comparison.

8.3.2 Ethical pre-mortems

This second step of the ethical toolkit intends to make designers think about how multiple small individual risks would be able to cause, or have caused an ethical disaster. Because this project is still a prototype and it has not yet caused any disastrous scenarios, this section will focus solely on pre-mortems. The pre-mortems are analysed by thinking creatively about possible scenarios based on the risks found by ethical risk sweeping. Below, one of the three pre-mortems is discussed.

Beginning rower isolated training

In this scenario, a first year student joins the local rowing club who is a big fan of virtual reality. This person was overjoyed when they found out there is a Virtual Rowing Coach at the club. After a short introduction this person started rowing with the installation on their own for a long training. In the following weeks, this person started to use it increasingly often, and due to the nature of the project, always trained on their own and never really talked to anyone about rowing technique. As a result of always rowing in a real boat in the virtual environment, this person started to believe they were surely able to grab a real boat and go for a row on the water. However, this turned out to be completely foolish as the person almost immediately fell into the cold water, which came as a shocking surprise. This incident did not only cause harm to the rowing individual, but also to the rowing club, as this boat was now damaged.

8.3.3 Remembering the ethical benefits of creative work

While there are of course a lot of things that can go wrong, it should not be forgotten that this work is made in order to do ethical good in the world. That is why in this step, ethical benefits are summarized and explained. Here, two of the five benefits are discussed.

More opportunities to row

Planning a rowing training can be difficult, due to limited coach availability and possibly teammate availability when there is a desire to row together. Especially when being a beginning level rower without aspiration to be a competitive rower, there are less coaches available. This project allows for more flexible training schedules because it can correct technique without a human and it makes it more fun to train individually. Additionally, the project can even be installed at home.

Better coaching potential

While needing fewer human coaches might sound bad for them, this project could actually increase their coaching potential. A combination of both human and computer-aided coaching would mean that complete beginners would be able to learn the basic technique using the Virtual Rowing Coach, while the human coach has more time to focus on more detailed individual errors of the slightly more experienced rowers. Furthermore, this project provides an objective evaluation of technique which most coaches might not be able to give.

8.3.4 Think about the terrible people

When a product is marketed to a great number of people, there will always be those who wish to use it with ill intentions. To prepare for the worst, these immoral unintended uses should therefore also be addressed, as well as ways to avoid or combat them. Here, two of the four unintended uses are discussed.

Reckless usage

Some people might be so excited to use virtual reality, that they start to row on the machine without any introduction. Other people might also want to show off how strong they are by immediately rowing very hard on the machine without good technique. Both of these scenarios would be detrimental to the project and to the rowing individual. The project could be damaged, but that depends on how sturdy it eventually becomes. Additionally, the individual might not be expecting the experience it will provide, not be aware of possible motion sickness, injure themselves, or fall off the seat. This could be solved with a supervisor present near the project, to give instructions in case anyone would like to try it out.

Admissions

The evaluation data that this project creates when a user rows on it, could easily be used as criteria for admissions to rowing clubs, rowing teams, gyms, or even to colleges. One way to avoid this would be to remove any results presented after rowing, which would however be a shame as terminal feedback is extremely helpful for improving technique. Another way is to present the feedback in a simpler form, which would make it harder to compare rowers, but might decrease the effectiveness of feedback. Finally, it would be possible to share the results only with the specific individual, for example via email.

8.3.5 Closing the loop: ethical feedback and iteration

It is important to realise that reflection on ethical implications is not a one-time task. Ethics is relative to the particular social context it concerns, which will always be changing [45]. Even technology can change social contexts so much so that at some point the technology itself could be viewed as unethical. Thus, regularly repeating ethical practice will make sure that the product stays a success for a long time.

In the case this project is continued outside the scope of a bachelor assignment into a real product, regular ethical practice should be integrated as an explicit part of the regular workflow. In addition, the important stakeholders should structurally be consulted and empathized with, in order to avoid generating manufactured desires and to learn about the possible ethical effects upon them.

9 CONCLUSION

To provide unsupervised learning of rowing technique to beginners for lowering the chance of injuries and to attempt to solve coaching problems in groups with varying skill levels, an immersive virtual reality rowing training system was created which can provide multimodal feedback.

Through several improvements, the setup from Koen Vogel [2] was realised in a narrow room where consistent and accurate motion tracking was achieved. Namely, the hand motion tracker was mounted on a glove and the seat motion tracker on a wooden plank. Also, the chest motion tracker was dismissed in favour of calculating the back angle with the head-mounted display. Thus, using only a head-mounted display and three motion trackers mounted on an indoor rowing machine, a rower's body can be estimated for technique analysis and for display of a virtual character.

Then, a room environment with a replica of the RP3 Model S was made, as well as a river environment with a single scull to simulate on-water rowing. This river environment was already made by Koen Vogel [2] and the single scull was modelled together with Annefie Tuinstra, a fellow student. All four participants found the on-water rowing simulation to be enjoyable and relaxing, and also found the room environment enjoyable but likely because of the presented feedback. Furthermore, the two expert rowing coaches found the on-water rowing simulation to be accurate.

Through interviews of four other expert coaches of first-year rowers, reading rowing guidebooks and a literature review, it was chosen to design feedback addressing hand trajectory and velocity, and back angle. Many different varieties of multimodal feedback on these rowing skills were created, and all feedback designs can be turned on in any preferred combination. These feedback designs are inspired by and building on two Cave Automatic Environments (SPRINT Rowing Training System [14, 15], M^3 Rowing Simulator [16, 17]) and a study that combines self-observation with expert modelling [40].

Because of the COVID-19 pandemic, several design cycles took place instead of one. By qualitative testing on four family members at the end of every design cycle the intuitiveness and effectiveness of feedback varieties and feedback combinations were evaluated.

It seems that a visual side-view is effective at understanding feedback, but afterwards a different visual display which is closer and corresponds with the position of the trained aspect is effective for really training the skill. Specifically, for handle trajectory a display to the side, and for handle velocity a display below. It also seems that visual feedback is always more intuitive and effective than auditory and haptic feedback. However, because visual feedback does not require much thought, it could likely introduce a dependency. Moreover, auditory and haptic feedback do not require the user to look in a direction, which is more optimal for rowing technique and has been mentioned to improve concentration. Therefore, auditory and haptic feedback still have great potential for teaching the rowing technique. Specifically, in this case, spatial sound velocity feedback and haptic trajectory feedback where direction of vibration is decided by the user.

Additionally, the visual-haptic trajectory combination shows good potential by allowing the user to switch focus between modalities and to enhance perception of details in the trajectory. The visual-auditory velocity combination shows less potential because the visual feedback is already very effective. Then, a combination of all three modalities on three different trainings can be effective for some and was actually preferred by one participant, but an entirely-visual combination was ultimately more preferred. However, during this entirely-visual combination velocity feedback was difficult to focus on, likely due to a visual overload and the small size of the target velocity ball.

To conclude, this research has shown many insights into how beginning rowers react to multimodal feedback, but to achieve more conclusive results larger scale research should be done. However, the set up platform shows great potential for future development.

10 RECOMMENDATIONS

A great number of recommendations can be made for future work. Therefore, the recommendations are split in three sections. Firstly, what could be improved about the current situation. Secondly, how the current situation could be expanded. Thirdly, what this project could eventually become in the future.

10.1 IMPROVE

Every feedback design can be improved. First, the visual trajectory should be made more intuitive by integrating large arrows in its design or showing only a small part of it around the current position. Then, the auditory and haptic velocity feedback could be improved by using the actual deviation in velocity at a position, instead of deviation from an on-going target animation. This animation could also be improved to have different drive-time ratios for the different stroke rates as now only the ratio of 1:2 is used for every stroke rate which does not actually represent real rowing [54]. However, the ideal drive-time ratios probably also differ between on-water, RP3, and Concep2 rowing.

Also, the noticeability of auditory and haptic feedback could be improved. Specifically, the dead zone of auditory velocity feedback should be made smaller as it was observed to be easier than other feedback designs. This would also increase its value as addition to visual velocity feedback because it then can point attention to details. On the other hand, haptic could be made more noticeable by immediately giving strong vibration outside the dead zone instead of a bandwidth. But, placing the vibration motors on bare skin would probably be a better solution.

In addition, the trajectory and velocity feedback in the side-view should overlap the character for visibility at the finish of the stroke. Also, in the single scull, calibration of feedback should be added. Not only for trajectory and velocity feedback, but also for posture feedback, because currently a shorter stroke length causes the animation to continuously accelerate.

The currently used character could be improved using the Final IK plugin[27] which allows for properly stretching a rigged model. Then, an accurate size character could be made for any size of users, maybe even with values entered before a session. This character could then also be made less uncanny (e.g. cartoonish) to be more user friendly.

10.2 EXPAND

Several recommendations for new feedback designs can be given. In this section, the designs are explained which can be realised with the current setup relatively easy.

More auditory exploration

First of all, the two concepts originally created for haptic feedback could be explored as auditory feedback. Namely, rhythm: where three or four notes would be played during the drive at normal speed and during the recovery at half speed. This could enhance the perception of the time ratio between the two. Also, the direction of deviation pitch feedback could be tested, because the finding of direction-indicative sound being more practical from [52] might not be most intuitive, as the participants were observed to struggle with this concept.

Haptic posture feedback

Additionally, the design cycle of posture feedback could be completed with haptic feedback on back angle, for example in the form of a chest band. But, this might not be as user friendly as a glove.

[27] https://assetstore.unity.com/packages/tools/animation/final-ik-14290

Advanced posture feedback
The visual posture feedback could also be expanded, as it proved to have good potential. Possibly, the arms (or hands) and back could turn transparent independent of each other, targeting handle and back angle feedback respectively. Then, the legs could also be integrated in a full posture correction feedback design which could also increase the stroke length. However, displaying target arms to a beginning rower would likely cause pulling.

Posture timing feedback
Because the recovery execution order is a very common error as pointed out by expert rowing coaches, the feedback design from Koen [2] could potentially be made more intuitive in a different form. Consequently, auditory feedback could be designed on the muscle execution. A concept for this was thought out during this project, namely: a triad (three notes) where every note represents when the legs, back, or arms are moving. Then, this could be played as left-right sound similar to the already created auditory feedback designs.

Other technique aspects
Finally, other technique aspects could be explored. Namely, achieving a higher stroke length and lower stroke rate because they are strongly related to stroke efficiency [35], or avoiding the pulling of the arms, which is inefficient for a rowing stroke. The latter might be difficult because of tracking accuracy, but it is a very common error according to rowing coaches, and commonly observed as an unintended reaction to velocity feedback.

Further develop existing feedback designs
Instead of exploring more feedback designs, one could also go more in-depth into the existing feedback designs and experiment with how to optimize retention of technique, possibly implementing terminal visual feedback. Though, it might also be interesting to further experiment how all three modalities of feedback could be combined in a useful and effective way.

10.3 For the future

In this section, recommendations are made for work that goes beyond the current setup and would require a lot more time.

Data
A program could be set up to gather the data from the rowing machine using a cable or Bluetooth. This data could then be used to evaluate technique, because visual improvements in technique do not necessarily cause improvements in rowing outcome [40].

Then, a recording function of all data could be implemented which could present terminal feedback to the rower and allow coaches to evaluate rowers. Additionally, functionality for rower profiles could be integrated for storage of technique data and character dimensions.

Motion tracking
Together with RP3 Rowing a rowing machine could be created with built-in motion tracking. Their rowing machines already measure the length of a stroke, so measurement of the distance between the seat and flywheel should be possible as well. Additionally, their CEO has mentioned that the height of handle is already calculated in a rowing machine which can simulate a rowing crab (full stop of boat) by changing the drag factor. Then, only the back angle then to be calculated, which would be done using the HMD.

Although, should the distance between the seat and flywheel not be feasible to calculate, a solution using the two HTC Vive controllers as motion trackers could be designed, which is an even more low-cost solution than the currently used setup.

Simulation

The three single-scull simulation concepts mentioned by the CEO of RP3 Rowing in section 7.2 could be accompanied with a very accurate on-water simulation including auditory and haptic feedback from the boat. This simulation would be useful for beginners to understand this intrinsic feedback, and expert rowers could have better retention of technique in a period of no on-water training.

Advanced virtual coach

A more advanced virtual rowing coach could be created which is able to communicate with the user to explain technique, and nudge certain body parts in a position using haptic technology. Furthermore, the user could even be presented options on what type of feedback they want to receive.

Alternatively, an automated feedback selection system could be designed which compares rowing errors and gives feedback on the greatest error. And so, depending on the persistence of an error the feedback could be given in extra modalities or in a stronger form.

Then, eventually this project could evolve into a user friendly product independent of human operators.

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A Videos

A.1 Auditory feedback

Note: The volume turned out to be very low in these videos so using headphones is recommended.

Trajectory (left-right pitch)
https://www.youtube.com/watch?v=uAfHT4o-5Vw

Trajectory (deviation pitch)
https://www.youtube.com/watch?v=sy5kU160Cc8

Velocity (spatial)
https://www.youtube.com/watch?v=TJB5ninSOlY

Trajectory and velocity (spatial with deviation pitch)
https://www.youtube.com/watch?v=5MXc-haYNj0

A.2 Final version showcase

https://www.youtube.com/watch?v=kD93bxN2cQ4

B ETHICAL DOCUMENTS

B.1 INFORMED CONSENT INTERVIEW

VRC1.0 – lt.ac.acc.rc – 2020 – v1.00

Ptcpt no.

INFORMED CONSENT INTERVIEW

Concerns
The University of Twente and Human Media Interaction are researching the use of virtual reality and motion tracking to provide real-time feedback on rowing technique. You, as an experienced coach of first year rowers, have been selected to take part in an interview contributing to this research. In the interview you will be asked what the most common mistakes are of beginning rowers, what forms of feedback you usually give, and what you think is the most effective type of feedback.

Main researchers:
Sascha Bergsma[1], Robby van Delden[1], Randy Klaassen[1], Dees B. W. Postma[1], Dennis Reidsma[1]
[1]University of Twente

Contact info
For questions you can contact Sascha Bergsma (7545VW Enschede, Acaciaplantsoen 75; +3161097024; s.bergsma-2@student.utwente.nl) or the Ethics Committee of the University of Twente (Drs. Petri de Willigen; UT Building: Zilverling 1051; +31534892085; ethics-comm-ewi@utwente.nl). The Ethics Committee exists of independent experts from the university and are available for questions and complaints surrounding this research.

Research: Virtual Rowing Coach
I hereby declare the following:

- I give consent for my participation in the interview.
- I give consent for making notes during the interview for research purposes.
- I declare that I am fully informed about the research. The purpose of the interview is explained, and I had the possibility of asking questions.
- I understand that I can quit my participation at any moment during or after the interview (within 24 hours), without a reason and without any consequences. In this case I can have the gathered notes deleted if I wish.

All research material will be processed and stored according to AVG guidelines. All data will be stored for a minimum of 10 years according to the VSNU guideline.

☐ I give permission to be credited by full name in the research paper.

Date: Location:

Name: Signature participant:

....

The extra copy of this consent form is for you to keep.

B.2 INFORMED CONSENT USER TESTING

VRC1.0 – lt.ac.acc.rc – 2020 – v1.00

Ptcpt no.

INFORMED CONSENT

Concerns
The University of Twente and Human Media Interaction are researching the use of virtual reality and motion tracking to provide real-time feedback on rowing technique, as explained in the information brochure "*Virtual Rowing Coach*" as given together with this form.

Main researchers:
Sascha Bergsma[1], Robby van Delden[1], Randy Klaassen[1], Dees B. W. Postma[1], Dennis Reidsma[1]
[1]University of Twente

Contact info
For questions you can contact Sascha Bergsma (7545VW Enschede, Acaciaplantsoen 75; +3161097024; s.bergsma-2@student.utwente.nl) or the Ethics Committee of the University of Twente (Drs. Petri de Willigen; UT Building: Zilverling 1051; +31534892085; ethics-comm-ewi@utwente.nl). The Ethics Committee exists of independent experts from the university and are available for questions and complaints surrounding this research.

Research: Virtual Rowing Coach
I hereby declare the following:

- I give consent for my participation during the research period accompanying this graduation project (April-July of 2020) and for the collection and use of anonymous data as described in the information brochure.

- I declare that I am fully informed about the research. The purpose, methods and possible risks (namely: motion sickness) are explained, and I had the possibility of asking questions.

- I understand that I can quit my participation at any moment during or after the test (within 24 hours), without a reason and without any consequences. In this case I can have the gathered data deleted if I wish.

- I understand that if I am between the age 16 to 18, both my parents will have to be informed of my participation in this research.

Recordings will solely be viewed by the concerned researchers and will never be made public or used in demonstrations, presentations, promotions, or media. All research material will be processed and stored according to AVG guidelines. All data will be stored for a maximum of 10 years according to the VSNU guideline.

☐ I give consent for making video recordings for research purposes.

☐ I give consent for the publication of *anonymous* research material collected during my participation in the research.

Date: Location:

Name: Signature participant:

………

The extra copy of this consent form is for you to keep.

B.3 INFORMATION BROCHURE

Technology is starting to play a bigger role in our lives and can help us in many ways to perform better. In sports, technology is already widely used in the form of smart watches, heart-rate sensors, precise movement measurement tools, and of course sport-simulating machines.

At the University of Twente, together with RP3 Rowing Haaksbergen and Human Media Interaction, we are doing research into sports and technology. Currently a virtual reality rowing installation is being developed with the goal of teaching the rowing technique to beginners.

This automatic virtual rowing coach makes use of four motion trackers, three attached to the rowing machine and one mounted onto the chest of the rower. Based on this motion tracking and on the data from the rowing machine, the rower will experience real-time feedback on their technique through a virtual reality headset and optional additional peripheral. It can for example give feedback about hand trajectory or order of legs, back, and arms movement.

The current research, led by the University of Twente, has the goal to design optimal auditory, visual, and vibrotactile feedback for this new sport technology. To do that we will develop this interactive feedback system and test it with our target group. This way we will design, together with you, the future of rowing training!

RP3 DYNAMIC

UNIVERSITY OF TWENTE.

Human Media Interaction.

INFORMATION BROCHURE

PROJECT: VIRTUAL ROWING COACH

(UNSUPERVISED ROWING TECHNIQUE LEARNING USING VIRTUAL REALITY)

This brochure provides information about the research project: *Virtual Rowing Coach*. It will help you to decide whether to participate in the research.

Sascha Bergsma – s.bergsma-2@student.utwente.nl
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dr. Randy Klaassen – r.klaassen@utwente.nl
dr. Dees B. W. Postma - d.b.w.postma@utwente.nl
D. Reidsma - d.reidsma@utwente.nl

Participation
You can participate when aged 16 or older, and it is completely voluntary. When aged between 16-18, both of your parents will have to made aware of your participation. At any moment you can indicate that you want to quit the research, without a reason and without consequences. Consent for participation only has to be given once and is then valid for the rest of the testing period April-July of 2020.

Wat happens exactly during the activities?
A single activity will last approximately 20 minutes. You will be asked to use a rowing ergometer while wearing a virtual reality headset, a chest strap and glove with a motion tracking device, and optional additional peripherals.

The activities are meant for you to understand the basics of the rowing technique and to improve by interpreting the given feedback. Mainly, the effectiveness of feedback is tested. Other research activities include questionnaires and interviews.

Are there any risks?
Please note that there is a known risk of motion sickness when immersed in virtual reality. Not many moving elements will be shown so the risk should be small. In case of physical discomfort, please stop the test by removing the headset and equipment. In that case, if you wish, your data will be deleted. This is possible within 24 hours of the test.

What data will be collected?
Before the test you will be asked to fill in a small survey, in order to gather limited personally identifiable data like age and gender. During the activity, video recordings will be made, motion sensor data will be collected, and questionnaires and interviews will be done.

How is data stored?
The data and video recordings are safely stored and anonymously processed according to AVG guidelines. Research data will be stored for a maximum of 10 years according to the VSNU guideline.

Who has access to the data?
The human observations, questionnaires, interviews and video recordings are solely accessible by people involved in the research. A list of names of people with access is available and can be requested from Sascha Bergsma.

How is the data used?
The data will be analysed primarily for a bachelor thesis assignment, but also for scientific research. It can be published in an openly accessible bachelor thesis (essay.utwente.nl) and in the 'regular' media, where it will be completely anonymized. Data will possibly also be used for future research, with similar guidelines to this research.

Furthermore, the results will be used as inspiration for the future development of sports feedback technologies.

Will my data be made public?
Research material where you are recognizable will never be showed to the public. Not in demonstrations, presentations, promotions, or media. We do want to make a part of the anonymous data public (for example the hand trajectories) for future research by others. Consent for this will be separately asked in the consent form.

Can I have my data deleted?
If you decide at any moment during or after an activity (within 24 hours) that you do not want to participate anymore, all your data from that session will be deleted if you wish. Video recordings of the activity will be shown to you afterwards, so you are aware of what is recorded. If the research materials are anonymized, they are no longer connected to you, so they can also no longer be deleted.

More information and independent advice
Would you like independent advice about participating in this research, or file a complaint? You can then come in contact with the Ethics Committee (Drs. Petri de Willigen; +31534892085; ethics-comm-ewi@utwente.nl). They exist of independent experts from the university and are available for questions and complaints surrounding this research.

For questions you can contact Sascha Bergsma, contact info is on the front side of this brochure.

C Interviews

C.1 Coaches of first-year rowers at D.R.V Euros 11-04-2020

What are common mistakes of beginning rowers on the indoor rowing machine?

Arend Spaans	-not taking the power to the finish with connection between legs and back -incorrect order of recovery starting at back reversal -bending knees to early in the recovery -not using only legs at the catch -not tightening core and back muscles at the catch
Thijs Rakels	-losing tension in body, mostly upperbody, which leads to injuries (lower back) and causes troubles for smoothly delivering force -pulling on the arms -overstretching arms before the catch
Stefan van Haren	-not prepared at the catch -not giving enough pressure at the catch -using back too soon -order of recovery
Leo van Adrichem	-posture (angles of legs, back, arms), however when changing posture you could diminish someone's ability to give force in the drive. -using back too early at catch, however you should not say just to use legs at because a rower also has to tighten their core and back muscles. -finishing too high (pulling arms, tightening shoulders) -not having stretched arms at the catch four main points: -front, legs & core tightened -finish, no weird curve in the handle trajectory (should be straight) -recovery, order of arms, back, legs -achieving the ideal stroke length (good back angle, stretched arms, riding until shins are horizontal)

In what ways do you teach them to improve their technique?

Arend Spaans	Visual -mirror -showing it yourself -videos Auditory -only verbal, make sure that common focus points have a recognizable call Haptic -standing in front of ergometer, holding the handle and letting them feel what it means to strengthen your core and use legs only -pressing on the back with your hand when you want to them to bend their back to a certain angle -pressing arms in the right position (horizontal underarms) Also tell *why* they should do it a certain way, during times when not rowing Exercises -build up, lengthen the stroke starting at the back -pimanov
Thijs Rakels	Visual -doesn't consider himself a good example, doesn't demonstrate much

	-mirror is a bad tool because when turning the head the position is changed a lot and isn't representative Auditory -the back reversal can be accentuated with sound, especially in the boat Haptic -nudge the rower to help fix certain bottlenecks, e.g. a rounded back State the problem, then give advice on how to improve Exercises letting them do a similar exercise, like jumping, and having them feel what the correct technique should be
Stefan van Haren	-there are different types of rowers, so you should learn your rowers and adjust feedback method to what works best for them. -tell rowers to hold a pose, for example half-way on the slide, then tell them how to adjust -explain in extreme detail Visual -videos of rowers -sit next to them, demonstrate technique -use mirror only sometimes, some rowers look in the mirror too often Audio -sounds can be used for synchronizing the back reversal, or the turning of the blade -the sound of the ergometer can be used, however the rower needs to be powerful in order for it to be useful Haptic -move hands to the right height of the handle before the catch -freeze the rower in the 3rd stop, nudge the back to right position, move shoulders down (shoulders need to be relaxed)
Leo van Adrichem	Visual -showing themselves on video -however with beginning rowers, he more often demonstrates the technique, does it a couple of times right, and a couple of times wrong. -mirror is good, but a rower first needs knowledge of what they are doing. Auditory -when making a noise at the catch, it is easier to time than looking or feeling -the noise of ergometer is useful, but in most situations there are many ergometers so you can't hear it good enough. -in the skiff you do everything based on sound Haptic -doesn't touch the rower that much to correct posture, as it introduces a force which isn't usually there -the rower needs to be able to perform the technique themselves, so you shouldn't guide them by limiting movements, as this makes them dependent on the guide. -vibrating feedback could communicate the deceleration of the boat -or the deviation from the optimal trajectory When you indicate a problem, you should always give a solution, otherwise the rower might change something which is already good. Leo also gave me a lot of tips for how I can correct technique in my project using the four motion sensors:

	-look at if the handle is accelerated at a constant rate during the drive -distance from seat to chest and to flywheel can indicate if the back is used too early -distance from handle to seat will indicate that the rower is finishing too high (pulling) or too low (not taking the force to the finish), when at the catch this can also indicate that the back is used too early -the trajectory of the hands is more a result of errors than an error itself, correcting it wouldn't improve much in the long run.

What feedback do you think works best and why?

Arend Spaans	Depends on the rower, there are very different kinds of rowers: -doer: wants to experiment -dreamer: wants to make connections between things -thinker: wants to understand everything thoroughly -decider: wants to just see how it's done and get commands Differential learning, for every focus point try to find both extremes. So for example, try catching very early and very late, and find what works best.
Thijs Rakels	-the rower has to understand what good technique feels like -you have to alternate between feedback methods, otherwise it eventually isn't effective anymore, or they become dependent on it -you always have to have the competition in mind, and train in the same scenarios as it.
Stefan van Haren	The best feedback is stopping the rower and put them in a certain position, to make them know what good technique feels like. Only after knowing what good technique is, you can make them focus on auditory cues.
Leo van Adrichem	For beginning rowers, demonstrate the technique, do it a couple of times right, and a couple of times wrong.

D ROWING STROKE MUSCLE MOVEMENT TIMESTAMPS

Based on Kim Crow from Australia rowing on the RP3 [11]

Time stamps of muscle movements (stroke rate 23) converted to stroke rate 20

Frame	Legs	Back	Arms		Frame	time (s) (converted to SR20)
72	start			Catch	0	0.00
79		start			7	0.27
90			start		18	0.68
93	stop	stop			21	0.80
101			reverse	Finish	29	1.10
109		start			37	1.41
116	start				44	1.67
120			stop		48	1.82
133		stop			61	2.32
151	reverse			Catch	79	3.00

E Ethical Analysis

This chapter provides a detailed analysis of all possible ethical implications of the Virtual Rowing Coach project, following the seven step ethical toolkit for engineering and design practice [45]. This is done in order to (i) better integrate the design practices of this project into the professional setting, (ii) make the ethical implications an explicit part of the project, (iii) regularize ethical practice in order to strengthen the skill of ethical analysis, and (iv) state a clear ethical methodology instead of following personal interpretations of ethics.

This ethical analysis was written as the final assignment for the course Reflection of the graduation semester. Moreover, the ethical analysis of Koen Vogel [2] was used for insights and inspiration.

E.1 Ethical risk sweeping

Ethical risk sweeping is an essential tool for good design and engineering practice, it consists of a broad analysis of any possible ethical risks. Thereby answering the question: “Which design choices could possibly cause significant harm to persons or other entities with a moral status, or cause acute moral controversy?”

Motion sickness

Virtual reality is known to evoke motion sickness. The most important cause of this is the dissociation between feeling and sight and occurs more often when physical activity or fast movements are involved. The presented system requires physical activity, but never displays very fast movements, unless the user decides to. Mainly in the on-water rowing scenario motion sickness should be considered a significant risk as there the hands of the virtual character move over each other as opposed to besides each other, and the user is surrounded by a large moving environment.

Sensory deprivation

When a user is immersed into the Virtual Rowing Coach, many senses are blocked from the outside world. A virtual reality head mounted display on its own already visually presents a whole other world. On top of that, many VR experiences include sound as well, including this project. Also, the haptic sense is distracted because of the rowing movement and of vibrating motors in the glove.

Generally, blocking out all these senses could lead to great physical accidents. But luckily in this case, the user is seated and partially constrained to a single movement, which means that chance is small. However, this chance still does exist and thus is covered in the next section. Other significant risks caused by sensory deprivation could include home invasions, leaving the stove on, or not hearing an important phone call.

Injuries

There is a low but still significant chance of falling of the rowing machine, especially among beginning rowers. Being immersed in virtual reality would only worsen such a situation, as the user will not be able to see what they are falling on to or know exactly at what height the ground is. Luckily, this chance only really exists when rowing at a high tempo, and “sliding off the seat” happens significantly less on the dynamic rowing machine (RP3) because the flywheel is accelerated and the seat stays approximately in place, as opposed to the standard rowing machine where the flywheel is static and the seat is accelerated.

Injuries could also occur because of inaccurate feedback, or because of extensive use of the system. Furthermore, it could make existing injuries worse because of stressing already damaged or sore muscle groups. Finally, the different and inaccurate representation of the user’s body in virtual reality could lead to the decreased ability to sense or control their own body’s movement, which can also cause injuries.

Privacy
When wearing a head-mounted display, the surrounding environment cannot be perceived anymore. This allows bystanders to watch the user, or the virtual reality view on the monitor without them noticing. These bystanders could look perversely at the rowing user for a long period of time, or possibly see technique performance indications on the monitor.

Additionally, sensitive data like height, arms and legs length, sex, and age are stored and linked to technique performance. This could pose a real privacy risk when this data leaks out.

Uncanny valley
In this project, the character representing the user in the virtual environment is not accurate due to motion sensing limitations and shortage of time to create personalized character models. For this project, the limbs of a character model were manually stretched to the size of the average user, which causes a slightly uncanny looking human, and incorrect skeleton behaviour. The fact that limbs are not always at the correct spot and the possibility of clipping objects through the character could definitely cause feelings of uneasiness.

Isolation
Virtual reality can cause a preference of a virtual world over the real one. This would mean an unhealthy isolation from personal issues, relationships, and society in general. This project, with its real-rowing simulation could make users addicted and maybe even make them prefer it over real rowing.

Sweating
Exercising while wearing a head-mounted display and in this case a glove as well, would increase sweating in those areas, especially for individuals that already sweat a lot. As a result, users could feel uneasy and would not want to row for longer periods of time.

Inability to perform target technique
This project presents a universally agreed upon target technique which most beginners should strive towards. However, it does not take into account the limited movements of people of older age, overweight people, or disabled people. The inability to perform the target technique could amplify the awareness of having limited movement and leads to misery because of body comparison.

Overestimation of capabilities
Realistic virtual task environments could make individuals believe that they are able to do the same in the real world. This is especially dangerous in a rowing scenario, as it is extremely common for beginners to fall into the water when attempting to row in a single scull. On top of that, hands movement are very different (cross each other) and rowing will feel different. It is in general quite hard for a complete beginner to row in a single scull, and the individual should thus be carefully guided in the case they want to row on the water.

Coach feels unneeded
When an experienced rower uses the eventual final version of this project, their coach might feel unneeded. This would especially be the case if the system is able to detect technique very detailed and give personally optimized feedback. However, the aim of this project is not to replace a coach entirely, but rather, to give simple feedback to beginning rowers which could be used besides the normal trainings with a coach.

Not fair in competitive world
When this project is able to improve technique even better than a regular coach, it might not be fair in the competitive world of rowing. Namely, a rower would be able to row for a long period of time while continuously receiving very detailed feedback on technique efficiency. Even though some related works are already in use, and more equipment in general allows for better rowing, this risk of unfairness should not be neglected.

E.2 ETHICAL PRE-MORTEMS AND POST-MORTEMS

This second step of the ethical toolkit intends to make designers think about how multiple small individual risks would be able to cause or have caused an ethical disaster. In other words; pre- and post-mortems. Pre-mortems are analysed by thinking creatively about possible scenarios based on the risks found by ethical risk sweeping, while post-mortems are ethical disasters which have already occurred. However, because this project is still a prototype and it has not yet caused any disastrous scenarios, this section will focus solely on pre-mortems.

<u>Gym-goer injury</u>

Imagine this project being placed in a gym, where anyone is able to row on it. One day, a person with minimal virtual reality experience who has never rowed before decides to step onto the machine to try the virtual reality experience out. This person enjoys it and starts working on their technique for a few minutes. At some point they feel like doing a sprint on the machine. The rowing machine is accelerated more and more, and so are the surroundings in the virtual environment. However, these rapid movements cause immense discomfort in the person who is rowing, and they get motion sickness. Additionally, the beginner slides off his seat just as most beginners do when first rowing fast. Consequently, because of dizziness from the motion sickness and the surprise of sliding of the seat, the person falls off the rowing machine. Because the head-mounted display is still on the person’s head, they cannot sense where the ground is and thus badly lands on their wrist, while the feet are still strapped on to the rowing machine.

This unfortunate person was not sufficiently informed about the risks of using the system, and heavily suffered the consequences: a broken wrist and a torn ligament. It would be possible for this person to also sue the gym and have it get shut down. In fact, the gym was also not properly informed off the risk and did not bother to set up a protocol for using the system. In the end, when these small risks are repeatedly neglected, it could cause a great issue for multiple stakeholders.

<u>Beginning rower isolated training</u>

In this scenario, a first year student joins the local rowing club who is a big fan of virtual reality. This person was overjoyed when they found out there is a Virtual Rowing Coach at the club. After a short introduction this person started rowing with the installation on their own for a long training. In the following weeks, this person started to use it increasingly often, and due to the nature of the project, always trained on their own and never really talked to anyone about rowing technique. As a result of always rowing in a real boat in the virtual environment, this person started to believe they were surely able to grab a real boat and go for a row on the water. However, this turned out to be completely foolish as the person almost immediately fell into the cold water, which came as a shocking surprise. This incident did not only cause harm to the rowing individual, but also to the rowing club, as this boat was now damaged.

<u>Olympic rowing team security breach</u>

Not only beginning rowers could suffer from the risks of this project but of course also the more experienced rowers, that is why this last hypothetical scenario was thought of. When this project makes it into its late prototyping stage, the Dutch national rowing association gets interested. Hence, a test version gets shipped in order for the Dutch Olympic team to train with it. This turns out to be a big success and the highly trained rowers learn a lot about technique and team synchronization. So much in fact, that the system was believed to be unfair in the rowing world. However, the prototype did not yet have secure data management. This led to fans of a different team hacking into the online unencrypted database and leaking all this data to the world. All competing teams now had access to this very sensitive information about the Dutch team, which would drastically influence the results of the upcoming Olympic games.

E.3 EXPANDING THE ETHICAL CIRCLE

When working as an individual not much critique will be provided by others, except in this case a supervisor. This makes it easy to fall into a tunnel vision mentality where you are obsessed about accomplishing one goal and are unable to accurately assess alternative perspectives. In order to avoid ethical negligence, and to truly understand the effects of this project, this section will analyse all direct and indirect stakeholders.

At-home beginning rowers

The main direct stakeholders are beginning rowers at home who would like to regularly train their rowing technique. A very similar set of people were actually regularly involved in the design process of this project by means of user testing. This means that their interests and desires are well consulted instead of assumed. Namely, by means of asking about and analysing their behaviour.

Gym-goers

In its current state, this project is not intended to be placed in a gym. However, eventually it could be so well developed that it is user friendly enough to be safely integrated in a gym. When this is the case, the desires of gym-goers should be consulted. It could very well be that these people are not looking for feedback on technique, but rather just want to enjoy some scenery (for example what Koen Vogel created [2]) or a game. Furthermore, this group could have, on average, less experience with virtual reality, thus would have a chance to be startled when using the project.

Beginning rowers at rowing club

This group is also an important stakeholder of this project. Contrary to beginning rowers at home, these people have more connections to other (more-experienced) rowers and coaches which would be able to motivate and supervise the individual. Despite being an important stakeholder, they have not yet explicitly been consulted about for example personal interests, desires, or values. However, the creator of this project has been a beginning rower at a rowing club three years ago and has a fair amount of knowledge of this group, so for the current state of the project, consultation of this stakeholder was not deemed necessary.

Coaches of beginning rowers

This is a more indirect stakeholder, but they can definitely use the project for assisting their trainings, or to objectively evaluate technique. These individuals are not yet consulted but definitely should be, in order to think about possible combinations of human and computer-aided coaching, and to make sure they are never negatively affected by overlapping functionality.

E.4 CASE-BASED ANALYSIS

Here, similar work or research is selected and analysed in order to learn from their doings in this ethical field. This is important as to not 'start from zero' every time an ethical situation is analysed.

Strivr - Virtual reality training solutions

A similar work is Strivr [46], an immersive technology training platform using virtual reality. It trains people how to act in critical situations, at work and in sports. For example, 'handling a robbery', 'handling difficult customers', 'learning about new technology in the store', and concerning the sport scenarios, pattern recognition and skill repetition can be trained in football, basketball, and skiing. In other words, people can train mentally without great physical load. It is an ethically tricky product as it is quite literally putting people in an unsettling experience, in order to learn from it.

The Virtual Rowing Coach project is similar to Strivr as generally, rowing in a real boat on your own can be quite a thrilling experience, and rowing requires a lot of pattern recognition and skill repetition just like the sports experiences in Strivr. However, in this case the person is actually really executing the movement instead of just observing, and the main focus is not to handle a stressful situation better, but to optimize technique.

What can be learned from Strivr is the fact that virtual reality is an effective medium for driving real-world behavioural change, and that putting individuals in a unsettling or thrilling virtual experience for the purpose of learning is something that many people are actually interested in experiencing. However unfortunately, not many details about minimizing ethical risks, or any of their failures could be found.

Technology in sport: Three ideal-typical views and their implications

Loland [47] examines the implications of three normative theories that concern performance in competitive sport and their implications for sport technology. Specifically, any means to realise human interests and goals in sport is considered sport technology. In the introduction, an important recurring ethical dilemma is mentioned; does a disruptive performance increasing technology change the nature of the game, or does it develop it to a higher level of performance? The three presented theories attempt to distinguish between acceptable and problematic technology in sport.

The first two theories are relatively straightforward. The first is the so-called non-theory, which is not entirely a theory of performance but rather of how sport can achieve external goals such as prestige and profit. It is a relativistic theory where any kind of technology is accepted as long as it helps to reach external goals.

In contrast, the second theory which is called the thin theory does not concern anything outside of competition. It simply accepts any technology which is a performance-enhancing one, and to which everyone has access to. The thin theory suggests that performance improvement is the goal that justifies all means.

Finally, the third 'thick' theory attempts to respect, protect, and cultivate the norms and values of sport. Namely, any equally accessible technology that requires efforts and skills, and that does not cause unnecessary harm, is acceptable. This implies that technology where the athlete can enhance performance without effort, is problematic. This way, the thick theory respects Rawls' formulation of the Aristotelian principle:

"Other things equal, human beings enjoy the exercise of their realised capacities, and this enjoyment increases the more the capacity is realised, or the greater its complexity" [48, p. 426]

The Virtual Rowing Coach would be an acceptable technology according to all three theories. It certainly allows for reaching the external goal of prestige and maybe even profit if rowing technique is improved to a high enough level. Furthermore, it is performance-enhancing, and requires athletic effort for this. Nevertheless, it should be ensured that this project is equally accessible, which could prove to be difficult, depending on its price, and potential early access versions. Finally, it is important to remember that all these theories still have flaws, but it is certainly good practice to learn about them in order to have a more well-grounded evaluation about the competitive fairness of this product.

E.5 Remembering the ethical benefits of creative work

While there are of course a lot of things that can go wrong, it should not be forgotten that this work is made in order to do ethical good in the world. That is why in this step, ethical benefits are summarized and explained.

Less injuries among beginners

Having a better rowing technique, means having a lower chance of injury. When installed in many places (rowing clubs, at home, gyms), beginning rowers can quickly learn the basics on their own by using the Virtual Rowing Coach, and thus avoid learning incorrect technique which would have led to injuries.

More opportunities to row

Planning a rowing training can be difficult, due to limited coach availability and possibly teammate availability when there is a desire to row together. Especially when being a beginning level rower without aspiration to be a competitive rower, there are less coaches available. This project allows for more flexible training schedules because it can correct technique without a human and it makes it more fun to train individually. Additionally, the project can even be installed at home.

Better coaching potential

While needing fewer human coaches might sound bad for them, this project could actually increase their coaching potential. A combination of both human and computer-aided coaching would mean that complete beginners would be able to learn the basic technique using the Virtual Rowing Coach, while the human coach has more time to focus on more detailed individual errors of the slightly more experienced rowers. Furthermore, this project provides an objective evaluation of technique which most coaches might not be able to give.

More fun

Learning new things by means of simple colourful feedback can be quite fun, especially when combined with visually pleasing surroundings. This is also shown by this study, as every user considered it an enjoyable experience, even when the surroundings were dull.

More rowers and more healthy people

When rowing training gets more fun, there will be more people wanting to try it out, which will lead to a larger influx of members at rowing clubs. Rowers would also want to row more often because of the rewarding experience it provides, which will make more people sportive and healthy.

E.6 Think about the terrible people

When a product is marketed to a great number of people, there will always be those who wish to use it with ill intentions. To prepare for the worst, these immoral unintended uses should therefore also be addressed, as well as ways to avoid or combat them.

Admissions

The evaluation data that this project creates when a user rows on it, could easily be used as criteria for admissions to rowing clubs, rowing teams, gyms, or even to colleges. One way to avoid this would be to remove any results presented after rowing, which would however be a shame as terminal feedback is extremely helpful for improving technique. Another way is to present the feedback in a simpler form, which would make it harder to compare rowers, but might decrease the effectiveness of feedback. Finally, it would be possible to share the results only with the specific individual, for example via email.

Hackers

When it comes to hackers, the way the data is presented is not relevant, as it will always be possible to breach into the system and gather it. Sensitive personal information could be stolen, in order to sell or leak it, or to blackmail the person. Additionally, the functionality of the project could be changed, for example to display all technique data in real time in order to make it useful for admissions, or to make a Virtual Rowing Coach at another club give inaccurate results. To combat this, a cyber security team should be involved.

Theft

The virtual reality equipment that this project uses is quite expensive, which increases the incentive to steal it. When placed in a gym or rowing club, it would not be hard to steal one or more motion sensors, and when it is installed in its own room, someone would even be able to take all virtual reality equipment with them. To avoid this, all equipment should be connected with metal cables, or put under camera surveillance.

Reckless usage

Some people might be so excited to use virtual reality, that they start to row on the machine without any introduction. Other people might also want to show off how strong they are by immediately rowing very hard on the machine without good technique. Both of these scenarios would be detrimental to the project and to the rowing individual. The project could be damaged, but that depends on how sturdy it eventually becomes. Additionally, the individual might not be expecting the experience it will provide, not be aware of possible motion sickness, injure themselves, or fall off the seat. This could be solved with a supervisor present near the project, to give instructions in case anyone would like to try it out.

E.7 Closing the loop: ethical feedback and iteration

It is important to realise that reflection on ethical implications is not a one-time task. Ethics is relative to the particular social context it concerns, which will always be changing [45]. Even technology can change social contexts, so much so that at some point the technology itself could be viewed as unethical. Thus, regularly repeating ethical practice will make sure that the product stays a success for a long time.

In the case this project is continued outside the scope of a bachelor assignment into a real product, regular ethical practice should be integrated as an explicit part of the regular workflow. In addition, the important stakeholders should structurally be consulted and empathized with, in order to avoid generating manufactured desires and to learn about the possible ethical effects upon them.

F SCRIPTS

F.1 TRAJECTORY AND VELOCITY FEEDBACK

F.1.1 Calculate deviation for trajectory and velocity

```
using UnityEngine;

public class CalculateDeviationTV : MonoBehaviour
{
    /// <summary>
    /// Calculates all deviations used for trajectory, velocity, and
combined feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    [SerializeField] public Transform handle;
    [SerializeField] public GameObject ballMaster;
    [SerializeField] private Transform traj3DDrive;

    [HideInInspector] public float verDeviationTraj;
    [HideInInspector] public float verDeviationBall;
    [HideInInspector] public float horDeviationBall;
    [HideInInspector] public Vector3 targetTrajPos;
    [HideInInspector] public float VerDeviationAmplifier = 3; // Vertical
deviation bounds are more quickly reached because there is less vertical
movement than horizontal

    [SerializeField] private Transform skiffTrajRaycastPoint;
    [SerializeField] private Transform skiffBallMaster;
    [SerializeField] private Transform skiffOarHandlePoint;
    [HideInInspector] public float verDeviationSkiffTraj;
    [HideInInspector] public float verDeviationSkiffBall;
    [HideInInspector] public float horDeviationSkiffBall;
    [HideInInspector] public Vector3 targetSkiffTrajPos;
    void Update()
    {
        // Calculate vertical deviation from trajectory
        if (StrokeController.strokeState ==
StrokeController.StrokeState.Drive)
        {
            // Drive = difference in y coordinates
            targetTrajPos = new Vector3(0, traj3DDrive.position.y,
handle.position.z); // used in auditory feedback
            verDeviationTraj = handle.position.y - targetTrajPos.y; // used
in haptic feedback

            targetSkiffTrajPos = new
Vector3(skiffTrajRaycastPoint.position.x,0.662f,
skiffTrajRaycastPoint.position.z); // target pos of oar at the part where
the trajectory image is
            verDeviationSkiffTraj = skiffTrajRaycastPoint.position.y -
0.662f; // y value of HandlePos when the oar is at top part of the
trajectory
        }
        else if (StrokeController.strokeState ==
StrokeController.StrokeState.Recovery)
```

```
        {
            // Recovery = raycast onto special without-gaps recovery model
            RaycastHit hit;
            if (Physics.Raycast(handle.transform.position, Vector3.down,
out hit) ||
                Physics.Raycast(handle.transform.position, Vector3.up, out
hit))
            {
                //Debug.DrawRay(handle.transform.position, Vector3.down *
hit.distance, Color.red);

                targetTrajPos = hit.point; // for (not implemented) target
ball during only traj training
                verDeviationTraj = handle.position.y - targetTrajPos.y; //
used in haptic feedback
            }

            RaycastHit hitSkiff;
            if (Physics.Raycast(skiffTrajRaycastPoint.position,
Vector3.down, out hitSkiff) ||
                Physics.Raycast(skiffTrajRaycastPoint.position, Vector3.up,
out hitSkiff))
            {
                //Debug.DrawRay(skiffTrajRaycastPoint.position,
Vector3.down * hitSkiff.distance, Color.red);

                targetSkiffTrajPos = hitSkiff.point;
                verDeviationSkiffTraj = skiffTrajRaycastPoint.position.y -
targetSkiffTrajPos.y;
            }
        }

        horDeviationBall = ballMaster.transform.position.z -
handle.position.z; // used in audio feedback
        verDeviationBall = ballMaster.transform.position.y -
handle.position.y; // used in visual together with horizontal to calculate
total deviation

        horDeviationSkiffBall = skiffBallMaster.position.z -
skiffOarHandlePoint.position.z;
        verDeviationSkiffBall = skiffBallMaster.position.y -
skiffOarHandlePoint.position.y;
    }
}
```

F.1.2 Visual trajectory and velocity

```
using System;
using UnityEngine;
using UnityEngine.UI;

namespace VRC
{
    /// <summary>
    /// Displays visual trajectory, velocity, and combined feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class VisualTV : MonoBehaviour
    {
```

```
        [Header("Training options")]
        [SerializeField] private bool trajectoryTraining;
        [SerializeField] private bool velocityTraining;

        public enum RP3DisplayType {Off, Side, Immersive, HeadUp, SideView}

        [Header("Display options")]
        [SerializeField] public RP3DisplayType RP3Display;
        [SerializeField] private bool skiffDisplaysActive; // All skiff
trainings only have one display option (the best ones)
        [SerializeField] private bool skiffSideViewActive;

        [Header("References")]
        [SerializeField] private CalculateDeviationTV calcDev;
        [SerializeField] private Material ballMat;
        [SerializeField] private GameObject trajectory3D;
        [SerializeField] private Material traj3DMat;
        private GameObject traj3DDrive;
        private GameObject traj3DRecovery;
        [SerializeField] private GameObject hudImage;
        [SerializeField] public GameObject[] velocityBounds;
        [SerializeField] private TrailRenderer[] velTargetTrails;
        [SerializeField] private TrailRenderer[] velCurrentTrails;
        [SerializeField] private MeshRenderer[] ballMeshes;
        [SerializeField] private RawImage[] trajectoryImages;
        [SerializeField] private TrailRenderer[] trajectoryTrails;
        [SerializeField] private Image skiffTrajectoryImage;
        [SerializeField] private TrailRenderer_Local
skiffTrajTargetLocalTrail;
        [SerializeField] public RawImage[] skiffVelBounds;
        [SerializeField] private TrailRenderer skiffTargetTrail;
        [SerializeField] private TrailRenderer skiffCurrentTrail;

        [SerializeField] private GameObject[] RP3DisplayOptions;
        [SerializeField] private GameObject[] skiffDisplayOptions;

        [SerializeField] private GameObject skiffSView;
        [SerializeField] private GameObject[] skiffSViewVelBounds;
        [SerializeField] private MeshRenderer skiffSViewBallMesh;
        [SerializeField] private RawImage skiffSViewTrajImage;
        [SerializeField] private TrailRenderer_Local skiffSViewTrajTrail;
        [SerializeField] private TrailRenderer_Local
skiffSViewVelCurrentTrail;
        [SerializeField] private TrailRenderer skiffSViewVelTargetTrail;
        [SerializeField] private Material skiffSViewBallMat;

        private float deviation;
        private float deviationRatio; // 0.0 = minimal deviation, 1.0
maximum deviation
        private const float MinDeviation = 0.10f; // Significant minimum
deviation from ball, from this deviation the feedback will start to be
displayed
        private const float MaxDeviation = 0.30f; // Deviation at which the
feedback is fully displayed
        private float deviationSkiff;
        private float deviationRatioSkiff;

        void Start()
        {
            traj3DDrive = trajectory3D.transform.GetChild(0).gameObject;
            traj3DRecovery = trajectory3D.transform.GetChild(1).gameObject;
```

```
        }

        void Update()
        {
            HandleDisplayOptions();
            HandleTrainingOptions();

            // Get deviation
            if (trajectoryTraining && !velocityTraining)
            {
                deviation = Math.Abs(calcDev.verDeviationTraj *
calcDev.VerDeviationAmplifier);
                deviationSkiff = Math.Abs(calcDev.verDeviationSkiffTraj *
calcDev.VerDeviationAmplifier);
            }
            else if (velocityTraining && !trajectoryTraining)
            {
                deviation = Math.Abs(calcDev.horDeviationBall);
                deviationSkiff = Math.Abs(calcDev.horDeviationSkiffBall);
            }
            else if (trajectoryTraining && velocityTraining)
            {
                deviation = Vector2.Distance(new Vector2(0, 0),
                    new Vector2(calcDev.horDeviationBall,
calcDev.verDeviationBall * calcDev.VerDeviationAmplifier));

                deviationSkiff = Vector2.Distance(new Vector2(0, 0),
                    new Vector2(calcDev.horDeviationSkiffBall,
calcDev.verDeviationSkiffBall * calcDev.VerDeviationAmplifier));
            }

            // Normalize deviation (map into range 0-1 where 1 is
MaxDeviation)
            deviationRatio = (deviation - MinDeviation) / (MaxDeviation -
MinDeviation);
            deviationRatioSkiff = (deviationSkiff - MinDeviation) /
(MaxDeviation - MinDeviation);

            // Make sure feedback never totally disappears
            if (deviationRatio < 0.08f) deviationRatio = 0.08f;
            if (deviationRatioSkiff < 0.08f) deviationRatioSkiff = 0.08f;

            // Put it onto transparency of feedback
            foreach (var image in trajectoryImages) image.color = new
Color(image.color.r, image.color.g, image.color.b, deviationRatio);
            ballMat.color = new Color(ballMat.color.r, ballMat.color.g,
ballMat.color.b, deviationRatio);
            traj3DMat.color = new Color(traj3DMat.color.r,
traj3DMat.color.g, traj3DMat.color.b, deviationRatio);
            foreach (var trail in velTargetTrails) trail.startColor = new
Color(trail.startColor.r, trail.startColor.g, trail.startColor.b,
deviationRatio);

            if (skiffDisplaysActive)
            {
                skiffTrajectoryImage.color = new
Color(skiffTrajectoryImage.color.r, skiffTrajectoryImage.color.g,
skiffTrajectoryImage.color.b, deviationRatioSkiff);
                skiffTargetTrail.startColor = new
Color(skiffTargetTrail.startColor.r, skiffTargetTrail.startColor.g,
skiffTargetTrail.startColor.b, deviationRatioSkiff);
```

```
                skiffCurrentTrail.startColor = new
Color(skiffCurrentTrail.startColor.r, skiffCurrentTrail.startColor.g,
skiffCurrentTrail.startColor.b, deviationRatioSkiff);
                foreach (var bound in skiffVelBounds) bound.color = new
Color(bound.color.r, bound.color.g, bound.color.b, deviationRatioSkiff);
            }

            if (skiffSideViewActive)
            {
                skiffSViewTrajImage.color = new
Color(skiffSViewTrajImage.color.r, skiffSViewTrajImage.color.g,
skiffSViewTrajImage.color.b, deviationRatioSkiff);
                skiffSViewVelTargetTrail.startColor = new
Color(skiffSViewVelTargetTrail.startColor.r,
skiffSViewVelTargetTrail.startColor.g,
skiffSViewVelTargetTrail.startColor.b, deviationRatioSkiff);
                skiffSViewBallMat.color = new
Color(skiffSViewBallMat.color.r, skiffSViewBallMat.color.g,
skiffSViewBallMat.color.b, deviationRatioSkiff);
            }

            // Only at high deviation, show the trails
            if (deviationRatio >= 1.5 * MaxDeviation)
            {
                foreach (var trail in trajectoryTrails) trail.emitting =
true;
                if (!trajectoryTraining && velocityTraining) foreach (var
trail in velCurrentTrails) trail.emitting = true;
            }
            else
            {
                foreach (var trail in trajectoryTrails) trail.emitting =
false;
                foreach (var trail in velCurrentTrails) trail.emitting =
false;
            }

            if (deviationRatioSkiff >= 1.5 * MaxDeviation)
            {
                // Enable local trail renderer scripts
                if (trajectoryTraining && !velocityTraining)
                {
                    if (skiffDisplaysActive)
skiffTrajTargetLocalTrail.enabled = true;
                    if (skiffSideViewActive) skiffSViewTrajTrail.enabled =
true;
                }

                if (velocityTraining && !trajectoryTraining)
                {
                    if (skiffDisplaysActive) skiffCurrentTrail.emitting =
true;
                    if (skiffSideViewActive)
skiffSViewVelCurrentTrail.enabled = true;
                }

                if (trajectoryTraining && velocityTraining)
                {
                    if (skiffSideViewActive) skiffSViewTrajTrail.enabled =
true;
                }
```

```
            }
            else
            {
                skiffTrajTargetLocalTrail.enabled = false;
                skiffCurrentTrail.emitting = false;

                skiffSViewTrajTrail.enabled = false;
                skiffSViewVelCurrentTrail.enabled = false;
            }
        }

        void HandleDisplayOptions()
        {
            if (RP3Display == RP3DisplayType.Side)
RP3DisplayOptions[0].SetActive(true);
            else RP3DisplayOptions[0].SetActive(false);
            if (RP3Display == RP3DisplayType.Immersive)
RP3DisplayOptions[1].SetActive(true);
            else RP3DisplayOptions[1].SetActive(false);
            if (RP3Display == RP3DisplayType.HeadUp)
RP3DisplayOptions[2].SetActive(true);
            else RP3DisplayOptions[2].SetActive(false);

            // Side view display is handled in other script

            if (skiffDisplaysActive)
            {
                if (trajectoryTraining && !velocityTraining)
skiffDisplayOptions[0].SetActive(true);
                else skiffDisplayOptions[0].SetActive(false);
                if (velocityTraining && !trajectoryTraining)
skiffDisplayOptions[1].SetActive(true);
                else skiffDisplayOptions[1].SetActive(false);

                //foreach (var obj in skiffDisplayOptions)
obj.SetActive(true);
            }
            else foreach (var obj in skiffDisplayOptions)
obj.SetActive(false);

            //if (skiffSideViewActive) skiffSView.SetActive(true);
            //else skiffSView.SetActive(false);
        }

        void HandleTrainingOptions()
        {
            hudImage.SetActive(true);

            if (trajectoryTraining)
            {
                if (!skiffDisplaysActive && !skiffSideViewActive)
                {
                    // Enable trajectories and trajectory trails
                    foreach (var image in trajectoryImages) image.enabled =
true;

                    trajectory3D.SetActive(true);
                    foreach (var trail in trajectoryTrails) trail.enabled =
true;
                }
                else
                {
```

```
                    foreach (var image in trajectoryImages) image.enabled =
false;
                    trajectory3D.SetActive(false);
                    foreach (var trail in trajectoryTrails) trail.enabled =
false;

                    if (skiffDisplaysActive)
                    {
                        skiffTrajectoryImage.enabled = true;
                        foreach (var bound in skiffVelBounds) bound.enabled
= false;
                        skiffTargetTrail.enabled = false;
                        skiffCurrentTrail.enabled = false;
                    }

                    if (skiffSideViewActive)
                    {
                        skiffSViewTrajImage.enabled = true;
                        foreach (var bound in skiffSViewVelBounds)
bound.SetActive(false);
                        skiffSViewVelTargetTrail.enabled = false;

                        skiffSViewVelCurrentTrail.Reset();
                    }
                }

                // Disable only-velocity bounds and trails
                foreach (var obj in velocityBounds) obj.SetActive(false);
                foreach (var trail in velTargetTrails) trail.enabled =
false;
                foreach (var trail in velCurrentTrails) trail.enabled =
false;

                if (velocityTraining)
                {
                    // TRAJECTORY & VELOCITY TRAINING

                    // Enable balls and trajTrails
                    if (!skiffDisplaysActive && !skiffSideViewActive)
                    {
                        foreach (var ballMesh in ballMeshes)
ballMesh.enabled = true;
                        foreach (var trail in trajectoryTrails)
trail.enabled = true;
                    }
                    else
                    {
                        foreach (var ballMesh in ballMeshes)
ballMesh.enabled = false;
                        foreach (var trail in trajectoryTrails)
trail.enabled = false;

                        if (skiffDisplaysActive)
skiffTrajectoryImage.enabled = false; // In skiff, there is no T&V training

                        if (skiffSideViewActive)
                        {
                            skiffSViewTrajImage.enabled = true;
                            skiffSViewBallMesh.enabled = true;
                        }
                    }
```

```
                }
                else
                {
                    // ONLY TRAJECTORY TRAINING

                    // Disable balls
                    foreach (var ballMesh in ballMeshes) ballMesh.enabled =
false;

                    skiffSViewBallMesh.enabled = false;
                }
            }
            else
            {
                // Disable trajectories, balls and trajTrails
                foreach (var image in trajectoryImages) image.enabled =
false;
                trajectory3D.SetActive(false);
                foreach (var ballMesh in ballMeshes) ballMesh.enabled =
false;
                foreach (var trail in trajectoryTrails) trail.enabled =
false;

                if (skiffDisplaysActive) skiffTrajectoryImage.enabled =
false;

                if (skiffSideViewActive)
                {
                    skiffSViewBallMesh.enabled = false;
                    skiffSViewTrajImage.enabled = false;
                }

                if (velocityTraining)
                {
                    // ONLY VELOCITY TRAINING

                    // Enable only-velocity bounds and trails
                    if (!skiffDisplaysActive && !skiffSideViewActive)
                    {
                        foreach (var obj in velocityBounds)
obj.SetActive(true);
                        foreach (var trail in velTargetTrails)
trail.enabled = true;
                        foreach (var trail in velCurrentTrails)
trail.enabled = true;
                    }
                    else
                    {
                        foreach (var obj in velocityBounds)
obj.SetActive(false);
                        foreach (var trail in velTargetTrails)
trail.enabled = false;
                        foreach (var trail in velCurrentTrails)
trail.enabled = false;

                        if (skiffDisplaysActive)
                        {
                            foreach (var bound in skiffVelBounds)
bound.enabled = true;
                            skiffTargetTrail.enabled = true;
                            skiffCurrentTrail.enabled = true;
```

```
                        }

                        if (skiffSideViewActive)
                        {
                            foreach (var bound in skiffSViewVelBounds)
bound.SetActive(true);
                            skiffSViewVelTargetTrail.enabled = true;

                            skiffSViewTrajTrail.Reset();
                        }
                    }
                }
                else
                {
                    // NOTHING

                    // Disable only-velocity bounds and trails
                    foreach (var obj in velocityBounds)
obj.SetActive(false);
                    foreach (var trail in velTargetTrails) trail.enabled =
false;
                    foreach (var trail in velCurrentTrails) trail.enabled =
false;

                    foreach (var bound in skiffVelBounds) bound.enabled =
false;
                    skiffTargetTrail.enabled = false;
                    skiffCurrentTrail.enabled = false;

                    foreach (var bound in skiffSViewVelBounds)
bound.SetActive(false);
                    skiffSViewVelTargetTrail.enabled = false;
                    skiffSViewVelCurrentTrail.Reset();
                    skiffSViewTrajTrail.Reset();

                    hudImage.SetActive(false);
                }
            }

            // For the immersive display, show drive trajectory during the
drive and likewise for recovery
            if (StrokeController.strokeState ==
StrokeController.StrokeState.Drive)
            {
                traj3DDrive.SetActive(true);
                traj3DRecovery.SetActive(false);
            }
            else if (StrokeController.strokeState ==
StrokeController.StrokeState.Recovery)
            {
                traj3DRecovery.SetActive(true);
                traj3DDrive.SetActive(false);
            }

            if (!skiffDisplaysActive)
            {
                skiffTrajectoryImage.enabled = false;
                foreach (var bound in skiffVelBounds) bound.enabled =
false;
                skiffTargetTrail.enabled = false;
                skiffCurrentTrail.enabled = false;
```

```
            }

            if (!skiffSideViewActive)
            {
                skiffSViewBallMesh.enabled = false;
                skiffSViewTrajImage.enabled = false;
                skiffSViewTrajTrail.enabled = false;
                foreach (var bound in skiffSViewVelBounds)
bound.SetActive(false);
                skiffSViewVelTargetTrail.enabled = false;
                skiffSViewVelCurrentTrail.enabled = false;
            }
        }

        void OnApplicationQuit()
        {
            ballMat.color = new Color(ballMat.color.r, ballMat.color.g,
ballMat.color.b, 1);
            traj3DMat.color = new Color(traj3DMat.color.r,
traj3DMat.color.g, traj3DMat.color.b, 1);
        }
    }
}
```

F.1.3 Auditory trajectory and velocity

```
using System;
using FMODUnity;
using UnityEngine;

namespace VRC
{
    /// <summary>
    /// Plays auditory posture feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class AuditoryPosture : MonoBehaviour
    {
        private CalculateDeviationPosture calcDevP;

        private enum SoundType {LeftRight, Spatial}

        [Header("Options")]
        [SerializeField] private bool playing;
        [SerializeField] private SoundType sound;

        [Header("References")]
        [SerializeField] private StudioEventEmitter leftEmitter;
        [SerializeField] private StudioEventEmitter rightEmitter;
        [SerializeField] private StudioEventEmitter spatialEmitter;

        private int targetNote;
        private int ownNote;

        void Start()
        {
            calcDevP = GetComponent<CalculateDeviationPosture>();
        }
```

```
        void Update()
        {
            if (playing)
            {
                if (sound == SoundType.LeftRight)
                {
                    leftEmitter.enabled = true;
                    rightEmitter.enabled = true;
                    spatialEmitter.enabled = false;

                    targetNote = (int) Map(calcDevP.targetBackRot, -28, 24,
-4, 4);
                    ownNote = (int) Map(calcDevP.ownBackRot, -28, 24, -4,
4);

                    leftEmitter.EventInstance.setParameterByName("pitch",
targetNote);
                    rightEmitter.EventInstance.setParameterByName("pitch",
ownNote);
                }
                else if (sound == SoundType.Spatial)
                {
                    leftEmitter.enabled = false;
                    rightEmitter.enabled = false;
                    spatialEmitter.enabled = true;

                    spatialEmitter.transform.position =
                        new Vector3(0, 0, calcDevP.backAngleDeviation /
10); // Emitter which is behind or in front

spatialEmitter.EventInstance.setParameterByName("position",
calcDevP.backAngleDeviation / 20);
                }

                float volume = Map(Math.Abs(calcDevP.backAngleDeviation),
5, 30, 0.40f, 1.00f);
                leftEmitter.EventInstance.setParameterByName("volume",
volume);
                rightEmitter.EventInstance.setParameterByName("volume",
volume);
                spatialEmitter.EventInstance.setParameterByName("volume",
volume);
            }
            else
            {
                leftEmitter.enabled = false;
                rightEmitter.enabled = false;
                spatialEmitter.enabled = false;
            }
        }

        private float Map(float value, float low1, float high1, float low2,
float high2)
        {
            // same as map() function in processing
            return low2 + (value - low1) * (high2 - low2) / (high1 - low1);
        }
    }
}
```

F.1.4 Haptic trajectory and velocity

```
using System;
using System.Collections;
using UnityEngine;

namespace VRC
{
    /// <summary>
    /// Controls haptic trajectory and velocity feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class HapticTV : MonoBehaviour
    {
        private enum VibrationType {Off, PushingT, PullingT, RhythmicV,
PushingV, PullingV}
        private enum RowingType {RP3, Skiff}

        [Header("Options")]
        [SerializeField] private VibrationType vibration;
        [SerializeField] private RowingType rowing;

        [Header("References")]
        [SerializeField] private CalculateDeviationTV calcDev;

        SerialPortUtility.SerialPortUtilityPro port;
        private int intensityValue;
        private int rhythmValue;

        private bool driveInitSent;
        private bool recoveryInitSent;

        void Start()
        {
            port = GetComponent<SerialPortUtility.SerialPortUtilityPro>();
            StartCoroutine(SendSerial());
        }

        void Update()
        {
            if (vibration == VibrationType.PushingT || vibration ==
VibrationType.PullingT)
            {
                if (rowing == RowingType.RP3) intensityValue = (int)
Map(calcDev.verDeviationTraj, 0, 0.1f, 0, 9);
                else intensityValue = (int)
Map(calcDev.verDeviationSkiffTraj, 0, 0.07f, 0, 9);

                if (intensityValue < -9) intensityValue = -9;
                if (intensityValue > 9) intensityValue = 9;
            }
            else if (vibration == VibrationType.RhythmicV)
            {
                //Debug.Log(calcDev.horDeviationBall);

                if (StrokeController.strokeState ==
StrokeController.StrokeState.Drive)
                {
                    // If slower than ball, your tempo is slower
```

```
                    // In drive, slower means in front of ball (negative
deviation)

                    // When done correctly, value is 5 which means 240 BPM
                    if (rowing == RowingType.RP3) rhythmValue = (int)
Map(calcDev.horDeviationBall, -0.1f, 0.1f, 4, 6);
                    else rhythmValue = (int)
Map(calcDev.horDeviationSkiffBall, -0.1f, 0.1f, 4, 6);

                    if (!driveInitSent)
                    {
                        // Clear, Rhythm Bottom 5, Rhythm Top 5
                        port.Write("crb5rt5");
                        driveInitSent = true;
                        recoveryInitSent = false;
                    }
                }
                else if (StrokeController.strokeState ==
StrokeController.StrokeState.Recovery)
                {
                    // In recovery, slower means behind ball (positive
deviation)

                    // When done correctly, value is 2 which means 120 BPM
                    if (rowing == RowingType.RP3) rhythmValue = (int)
Map(calcDev.horDeviationBall, 0.1f, -0.1f, 1, 3);
                    else rhythmValue = (int)
Map(calcDev.horDeviationSkiffBall, 0.1f, -0.1f, 1, 3);

                    if (!recoveryInitSent)
                    {
                        // Clear, Rhythm Bottom 2, Rhythm Top 2
                        port.Write("crb2rt2");
                        recoveryInitSent = true;
                        driveInitSent = false;
                    }
                }

                if (rhythmValue < 1) rhythmValue = 1;
                if (rhythmValue > 7) rhythmValue = 7;
            }
            else if (vibration == VibrationType.PushingV || vibration ==
VibrationType.PullingV)
            {
                if (rowing == RowingType.RP3) intensityValue = (int)
Map(calcDev.horDeviationBall, 0, 0.2f, 0, 9);
                else intensityValue = (int)
Map(calcDev.horDeviationSkiffBall, 0, 0.2f, 0, 9);

                if (intensityValue < -9) intensityValue = -9;
                if (intensityValue > 9) intensityValue = 9;
            }
            else
            {
                intensityValue = 0;
            }
        }

        public IEnumerator SendSerial()
        {
            while(true)
```

```
            {
                if (vibration == VibrationType.PushingT)
                {
                    if (intensityValue < 0) port.Write("it0ib" +
Math.Abs(intensityValue));
                    else if (intensityValue >= 0) port.Write("ib0it" +
intensityValue);
                }
                else if (vibration == VibrationType.PullingT)
                {
                    if (intensityValue < 0) port.Write("ib0it" +
Math.Abs(intensityValue));
                    else if (intensityValue >= 0) port.Write("it0ib" +
intensityValue);
                }
                else if (vibration == VibrationType.RhythmicV)
                {
                    if (StrokeController.strokeState !=
StrokeController.StrokeState.Idle)
                    {
                        Debug.Log(rhythmValue);
                        // Change top motor rhythm
                        port.Write("rt" + rhythmValue);
                    }
                }
                else if (vibration == VibrationType.PushingV)
                {
                    if (intensityValue < 0) port.Write("it0ib" +
Math.Abs(intensityValue));
                    else if (intensityValue >= 0) port.Write("ib0it" +
intensityValue);
                }
                else if (vibration == VibrationType.PullingV)
                {
                    if (intensityValue < 0) port.Write("ib0it" +
Math.Abs(intensityValue));
                    else if (intensityValue >= 0) port.Write("it0ib" +
intensityValue);
                }

                yield return new WaitForSeconds(0.1f);

                if (vibration == VibrationType.Off)
                {
                    // Clear variables and turn motors off
                    port.Write("c");
                    while (vibration == VibrationType.Off)
                    {
                        // Paused
                        yield return new WaitForSeconds(0.1f);
                    }
                }
            }
        }

        void OnApplicationQuit()
        {
            // Clear
            port.Write("c");
        }
```

```
        private float Map(float value, float low1, float high1, float low2,
float high2)
        {
            // same as map() function in processing
            return low2 + (value - low1) * (high2 - low2) / (high1 - low1);
        }
    }
}
```

F.1.5 Haptic Arduino code

```
#include "BluetoothSerial.h"
#include "WiFi.h"

// Vibrating motor pins
const int vib1 = 22;
const int vib2 = 23;

// PWM properties
const int freq = 5000;
const int vib1Channel = 1; // bottom vibration motor
const int vib2Channel = 2; // top vibration motor
const int resolution = 8;

// Vibration state control
enum vibrationState {intensityState, rhythmicState};
vibrationState vibState = intensityState;

// Intensity vibration variables
int vib1Intensity = 0;
int vib2Intensity = 0;

// Rhythmic vibration variables
bool vib1Vibrating = false; // remembers if the motor is vibrating or not
bool vib2Vibrating = false;
int vib1BPM = 0; // tempo
int vib2BPM = 0;
float minute = 60000;
int vib1TimeAtLastBeat = 0; // keeps track of time passed at the time of
the previous beat
int vib2TimeAtLastBeat = 0;

BluetoothSerial SerialBT;

#if !defined(CONFIG_BT_ENABLED) || !defined(CONFIG_BLUEDROID_ENABLED)
#error Bluetooth is not enabled! Please run `make menuconfig` to enable it
#endif

void setup() {
  setCpuFrequencyMhz(80);
  // Save energy by turning WiFi off
  WiFi.disconnect(true);
  WiFi.mode(WIFI_OFF);

  pinMode(2, OUTPUT);
  pinMode(vib1, OUTPUT);
  pinMode(vib2, OUTPUT);

  // Set up PWM control for both motors
  ledcSetup(vib1Channel, freq, resolution);
  ledcSetup(vib2Channel, freq, resolution);
  ledcAttachPin(vib1, vib1Channel);
```

```
  ledcAttachPin(vib2, vib2Channel);

  Serial.begin(115200);
  SerialBT.begin("ESP32_Sascha"); //Bluetooth device name
  Serial.println("The device started, now you can pair it with
bluetooth!");
}

void loop() {

  if (vibState == intensityState) {
    ledcWrite(vib1Channel, vib1Intensity);
    ledcWrite(vib2Channel, vib2Intensity);
  }
  else if (vibState == rhythmicState) {
    // Handle rhythmic vibration for vib1 (bottom motor)
    if (vib1BPM != 0) {
      if (millis() - vib1TimeAtLastBeat > minute / (vib1BPM * 2)) {

        if (!vib1Vibrating) ledcWrite(vib1Channel, 255 /*0.31 * vib1BPM +
115 + 10*/);
        else if (vib1Vibrating) ledcWrite(vib1Channel, 0);
        vib1Vibrating = !vib1Vibrating;

        vib1TimeAtLastBeat = millis();
      }
    } else {
      ledcWrite(vib1Channel, 0);
      vib1Vibrating = false;
    }
    // Handle rhythmic vibration for vib2 (top motor)
    if (vib2BPM != 0) {
      if (millis() - vib2TimeAtLastBeat > minute / (vib2BPM * 2)) {

        if (!vib2Vibrating) ledcWrite(vib2Channel, 255 /*0.31 * vib1BPM +
115*/);
        else if (vib2Vibrating) ledcWrite(vib2Channel, 0);
        vib2Vibrating = !vib2Vibrating;

        vib2TimeAtLastBeat = millis();
      }
    } else {
      ledcWrite(vib2Channel, 0);
      vib2Vibrating = false;
    }
  }

  // Read bluetooth serial
  while (SerialBT.available()) {
    // Orders come in as:
    // ib1, ib2, ... , ib9 = intensity for bottom motor
    // it1, it2, ... , it9 = intensity for top motor
    // rb1, rb2, ... , rb9 = rhythm for bottom motor
    // rt1, rt2, ... , rt9 = rhythm for top motor
    // c                   = clear all variables / turn motors off

    char inOrder = SerialBT.read(); // i = intensity, r = rhythm
    char inMotor = 0;

    if (inOrder == 'i') {
      inMotor = SerialBT.read(); // b = bottom, t = top
```

```
        // Change state
        vibState = intensityState;
        // Reset other state
        vib1BPM = 0;
        vib2BPM = 0;

        char inChar = SerialBT.read();
        byte inDigit = 0;
        int intensity = 0;

        inDigit = inChar - '0';
        if (inDigit < 10) { // Avoid serial communication errors

          // Intensity can be 0, or between 51 and 255;
          intensity = (inDigit + 1) * 25.5;
          if (inDigit == 0) intensity = 0;

          if (inMotor == 'b') vib1Intensity = intensity;
          else if (inMotor == 't') vib2Intensity = intensity;

          Serial.println(intensity);
        }
      }
      else if (inOrder == 'r') {
        inMotor = SerialBT.read(); // b = bottom, t = top

        // Change state
        vibState = rhythmicState;
        // Reset other state
        vib1Intensity = 0;
        vib2Intensity = 0;

        char inChar = SerialBT.read();
        byte inDigit = 0;
        int bpm = 0;

        inDigit = inChar - '0';
        if (inDigit < 10) { // Avoid serial communication errors

          // inDigit value to BPM:
          // 0 = 0 BPM, 1 = 40 BPM, 2 = 60 BPM, 5 = 120 BPM, 9 = 200 BPM
          // This method makes it possible to assign 120 BPM and 60 BPM
easily,
          // and to reset it using the value 0
          bpm = (inDigit + 1) * 20;
          if (inDigit == 0) bpm = 0;

          if (inMotor == 'b') vib1BPM = bpm;
          else if (inMotor == 't') vib2BPM = bpm;

          Serial.println(bpm);
        }
      }
      else if (inOrder == 'c'){
        // Clear variables
        vibState = intensityState;
        vib1Intensity = 0;
        vib2Intensity = 0;
        ledcWrite(vib1Channel, 0);
        ledcWrite(vib2Channel, 0);
```

```
            vib1BPM = 0;
            vib2BPM = 0;
            vib1Vibrating = false;
            vib2Vibrating = false;
            vib1TimeAtLastBeat = 0;
            vib2TimeAtLastBeat = 0;
        }
    }
}
```

F.2 POSTURE FEEDBACK

F.2.1 Calculate deviation for posture

```
using UnityEngine;

namespace VRC
{
    /// <summary>
    /// Calculates deviations used for posture feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class CalculateDeviationPosture : MonoBehaviour
    {
        [SerializeField] private GameObject spineJointOwnMedium;
        [SerializeField] private GameObject spineJointOwnTall;
        private GameObject spineJointOwn;
        [SerializeField] private Transform spineJointTarget;

        public float ownBackRot;
        public float targetBackRot;
        [HideInInspector] public float backAngleDeviation;

        void Start()
        {
            spineJointOwn = spineJointOwnTall.activeInHierarchy  ?
spineJointOwnTall : spineJointOwnMedium;
        }

        void Update()
        {
            ownBackRot =
UnityEditor.TransformUtils.GetInspectorRotation(spineJointOwn.transform).x;
            targetBackRot =
UnityEditor.TransformUtils.GetInspectorRotation(spineJointTarget.transform)
.x;

            //Debug.Log("own: " + ownBackRot);
            //Debug.Log("target: " + targetBackRot);

            backAngleDeviation = targetBackRot - ownBackRot;

            //Debug.Log(backAngleDeviation);
        }
    }
}
```

F.2.2 Visual posture feedback

```
using System;
using UnityEngine;
using UnityEngine.UI;

namespace VRC
{
    /// <summary>
    /// Displays visual posture feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class VisualPosture : MonoBehaviour
    {
        private CalculateDeviationPosture calcDevP;

        private enum FeedbackType {Off, Whole, OnlyBody, Capsule}
        private enum RowingType {RP3, Skiff}

        [Header("Options")]
        [SerializeField] public bool active;
        [SerializeField] private FeedbackType feedback;
        [SerializeField] private RowingType rowing;

        [Header("References")]
        [SerializeField] private RawImage postureImageFront;
        [SerializeField] private RawImage postureImageSide;
        [SerializeField] private Camera postureCamera;
        [SerializeField] private GameObject postureRP3;
        [SerializeField] private GameObject postureRowerRP3;
        [SerializeField] private GameObject postureSkiff;
        [SerializeField] private GameObject postureRowerSkiff;

        private const int MinDeviation = 8;
        private const int MaxDeviation = 30;

        void Start()
        {
            calcDevP = GetComponent<CalculateDeviationPosture>();
        }

        void Update()
        {
            // Fade feedback
            float backDeviationRatio =
(Math.Abs(calcDevP.backAngleDeviation) - MinDeviation) / (MaxDeviation -
MinDeviation);
            if (backDeviationRatio < 0.08f) backDeviationRatio = 0.08f;

            postureImageFront.color = new Color(postureImageFront.color.r,
postureImageFront.color.g, postureImageFront.color.b, backDeviationRatio);

            // Turn on posture display
            if (active) postureImageFront.enabled = true;
            else postureImageFront.enabled = false;

            // Switch feedback (ergometer/body/capsule) by changing the
culling mask of the side view camera
            if (feedback == FeedbackType.Whole)
```

```
            {
                postureCamera.cullingMask |= 1 <<
LayerMask.NameToLayer("PostureRP3Skiff");
                postureCamera.cullingMask |= 1 <<
LayerMask.NameToLayer("PostureRower");
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureCapsule"));
            }
            else if (feedback == FeedbackType.OnlyBody)
            {
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureRP3Skiff"));
                postureCamera.cullingMask |= 1 <<
LayerMask.NameToLayer("PostureRower");
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureCapsule"));
            }
            else if (feedback == FeedbackType.Capsule)
            {
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureRP3Skiff"));
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureRower"));
                postureCamera.cullingMask |= 1 <<
LayerMask.NameToLayer("PostureCapsule");
            }
            else
            {
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureRP3Skiff"));
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureRower"));
                postureCamera.cullingMask &= ~(1 <<
LayerMask.NameToLayer("PostureCapsule"));
            }

            // Switch between RP3 and skiff target rower
            if (rowing == RowingType.RP3)
            {
                postureRP3.SetActive(true);
                postureRowerRP3.SetActive(true);
                postureSkiff.SetActive(false);
                postureRowerSkiff.SetActive(false);
            }
            else if (rowing == RowingType.Skiff)
            {
                postureRP3.SetActive(false);
                postureRowerRP3.SetActive(false);
                postureSkiff.SetActive(true);
                postureRowerSkiff.SetActive(true);
            }
        }
    }
}
```

F.2.3 Auditory posture feedback

```
using System;
using FMODUnity;
using UnityEngine;

namespace VRC
```

```
{
    /// <summary>
    /// Plays auditory posture feedback
    ///
    /// Virtual Rowing Coach project
    /// Made by Sascha Bergsma - s.bergsma-2@student.utwente.nl
    /// </summary>

    public class AuditoryPosture : MonoBehaviour
    {
        private CalculateDeviationPosture calcDevP;

        private enum SoundType {LeftRight, Spatial}

        [Header("Options")]
        [SerializeField] private bool playing;
        [SerializeField] private SoundType sound;

        [Header("References")]
        [SerializeField] private StudioEventEmitter leftEmitter;
        [SerializeField] private StudioEventEmitter rightEmitter;
        [SerializeField] private StudioEventEmitter spatialEmitter;

        private int targetNote;
        private int ownNote;

        void Start()
        {
            calcDevP = GetComponent<CalculateDeviationPosture>();
        }

        void Update()
        {
            if (playing)
            {
                if (sound == SoundType.LeftRight)
                {
                    leftEmitter.enabled = true;
                    rightEmitter.enabled = true;
                    spatialEmitter.enabled = false;

                    targetNote = (int) Map(calcDevP.targetBackRot, -28, 24,
-4, 4);
                    ownNote = (int) Map(calcDevP.ownBackRot, -28, 24, -4,
4);

                    leftEmitter.EventInstance.setParameterByName("pitch",
targetNote);
                    rightEmitter.EventInstance.setParameterByName("pitch",
ownNote);
                }
                else if (sound == SoundType.Spatial)
                {
                    leftEmitter.enabled = false;
                    rightEmitter.enabled = false;
                    spatialEmitter.enabled = true;

                    spatialEmitter.transform.position =
                        new Vector3(0, 0, calcDevP.backAngleDeviation /
10); // Emitter which is behind or in front
```

```
spatialEmitter.EventInstance.setParameterByName("position",
calcDevP.backAngleDeviation / 20);
                }

                float volume = Map(Math.Abs(calcDevP.backAngleDeviation),
5, 30, 0.40f, 1.00f);
                leftEmitter.EventInstance.setParameterByName("volume",
volume);
                rightEmitter.EventInstance.setParameterByName("volume",
volume);
                spatialEmitter.EventInstance.setParameterByName("volume",
volume);
            }
            else
            {
                leftEmitter.enabled = false;
                rightEmitter.enabled = false;
                spatialEmitter.enabled = false;
            }
        }

        private float Map(float value, float low1, float high1, float low2,
float high2)
        {
            // same as map() function in processing
            return low2 + (value - low1) * (high2 - low2) / (high1 - low1);
        }
    }
}
```

F.3 Other

Multiple other small scripts were created which were not essential to the project enough to include here. Also, all scripts created by Koen Vogel, of which a few are used in this project, can be found in Appendix B of [2].

G LITERATURE MATRIX

	SPRINT	SPRINT	SPRINT	M^3	M^3	M^3	Concept2	Concept2	RP3	on-water	Defining feedback	Automatic error detection	Automatic error detection
Paper	[32] “Vibrotactile perception assessment for a rowing training system” E. Ruffaldi, A. Filippeschi, A. Frisoli, O. Sandoval, C. Avizzano, M. Bergamasco. (2009)	[33] “Visuo-vibrotactile trajectory training in rowing experiment” E. Ruffaldi, A. Filippeschi, O. Sandoval, D. Gopher. (2009)	[34] “Preliminary evaluation of timing training accelerator for the SPRINT rowing system” A. Filippeschi, E. Ruffaldi, M. Korman. (2011)	[35] “Sonification and haptic feedback in addition to visual feedback enhances complex motor task learning” R. Sigrist, G. Rauter, L. Marchal-Crespo, R. Riener, P. Wolf. (2014)	[36] “When a robot teaches humans: Automated feedback selection accelerates motor learning” G. Rauter, N. Gerig, R. Sigrist, R. Riener, P. Wolf. (2019)	[37] “Terminal feedback outperforms concurrent visual, auditory, and haptic feedback in learning a complex rowing-type task” R. Sigrist, G. Rauter, R. Riener, P. Wolf. (2013)	[38] “Movement sonification: effects on motor learning beyond rhythmic adjustments” A. Effenberg, U. Fehse, G. Schmitz, B. Kreuger, H. Mechling. (2016)	[39] “Examining the effect of real-time visual feedback on the quality of rowing technique” S. Fothergill. (2010)	[40] “Accelerating skill acquisition in rowing using self-based observational learning and expert modelling during performance” R. Anderson, M. Campbell. (2015)	[41] “Interactive sonification in rowing: Acoustic feedback for on-water training” N. Schaffert, K. Mattes. (2015)	[42] “Feedback, affordances, and accelerators for training sports in virtual environments” E. Ruffaldi, A. Filippeschi, C. Avizzano. (2011)	[43] “Modeling the model athlete: Automatic coaching of rowing technique” S. Fothergill, R. Harle, S. Holden. (2008)	[44] “Real-time error detection for a rowing training system” L. Johard, A. Filippeschi, E. Ruffaldi. (2011)
Task: Feedback types:	trajectory (only hands, in a square) visual, haptic (vibro)	trajectory (only hands, rowing-like) visual, haptic (vibro)	rowing gesture timing audio + vib + KR = audio + KR	trajectory and velocity in trunk-arm rowing visual audiovisual visuohaptic	trajectory (trunk-arm rowing), velocity ratio visual, audio, haptic		full rowing technique visual, audio	general: trajectory, forces, seat-handle dist., graphs! visual (graphs)	full stroke at different stroke rates visual (self-observation + expert overlay)	on-water rowing audio			
1. What are the existing virtual and non-virtual rowing technique improvement installations?	SPRINT rowing simulator with screen. Sculling and sweep rowing simulator. Provides visual and haptic feedback. The hands’ trajectory “turns out to be the most important factor influencing the overall performance” (p. 2)	SPRINT	SPRINT Full rowing stroke	M^3 rowing simulator in CAVE. Test on whether auditory or haptic adds to visual feedback.	M^3 rowing simulator in CAVE. Sweep rowing simulator. Provides augmented visual, auditory and haptic feedback.		Concept2 ergometer. Direct mapping of kinematic and dynamic motion parameters to electronic sounds. Continuous 4-dimensional sound based on two kinematic and two dynamic movement parameters.	Concept2 ergometer, with motion cameras. Showing people curves of four different parameters of the stroke.	RP3 ergometer with screen in front showing a side view of them with an expert rower ghost on top.	Acoustics feedback system for elite on-water rowing using real-time sonification of boat acceleration. The aim was to sensitize the athletes to a smoother execution of the rowing stroke.		Concept2 ergometer rowing tracked with a motion capture system. It determines the quality of individual aspects of rowing technique using binary classification. Twelve features of a stroke were measured, and normalized in order to compare them. A coach trained the system by labeling example trajectories. Single aspect coaching was compared to multiple aspect coaching. Achieved classification results were encouraging: recognition of strokes from unseen people gave 5-21% misclassification for three of the experiments.	SPRINT
2. How should technique be measured?	How close the hands are to the 20° by 20° square trajectory. The stroke is split in four phases as well: catch/ drive/finish/recovery.	Close to reference model of trajectory	Correct timing of back and arms.	Spatial and velocity deviations from the target trajectory.	Monitor the movement error; the deviation of the current performance to the defined training goal. Adress the largest error out of different perfomance metrics. In this case the task was: learn an oar blade trajectory. Five errors were measured: the velocity profile (fast in the water and slow in the air) and four spatial errors: immersion into the water, movement through the water, movement out of the water, and movement through the air		Four movement parameters. Dynamic: grip force and footrest forces Kinematic: grip pull-out length and sliding seat position	Measure height of handle, pressure on footboard, handle, and (horizontal) distance between seat and handle (useful for coach) Technique measurement: -Force, area under handle curve -Efficiency, % of total kinetic energy, estimated from movements of handle and seat -Similarity to ideal performance (tempo-spatial) -Consistency	Rowing technique Stroke length & rate are strongly related to stroke efficiency [35] Rowing outcome Distance, avg. power An increase in stroke length is positive, decrease in stroke rate is positive. SL & SR may not reflect the finer technical points of the rowing technique Visual improvements in rowing technique do not necessarily cause improvements in rowing outcome.	Boat acceleration reflects the direct result of all forces acting on the rowing boat at any given moment. Thus, it is considered to be a reliable measure of effectiveness of the rowing stroke.		-Distance travelled -Speed moments -Shape smoothness -Length -Wobble -Ratio -Height -Drive smoothness -Drive angle -Shape moments -Recovery smoothness -Recovery angle **TODO:** figure out exact meaning for all features.	
3. Which auditory, visual and haptic feedback should be given based on technique?	Visual: Used as reference for the trajectory. Black screen with four balls at corners of square, and a fifth moves with the hands. Haptic: Vibro-motors on wrist (upper, lower), middle finger and elbow. Vibrate when error is > 1°, max is at 1.5°. Feedback on motion inversion is also given.	Vibrating: Two wrist belts (bandwidth vibrating feedback) Visual: Red and green balls, current and ideal trajectory Vibro-visual: both	Audio Two beeps at motion onsets of back and arms Haptic vibration: When error exceeded a threshold Knowledge of results (not explained) (Visual: stroke pace)	Visual: Target pos and vel of oar was displayed at the right, target oar became less transparent when close to target. Trace for terminal feedback, when deviation is large. More red when deviating more. +Auditory: Sonification of oar movement, right own oar, left target oar. Pitch increased linearly with horizontal oar angle. +Haptic:	Individualized feedback sequence: select feedback that adresses the greatest error, give alternative (secondary) if error stays. Spatial error feedback: 1. visual trace 2. haptic path control (guide) Velocity error feedback: 1. auditory: right own oar, left target oar. 2. haptic position control Subdivision in four phases proved to be suitable for learning to row. **(look at ref 16/17)**		3 groups V: video information, instruction and feedback (own rowing) videos on big screen in front. AV_{nat}: additional sound of flywheel and seat are taped and mediated via headphones AV_{soni}: additional multichannel continuous motion-sound based on 4 parameters **→explain sound**	Visual feedback Four graphs -Measure height of handle, trajectory -Force on handle -Force on foot stretcher -Horizontal distance between seat and handle (useful for coach) All with target performance, which is recorder prior under supervision of coach	Screen of own rowing plus ghost of expert rower.	A sound sequence is formed by sonification of the boat acceleration-time-trace data, whereby zero acceleration was set at 440 Hz. The sound was presented through a loudspeaker in the boat. The coach was also able to listen to the acoustic feedback together with the athletes or alone.	**Feedback descriptors:** Meaning -Meaning: informative, of error or performance, and guidance. Medium -Modality: channel -Mediator: entity Format -Dynamics: static/ dynamic -Concurrency: in / out of sync with action. -Frequency. -Continuity: continuous/ discrete -Adaptation: to the trainee’s skill level	Only feedback from coaches was given to help the participant to maintain the improved technique during the performance. No automatic feedback was given.	

				Moves the oar into the target trajectory, more deviation = more force. Dead zone around target trajectory (1 degree) **All feedback mostly disappeared when the movement was performed correctly. Bandwidth feedback.**									
4. Which feedback is effective and why?	The combination of visual and vibrotactile feedback is more effective than either on its own. Visual feedback allows the user to guess the forthcoming error. However, it causes a slower execution than with only vibrotactile feedback, because the user is trying to do it accurately.	VIB showed the best improvement VIS improved a lot the first day, but improvement disappeared the day after, showing a dependency on the presence of feedback VIB+VIS is half between "Vibrotactile feedback is the best one to guarantee a performance improvement independent on the presence of feedback."	Effects of vibrotactile feedback are not noticeable when adding it to auditory timing beeps for back and arms onset (and KR).	Visual feedback alone was already effective, sonification and haptic benefits were more subtle. Trace is combination of concurrent and terminal feedback. As concurrent can cause corrections of task-irrelevant errors, and terminal makes systematic errors apparent and may enhance self-estimation. Feedback should not overload the learner and allow the processing of intrinsic feedback when movement is done correctly. Visual feedback is able to intuitively instruct the novel, complex movement structure. Also it was designed to avoid correction of task-irrelevant errors (transp, deviation trace) VA performed significantly better concerning velocity, as well as a high transfer of skill to non-feedback conditions. Doesn't evoke dependency. Not only experts profit from sonification, but also beginners, at least if it includes a reference sonification, and in this case combined with visual feedback. "sound was kept in mind when performing without feedback" internal representation, part of their feeling. VH reduced spatial errors however, skill wasn't maintained to the retention test. More coping than remembering, it overloaded them. It showed highest velocity error because reactive feedback hindered fluent movement as well as scoring the lowest in comfort. Reactive feedback seems to be too challenging and overloads and should be adapted to the skill level. Compared to walls, bandwidth forces the active seeking of the correct path and remembering it. Enhance awareness. Reactive forces were masked by the drive	This automated feedback selection strategy showed a significantly higher learning rate. Because it addresses the greatest error (between the five rowing errors measured) with visual or auditory feedback, and adds a secondary haptic feedback if that error appears twice or more.	Concurrent feedback has been found to be effective for learning more complex tasks. Concurrent feedback can provide guidance through the complex movement.	Movement sonification enhances motor learning of a complex gross motor skill, as it even exceeds rhythmic adjustments by adressing kinematic chains or whole body coordination. In this case it is provided in combination with visual feedback of the user's own rowing. The effectiveness of auditory movement information alone has not been proven yet.	-using the system after coaching has little effect -during race-pace, there is a correlation between more feedback and better performance -during fatigue, more feedback, more target The system is of some use to maintain consistency, especially when fatigued or is absent.	Experimental group showed significant improvement in rowing outcome (distance & avg. power) "a combination of both concurrent self-observation and real-time expert modelling is an effective method of skill acquisition." Both groups improved in avg. power. (+consistency)	Changes in tone pitch during the rowing cycle, especially during propulsive-critical phases enhanced athletes' perception of the movement execution. The sound supported improvement of timing of single parts of the movement, as well as coordination among the athletes.			

				phase, so they were not effective during it. Haptic of VH feedback always disturbed the subject, but VA allowed them to switch their focus from on to the other. Addition of movement sonification to visual feedback allows learning of spatial and temporal (time-related, here: velocity) aspects in parallel. **Motor learning benefits from feedback that guides the focus of the learner on the source of information that is needed to recall the movement in conditions without feedback.** **→ bandwidth feedback, only displayed when exceeds threshold.**									
5. At what frequency should feedback be given?	Continuous feedback, training sessions of 120s followed by 40s assessment and 30s rest time.				One block consisted of first 3 min with feedback, then 1 min without. On both day 1 and 2 the participants performed five blocks.		Feedback was provided only in the middle 10 cycles (30s) of a block of 50 (lasting 2:30 min), otherwise all participants heard noise (sea rushing).		Always feedback, session lasted 330s	In blocks, sections with and without feedback. Each section lasted 3 minutes.			