CREW ROWING IN VIRTUAL REALITY

Msc Interaction Technology
Jordi Weldink - s1731912

Supervisors:
dr. Dees Postma
dr. ir. Dennis Reidsma
dr. Armağan Karahanoğlu

Co-developer:
Casper Sikkens

July 2024
University of Twente

ABSTRACT

The aim of this thesis is to investigate the potential of Virtual Reality in facilitating the training of interpersonal coordination in sports, particularly for crew rowing. To research this, two contributions were realized: 1) a multi-person VR rowing platform capable of hosting (co-located) crews, extending upon the extant VR4VRT-system [van Delden et al. 2020], and 2) the application of visual augmented feedback that is tailored towards rowing dyads to facilitate functional interpersonal coordination.

To evaluate these contributions, a within-subject design was applied to compare interpersonal coordination for different conditions related to visual coupling. In total 8 rowing dyads, rowed for 5 minutes on a stroke rate of 20 spm in the Non-VR (NVR), VR, and augmented feedback (AF) conditions.

Results indicate the potential of a mixed-reality, multi-person rowing platform in its first-ever steps to facilitate the training of interpersonal coordination within crew rowing, specifically co-located rowing dyads. By expanding upon the extant VR4VRT-system, the platform was able to host co-located rowing dyads, facilitate rowing dyad interactions, and provide personalized real-time augmented feedback to support the stroke and bow rower in their respective roles that visualizes, the otherwise intangible, interpersonal coordination. Nevertheless, the Continuous Relative Phase (CRP) and Generalised Additive Models (GAMs) graphs indicates a significant phase shift with respect to non-VR rowing, especially near the relevant catch timing. These implied systematic error can be explained by a simplification of the virtual rower and their movement patterns leading to a decrease in behavioural realism for virtual rowing.

Despite this, the multi-person rowing platform has shown to be able to facilitate interpersonal interactions within a visually coupled co-located rowing dyad, which is the first step towards training the skill of interpersonal coordination.

ACKNOWLEDGEMENTS

Just like crew rowing is denoted as the archetype of teamwork, joint action and coordination, this thesis goes beyond my individual effort. It has been the embodiment of collective efforts from others that stepped onto this journey alongside me – truly a multi-person rowing platform. Therefore, this section is dedicated to you!

First and foremost, I am extremely grateful to my supervisor Dees Postma for making this entire endeavour possible, despite its lengthy pursuit. We finally did it! As you mentioned, it really marks the end of era. To be fair, words simply fall short to express how important your guidance has been to me on both a professional and personal level. Having your advice, continuous support, patience and positive mindset week-in week-out were invaluable to me and helped this project go beyond imagination

Secondly, I would like to thank Casper Sikkens for his incredible support in the development and overall realisation of the mixed-reality rowing setup. Your expertise on (social-) VR, rowing and game design really pushed the boundaries of this project. Not to mention, the sheer amount of coffee and stroopwafels that fuelled our mental fortitude during these times.

Furthermore, I also want to express my pleasure of working with the fellow researchers and students from the Rowing Reimagined group from both the UT and VU. I would like to thank Bart, Frederique, Mirka for helping out and thinking along with the VR rowing installation. Moreover, I would also like to thank the experts Matthijs and Laura Cuijpers for their expertise, advice and feedback. Taken together, all of you have been important building blocks for the multi-person rowing platform as it is now.

Next, I will not extend my reservations, but my appreciation towards the Interaction Lab, especially Daniel, Koen and Rens, for enabling this study on co-located rowers by offering all the facilities that this project required such as VR equipment, expertise, lab space and allowing me to do off-campus research. Could not have done it without you. This also includes the fellow students and researchers from the lab, you guys helped me out in playtesting and sparring tremendously.

Besides that, a special thanks to Rinalds and Marie-Laure. After hours of development, cursing VR equipment and sparring together we finally managed to complete all of our theses. I am really grateful for our time together in the HMI- and Interaction Lab.

Moreover, I want to thank rowing association D.R.V. Euros and Cas Weenink for the warm welcome, the facilities to run this study, and the help for recruitment of participants. Furthermore, thanks to all the enthusiastic rowing dyads that voluntarily immersed themselves for their rowing effort and invaluable feedback on the virtual rowing installation. Also thanks to RP3 and Jan Lammers for providing us with the dynamic ergometers used to facilitate two co-located rowers at once, which was essential for the design and development of this multi-person virtual rowing installation.

Finally, I want to express my gratitude to my family and friends whose encouragement and understanding provided me with the foundation for my student journey and ultimately this thesis. It was not always easy, but thanks again for your support and belief throughout, could not have finished this without you.

Table of Contents

1 INTRODUCTION

Interpersonal coordination is a key determinant in facilitating successful collective behaviors in all sports, especially crew rowing. It refers to the tendency of athletes to synchronize their movement with the performance environment e.g. in team ball sports, or combat sports like that consist of teammates, opponents, the football field and the ball [Davids et al. 2013]. In sports, this form of coupling is also known as perception-action coupling. Where athletes constantly perceive information from others and the environment in order to adapt their actions - "we must perceive in order to move, but we must also move in order to perceive" [Gibson 2014]. In team sports (e.g. football, volleyball or relay race) individuals have to co-adapt their behavior towards increasing their goal-directed opportunities in a dynamic context (e.g. put the football striker in a favorable position to score, set and time the volleyball in a correct position for the hitter, or to match the pace of the previous runner for passing the baton)[Araújo and Davids 2016]. With these examples of functional adaptations in mind, interpersonal coordination can be understood as one of the underlying factor of performance, because athletes need to learn how to perceive and interact with others, and the performance environment to achieve their (shared) goal [Araújo and Davids 2016].

In crew rowing, the coordination of movement patterns is deemed functional and ideally practiced on water. Poor coordination is expected to invoke unnecessary movement transfer to the boat (e.g. pitch, heave) and elongate the travel distance to the finish [Cuijpers 2019]. Meaning that coordinated movement patterns and maintaining their stability are key to achieving success. It is no surprise that [Cuijpers 2019] refers to the sport as the archetype of joint action, teamwork and interpersonal coordination. From the stroke to bow, the crew is seated behind each other and being aligned in the direction of motion. This so-called follower-leader relation is crucial, because it implies that rowers synchronize based on different perceptual information. Besides the continuous joint action, rowers have to learn how to determine and time their actions based on perceptual information provided by the environment, forces on the boat and optical flows like water passage [Millar et al. 2013]. In other words, crew synchronization can be trained by helping rowers become more attuned to perceptual cues that are relevant for maintaining stable and functional interpersonal coordination. However, this requires months of practice, since coaching and skill acquisition involve conveying information, structuring practise, and administration of feedback [Farley et al. 2020]. In addition, rowing in the performance environment i.e. on-water, is not always possible due to practical constraints like availability and outdoor settings [van Delden et al. 2020]. These are partly overcome by rowing on in-door (dynamic) ergometers, because they can simulate on-water rowing dynamics while training indoors. The problem is that these are often focused on measuring the individual rower who interprets the presented knowledge of results from the ergometer monitor. Taken together, there are possibilities for ex-situ systems [Postma et al. 2022] that enable rowers (and coaches) to train outside of the traditional setting when interactive ergometer trainers are capable of hosting and facilitating co-located rowing crews.

Sports Interactive technology has the potential to facilitate skill acquisition of interpersonal coordination. Besides its focus on interactive training and competition, it involves quote "novel kinds of digital-physical exercise systems" and aims to promote the desired outcomes through Human-Computer Interaction "that occurs with and around the acting body" [Postma et al. 2022]. These types of interactive technologies provide automatic assessment from tracking bodily input till the presentation of the feedback to the athlete. Therefore, Sports Interaction technology has potential to complement the deficiency of the rower's ability to perceive relevant timing- and movement qualities by providing augmented information in the form of autonomous personalized real-time feedback. Which is in line with the need for accurate and timely feedback on coordinated movement patterns and their stability.

In particular, the application of Virtual Reality training environments in rowing [Ruffaldi and Filippeschi 2013; van Delden et al. 2020] (and others sports) to train sport-specific skills is promising (e.g. energy management [Hoffmann et al. 2014])[Varlet et al. 2013]. Such systems are also capable of providing immediate, situated and personalized augmented feedback. VR is capable of providing a controlled environment that empowers athletes to train without time and place constraints while providing realistic immersive sports training that approximates their real-life counterparts [Postma et al. 2022]. For instance in team ball sports, perceptual-cognitive skills can be trained without the risk of injury (e.g. decision-making [Cardin et al. 2013; Tsai et al. 2019]). Similarly, in martial arts, visualization or forecasting are used to train anticipation [Kamaya et al. 2018; Krabben et al. 2019]. These examples often overcome the limitations of video analysis or situatedness. In the case of using VR to interpersonal skills, its potential is mostly pointed out by reviews [Farley et al. 2020; Faure et al. 2020; Krabben et al. 2019; Schmid Mast et al. 2018]. These show that successful application of VR in sports skill acquisition is based on retention and transfer to real-world situations, even though these aspects are often indicated to be evaluated by future research.

This thesis aims to utilize Sports I-Tech to train interpersonal coordination among rowing crews by expanding upon the extant VR4VRT-system by [van Delden et al. 2020]. This 'Virtual Reality for Virtual Rowing Training' system already offers a virtual environment that facilitates individual rowing training by combining the dynamic RP3 ergometer and VR motion tracking. The step from individual to crew rowing requires several iterations: the new system needs to understand and augment the perceptual information that is acted upon according to the follower-leader relation. Furthermore, the application of multi-modal feedback channels to promote interpersonal coordination and not overwhelm the rowers. In addition, the physical setup needs to be extended such that the rowers feel and experience being in the same boat. The main research questions for this thesis is as follows:

"How can Sports Interactive Technology be used
to facilitate training of interpersonal coordination in sports,
specifically for crew rowing?"

1.1 Contributions

To explore the potential of VR for rowing, particularly as tool to help rowing dyads to train the skill of interpersonal coordination, this thesis offers two contributions:

First, the development of a multi-person, mixed reality, rowing platform that is a unique joint learning system that incorporates team dynamics to train interactions within a rowing crew. By expanding upon the extant VR4VRT-system [van Delden et al. 2020], the step from individual to virtual crew training has been realized. By applying the ability to track rowing movements on dynamic ergometers (RP3), the system can effectively process and manage the captured rowing dynamics per rower. Additionally, when immersed, users can setup their virtual counterpart through embodiment of a virtual avatar body and configure their alignment to a virtual ergometer. Once done, they claim their seat position in the virtual boat, and the crew is ready to start with the rowing practise.

Empirical evidence of this thesis indicated that the platform facilitated immersed rowing dyads to elicit realistic movement behaviour and interactions towards the required interpersonal coordination. These preliminary results do require more research in making the platform deliver a more stable and synchronized experience, before rowing practise within rowing crews.

In this way, the system transcends the individual rower, as not only each rower is now represented by virtual rower, but similar to real-life rowing, the crew is able to visually perceive themselves, other rowers and results of the performed rowing strokes from their seated position in the virtual boat. Empirical evidence indicated that the platform facilitated immersed rowing dyads to elicit realistic movement behaviour and interactions towards the required interpersonal coordination. However, these preliminary results do require more research before being able to accurately simulating on-water crew interactions in the virtual space.

Secondly, the application of real-time augmented feedback to promote interpersonal coordination within rowing crews by visually supporting the stroke and bow in their respective roles. As the system handles and manages the incoming data per rower, it simultaneously informs the generation of real-time augmented feedback. Abstract visuals forms, in which simple visuals composed from shape, form, color and line, were designed and developed to provide knowledge of performance personalized to the stroke and bow rower. Helping them to perceive timing and movement qualities relevant for maintaining stable and functional interpersonal coordination related to their specific role, that are otherwise intangible.

The empirical results do highlight the potential benefit of real-time personalized augmented feedback in positively influencing the rowing crew's behaviour, specifically it's suggested potential to provide more stability in synchronization for immersive rowing. However, due to time constraints, this study did neither investigate the feedback´s effectiveness over a longer period of time, nor used fitting feedback schemes. Therefore, future research should focus on learning protocols and bandwidth feedback schemes to evaluate the retention and transfer to real-world rowing situations.

The rest of this thesis is structured as follows: First of all, the background section provides context on the VR4VRT-system [van Delden et al. 2020] as foundation to expand upon, crew rowing and interpersonal coordination. Next, the related work reviews the existing virtual rowing simulators for both individual- and crew rowing. Since such simulators for crew rowing is rather unexplored, this section also reviews the state-of-the-art Sports I-Tech that is able to facilitate sports training of interpersonal skills, and subsequently discusses how Virtual Reality can be made successful for the skill acquisition of interpersonal coordination. Then the next two sections describe the how the contributions of this thesis, namely 1) the multi-person, mixed reality, rowing platform and 2) the application of real-time visual augmented feedback personalized to the stroke and bow rower role, was designed, developed and tested. To investigate how these facilitate interpersonal coordination within a rowing dyad, an empirical study was conducted to compare the interpersonal coordination that involved no immersive rowing (Non-VR), immersive rowing (VR), and immersive rowing including the presence of Augmented Feedback (AF). Finally, the results section presents the analysed data on rowing dyad level between the conditions, from which a general discussion follows that interprets what the key findings mean, why they are important and provide recommendations for future research.

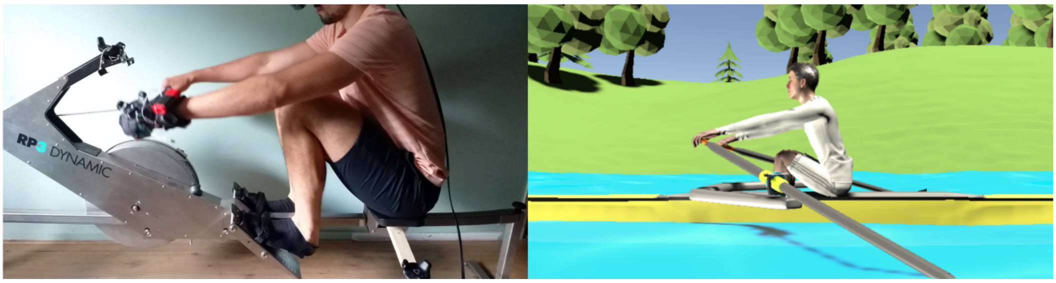


Fig. 1. The extant VR4VRT-system: capture and display real-time rowing dynamics in the virtual space

2 BACKGROUND

This section provides the required context on the 'to be expanded' foundation provided by the VR4VRT-system by [van Delden et al. 2020] that uses a combination of the RP3 ergometer and VR motion tracking, and the discipline of crew rowing, specifically on how rowers are coupled to each other and the performance environment within a rowing dyad.

2.1 The VR4VRT-system

For this thesis, the VR4VRT-system is the foundation for the development of a multi-person rowing platform in VR [1]. This system is an already existing interactive ergometer trainer that uses off-the-shelf components to offer virtual row training aimed at improving the (novice's) rowing technique through the application of concurrent augmented feedback. By expanding upon this already present system, the step from individual rowing training to crew rowing training, specifically rowing dyads, has been realized. To understand this expansion, this section will provide the required background on the VR4VRT-system. Particularly, about the general architecture, VR setup and training-and feedback elements.

The VR4VRT-system setup combines an dynamic ergometer (RP3) with HTC Vive motion trackers into a VR rowing setup (see figure **??**). Providing a cost-effective hardware-software combination that captures the rower's dynamics into the virtual world. The system is setup by equipping the dynamic ergometer with motion trackers on the seat- and flywheel to track the moving parts of the ergometer. Additionally, the user wears a motion tracker on a left-handed glove and Head Mounted Display (HMD) that is connected to the computer. Which in turn, runs the SteamVR and Unity software application. Where SteamVR handles the incoming motion tracking input through lighthouses surrounding the ergometer, and the Unity game engine is responsible for simulating the real-time 3D rowing environment using this rowing input, which is streamed back to user via the HMD.

In this VR setup, the motion tracking setup is effective in accurately capturing the rower's limb posture. [van Delden et al. 2020] identified that tracking the handle, seat- and flywheel of the ergometer is capable of representing the rower's hands, hip- and feet. Moreover, they successfully implemented a stroke detection algorithm based on this representation to accurately identify when rowing in the drive- or recovery phase and how to cope with the transition between these phases, making the system capable of managing all phases of the rowing cycle movement in real-time. However, this only works if the presented assumptions are met. Meaning that the user is correctly seated and rowing as intended i.e. the hands are on the ergometer handle, and the feet are tied to the footrest. This implies the distances between the limbs is the same, and can therefore be used to accurately showcase the virtual rower.

For the virtual row training, the system offers modular extensions for which the user select the required type and mode of feedback (see [van Delden et al. 2020] for reference).

The VR4VRT-system identified relevant training-and feedback elements for novices. These include the overlap i.e. the movement execution order of the (and timing) of the arms, back and legs during the recovery phase. Secondly, the velocity of the hands referring to maintaining a standard drive-to-recovery ratio in hand velocity. Thirdly, the handle trajectory which refers to the height of the handle during drive and recovery. And lastly, the angle of the back. The latter two are highly relevant for this thesis as well.

Besides the type of feedback, various bandwidth feedback forms were also designed and implemented, among which: visual velocity- and trajectory feedback on the handle in multiple forms e.g. a visual trajectory drawing next to the handle, or in-front placed side view posture feedback both including a form of expert overlay (see Modular Extensions for more details). Important to note is that the interviewed expert coaches agreed that 'effective feedback cannot really exist as feedback methods needs to be alternated', moreover stating that different types of rowers learn in different types of ways.

Taken together, the extant VR4VRT-system enables research outside of the actual rowing performance environment and showcases its potential for individual row training in multiple training and feedback forms. As the system already has a functional setup for capturing rower dynamics, and offers relevant augmented feedback types and forms, it forms a suitable foundation for this thesis to take the step from the individual to crew rowing.

2.2 Row Perfect 3 dynamic ergometer (RP3)

Rowing on dynamic ergometers, such as the utilized RP3 model-T[2] in the VR4VRT-system [van Delden et al. 2020], are capable of simulating the mechanics of on-water rowing. In contrast to static ergometers, dynamic ergometers incorporate a moving flywheel mechanism on the sliders. Meaning that both the RP3 seat and flywheel move along the sliders. This dynamic characteristic on an ergometer results in a more realistic leg drive and prevent rowers from directly absorbing their own body's mass momentum. In other words, the kinematics of dynamic ergometers closely mimic the on-water rowing experience, making them effective tools for researching rowing dynamics outside of the actual performance environment. Interviews performed by [Tuinstra 2021] highlight the usefulness of ergometers in eliminating external factors, aside from overcoming the practical constraints. Additionally, a survey showed that the RP3 is more used among experienced rowers to train their technique. For more information, see [Hooper 2009] or refer to the RP3 science page[3].

2.3 Crew Rowing

The discipline of crew rowing requires continuous coordination of behaviour and movement. It is unique as other examples of implicit synchronization involve face to face interaction (e.g. combat sports), meaning that person *A* can see and perceive bodily information from person *B*. However, this not the case when thinking about the seating composition for rowing crews, where for instance the stroke rower has to coordinate without access to any bodily information from other rowers. The dissertation by [Cuijpers 2019] describes crew rowing as the ideal experimental paradigm to study interpersonal coordination as quote "In a rowing crew, agency is shared over multiple rowers. There

---

[1] VR4VRT: Virtual Reality for Virtual Row Training: https://www.youtube.com/watch?v=VLIPqat_pCY

[3] Website of the RP3 Model-T, and RP3 science page: https://rp3rowing.com/product/model-t and https://rp3rowingusa.com/science/

is no hierarchical control, but rather the behaviour of the crew emerges from the interactions of the components that constitute the system". To better understand what crew rowing encompasses, the rest of this subsection provides relevant background on some of these components, namely 1) the within-crew interactions facilitated through different forms of coupling, and 2) the follower-leader dynamic between the stroke and bow rowers.

2.3.1 Forms of coupling between rowers. Within a rowing crew, rowers are coupled to each other and the rowing environment. As the perception and action are intertwined, rowers have to determine their actions based on perceptual information provided by the environment including movements from the others and the boat. Besides the perceptual coupling (visual, auditory, haptic), rowers are also mechanically coupled through the boat. For the development of a multi-person, mixed reality, rowing platform that aims to virtually simulate and train within-crew interactions, the most important forms of coupling to point out are the mechanical- and visual coupling.

Mechanical coupling. Mechanical coupling is a form of coupling that physically connects rowers through the motions and forces acting on the boat. It differs from perceptual coupling as it facilitates between-rower interactions non-stop and cannot be turned off. Making it a stringent form of coupling, as the boat will always showcase some form of movement when on water (e.g. shaking). Interviewed coaches even call to "row with the boat" [Seifert et al. 2017]. This can also be realized on dynamic ergometers, by mechanically coupling them through sliders, and even handle- or crossbar connections. Moreover, the resistance level can be adjusted to further simulate realistic kinesthethics i.e. sensory perception of movement of the boat (see Ergometer Physics). Aside from the fact that the research on mechanically coupled humans is relatively unexplored, the study conducted by [Cuijpers 2019] researched both mechanical and non-mechanically coupled rowing dyads. Noting that mechanical coupling is an "attractor" for in-phase coordination, while also providing insights suggesting that its presence made coordination less variable, and therefore suitable for interpersonal experiments like this one. Taken together, mechanical coupling is a continuous form of physical coupling that is suggested to play a prevalent role in maintaining stable interpersonal coordination.

In contrast to mechanical coupling, visual coupling can be turned off as it is sensitive to perturbations, like staying focused and keeping attention ([Cuijpers et al. 2015])

Visual Coupling. Due to the seating composition, rowers have different access to visual information in the boat. When considering the rower's viewpoint, the available visual information for the stroke rower is solely based on the environment, whereas the bow rower has additional access to segmental information (i.e. limb motions) from the stroke rower's moving back. Furthermore, the rowers are oriented opposite of the boat's direction. In essence, rowers have to coordinate their movement based on a visual information-deficit.

Interviews with Olympic rowers and coaches by [Millar et al. 2013] put emphasis on the phrase "rowing with the boat" as coordination is about connecting the rower's movement with those of the boat", especially during the recovery phase. The interviews reveal that rowers compensate for the information-deficit through a mixture of optical flows i.e. patterns of perceived motions caused by relative motion between in this case the rower and the direct environment. Prevalent examples include the other rower's segmental information, and the water passage relative to the boat. More specifically, the stroke was found to often use the water passage and (looming) stern of the boat, especially its dipping at the catch to time their movement. Whereas the bow rower was reported used the front rower's back segmental information and water passage relative to the front rower/boat. Overall, rowers uses different visual looming/optical flow sources to achieve interpersonal coordination within a rowing crew.

But how does this translate to crew rowing in VR? A study by [Meerhoff et al. 2014] that investigated distance regulation (backward-forward following) based on visual information can be consider similar to the follower-leader relation within virtual rowing dyads. In that study, participants had to do a backward-forward task following of either a virtual 3D-avatar with limb motions or a looming 3D sphere on screen. Consecutively, these tasks can be compared to the segmental information from the stroke rower's back and looking at the optical expansion from a looming stern. Results from the study indicate that although segmental information is more accurate and has faster response timing, both conditions were reported to be successful in guiding participants. In other words, distance regulation as a form of visual coupling between virtual objects and avatars can be realized in a virtual rowing environment.

2.3.2 Follower-leader Relation. The cooperation between the stroke and bow rower is typed as a follower-leader relation (or leader-follower). In which the stroke, closest to the stern, sets and maintains a consistent and easy to follow stroke rate. And on the other hand, closest to the bow, is the bow rower that follows the stroke's lead. [Hill 2002] underlines this relation by stating that the force patterns in a rowing dyad are not the same. Stroke rowers need a steeper force pattern after the catch and peak earlier at the finish, while the bow should peak later and progress faster to the finish as to prepare for the new rowing cycle. In order to facilitate interpersonal coordination, the multi-person rowing platform should respect this follower-leader relation, since it has implications for the within-crew interactions.

Research on crew phenomenology provide insights on the follower-leader dynamics within a rowing dyads. A case study of a coxless junior pair, combined experiential and bio-mechanical data in a so-called course-of-experience analysis to investigate the stroke rower's perception of "being pushed" by the bow rower [Sève et al. 2013]. This 'pushed' experience was expected to be explained the bow starting earlier at catch. In contrast, by mapping the bio-mechanical data to the stroke's experience, the data revealed that due to the difference in stroke amplitude and first half of the recovery phase, the stroke needed to catch up to the bow's movement in order to get in sync for the catch. This shows that within a rowing dyad, both rowers make functional adaptations in their movement patterns to ensure the best possible coordination while rowing.

Similarly, [Seifert et al. 2017] used two coxless pair to investigated how rowers coordinate their behaviour and experience. Overall, the study shows that when high variability in interpersonal coordination occurred, the resulting behaviour was either functional or perturbing (stable or change in boat velocity), experienced as either meaningful or meaningless, and the joint experience is either similar or diverging (see Table 1 for examples). Result for instance show that bow rower had higher variability than the stroke in kinematics and kinetics (forces and motions). This indicated that the stroke had to compensate and/or communicate with the bow rower to stabilize the interpersonal coordination within the rowing dyad (also reported in interviews by [Millar et al. 2013]).

Likewise, the study by [Feigean et al. 2017] investigated how a newly formed sweep-rowing dyad adapted their rowing patterns, but then over the course of 6 weeks. Findings show that both rowers were able to adapt their own individual movement patterns when trained to row as a team. More specifically, the improvement in collective crew behaviour was a result of the stroke rower become more stable in performance, whereas the bow even surprisingly increased in variability. Suggesting that the bow became better coupled to the stroke. Like [Millar et al. 2013], the adaptability of individual patterns was found to be key in training towards positive collective crew behaviour.

Taken together, the follower-leader relation describes the general dynamic between the stroke and bow rower, but is considered flexible and variable to allow for functional adaptations in practise. Studies on crew phenomenology show that rowers both adapt their individual movement patterns towards positive collective crew behaviour, even when their own movement patterns becomes more variable in the process.

3 RELATED WORK

Existing work in the context of virtual rowing simulators use multi-modal feedback forms on displays, immersive CAVE and VR systems to train rowing-related skills. These mainly focus on training the individual rower's technique, whereas installations involving multiple (co-located) rowers are rather unexplored. To consolidate, this section also reviews the state-of-the-art Sports I-Tech that is able to facilitate sports training of interpersonal skills (by providing real-time augmented feedback forms), and subsequently discusses how VR can be made successful for skill acquisition in terms of real-life rowing approximation and implementation.

3.1 Virtual Rowing Simulators

The majority of the virtual rowing simulators are aimed at the individual rower [Gerig et al. 2017; Hoffmann et al. 2014; von Zitzewitz et al. 2008] in both research- and commercial contexts, whereas use-cases for multi-person rowing simulators that host multiple co-located rowers are limited [Shim et al. 2018; Varlet et al. 2013]. Like the the VR4VRT-system [van Delden et al. 2020], others have also developed their custom-made rowing simulators, particularly in a high-fidelity CAVE setup. However, the multi-person rowing simulators lack in the ability to provide full immersion because rowers often share the same screen display with fixed viewpoint, and do not (entirely) facilitate realistic within-crew interactions.

The SPRINT Rowing Training System by [Ruffaldi and Filippeschi 2013] provides training for technique, energy management and team coordination skills of rowers by means of a multi-modal rowing platform (e.g. visuals, haptics), a digital representation of the skills to train, augmented feedback (e.g. [Ruffaldi et al. 2011]) and training protocols. The SPRINT rowing platform has both a lightweight version that uses a Concept 2 ergometer and screen display, and an immersive CAVE setup that uses the VICON motion tracking system and mechanically operational oars to train both sculling and sweep rowing. Additionally, the CAVE setup introduce personalized calibration based on the user's size, and is not limited in pitch and heave movements. [Hoffmann et al. 2014] used the lightweight SPRINT version and showed that VR can effectively teach novice rowers about the skill of energy management, an optimal to be followed pace strategy for a 2000 meter race. In the study, novice rowers divided in an avatar group and control group trained to complete this distance as fast as possible. The avatar group was instructed to follow the virtual opponent rower that adopted an optimal pacing strategy including visual line feedback, whereas the control group had no digital means for indoor row. Results showed increased performance of the avatar group and that VR is useful for the skill acquisition, retention and transfer of the energy management strategy.

With a similar setup, another CAVE implemented system called the M3-trainer provides automatic motor learning ([Rauter et al. 2011]). This robot-assisted virtual trainer provides concurrent augmented feedback (audio, visual and haptic) to individual athletes. The rower is seated inside a shortened rowing skiff and equipped with a shortened oar. This allows for performing the rowing stroke with rotational degrees of freedom for all three axis. Moreover, the M3 trainer is able to adapt to the rower's needs by choosing the feedback modality and strategy. For instance [Gerig et al. 2017]) uses the M3 trainer to showcase realistic augmented feedback forms, visually displayed next to the oar, on error augmentation of the oar angle including visualization of expert rower reference data. In another study, [von Zitzewitz et al. 2008] showed that experienced rowers were convinced of this simulator's usability for training purposes. Despite the high ratings for realism, they also point out the shortcomings related to direction and force like the limited rotational degrees the setup of freedom and lack of passive sliding mechanism like the RP3 ergometer to simulate realistic on-water rowing dynamics.

The commercially available rowing simulators often use high-quality and (ultra-)realistic virtual environments to immerse and entertain their users.

The Holodia's Holofit VR fitness app [4] is aimed at providing immersive enjoyment that includes virtual rowing. Users have the option to connect an indoor ergometer to the app making it possible to experience mixed-reality rowing. Interestingly, the app has the option to (re-)align the rower's horizon and provide feedback with knowledge of results (KR). Moreover, they also offer workouts and online competition formats to further engage their users.

Another example is the EXR [5], which enables similar virtual rowing experiences on displays from a 3rd person, or side-view perspective. In addition, users can choose to traverse well-known rowing environments around the world.

Finally, the Kayak Mirage VR [6] game focuses on virtual kayaking and by using only VR controllers. However, it is exemplary in terms of gameplay, multi-modal experience and providing ultra-realistic water dynamics for instance when the kayak paddles enter and exit the water.

Apart from the inclusion of virtual rower opponents, rowing simulators involving multiple (co-located) rowers are limited. [Shim et al. 2018] created a participatory rowing game for two players based on motion similarity. In this setup, two users were placed behind each other in front of a large curved screen without any rowing equipment. Optical motion capture cameras actively track the motion of the arms. Based on the motion similarity of the arms, the boat was accelerated. A closely related study by [Varlet et al. 2013] investigated if novice rowing dyads can possibly learn the skill of interpersonal coordination with a virtual teammate moving based on an elite rower, show accelerated learning with concurrent visual feedback and if the skill transfers to the real-world setting. The setup utilizes the SPRINT system [Ruffaldi and Filippeschi 2013] with mechanically linked ergometers (same ergometer setup as [Cuijpers 2019]) including a display to visualize a virtual stroke rower in front of the co-located rowing dyad.

However, this virtual teammate is based on prerecorded movement from an experienced national rower. Making it unilateral synchronization, which is not sufficient for the interest in training interpersonal coordination within a co-located rowing dyad. Moreover, the rowers were muted and solely relied on concurrent visual feedback. During rowing, the virtual teammate is colored on based on interpolation between red and green colors respectively indicating no synchronization to perfect synchronization. Due to the small height of the virtual teammate, participants reported to have difficulties with identifying visual information and cues. On the other hand, the concurrent visual feedback was found to be a positive influence on the coordination. Overall, the findings show improvements on the coordination skill for both the virtual and real teammate indicated by smaller phase lags, including its transfer-ability.

In general, virtual rowing simulators offer autonomous unsupervised training modules to improve (parts) of the rowing technique, often focused on novice individual rowers. Real-time captured movement data is often compared to reference data like prerecorded expert movements, or a specific set of recurring rules as the rowing movement is cyclic in nature e.g. maintain a specific drive-to-recovery ratio. Based on that, concurrent (multi-modal) augmented feedback is generated and provided to the rower as an external source of feedback. However, the effectiveness of augmented feedback is only reported in studies that used a learning protocol (e.g. [Varlet et al. 2013]). Aside from the VR4VRT-system, no other VR rowing platforms were found that uses VR Head Mount Display (HMD) to fully-immerse rowers, let alone being capable of facilitating multiple (co-located) rowers.

---

[6] Holodia's Holofit VR fitness - https://www.holodia.com/, example of rowing in a seating position: https://www.youtube.com/watch?v=2ulbzoOyYLs

[6] EXR - Experience Virtual Indoor Rowing - https://exrgame.com/

[6] Kayak VR: Mirage - https://kayakvr.com/

To consolidate for the lack of knowledge, the rest of the subsections discuss relevant Sports Interactive Technologies and how to successfully implement skill acquisition in immersive environments.

3.2 Review of Sports I-Tech to facilitate interpersonal coordination for co-located athletes

This section discusses relevant Sports Interactive Technology that is able to facilitate sports training of interpersonal skills (by providing real-time augmented feedback forms). The general perspective among papers is that improving interpersonal skills is important for team performance [Araújo and Davids 2016; Kermarrec et al. 2014; Steiner et al. 2017]. Moreover, reviews related to 'VR and sports training' put clear emphasis on the potential of VR technology for training sport-specific skills in sports, particularly as potential tool to promote interpersonal skills (e.g. team ball sports [Faure et al. 2020]; combat sports [Krabben et al. 2019; Yuqing et al. 2021].

Despite the indicated importance, the applicability of findings on training of interpersonal skills to crew rowing based off team ball sports and combat sports is constrained. First of all, [Faure et al. 2020] mentions that the team ball sports are endurance sports, and is therefore rather limited on skill-based sports like crew rowing. Moreover, [Faure et al. 2020] also reports that no studies were found that investigated shared VR experiences, or situations where athletes had to continuously interact (like [?]. Secondly, combat sports is focused more on syncopation rather then cooperation, as the key ability of brinkmanship is the equivalent of anti-phase coordination (i.e. asynchronous/out of phase), where combatant dyads try to quote "purposefully and accurately perceive and act near action boundaries" [Krabben et al. 2019]. Therefore, only studies where a Sports I-Tech system is used to maintain, stabilize or train interpersonal skills in a cooperative experience/situations, either physical activity or sport, can be meaningful for training interpersonal coordination within a rowing crew.

Besides the virtual rowing simulators, examples of relevant Sports I-Tech include physical activities with co-located players guided by digital-physical interactive systems that focus on interpersonal distance regulation.

SixFeet is an installation that promotes physical activity and social relatedness by offering participants a way to safely engage in physical activities during the Corona pandemic [D.B.W. Postma and Ranasinghe 2021]. The physical play space consist of Multiple LED foot-switch stations that were placed in a circular orientation and register players that come and go. Then, a smart algorithm ensures that players can dynamically share this same physical space without crossing each other's path and regulate the interpersonal distance norm. As the rower seats are at a fixed distance, the concept of a smart algorithm to maintain and stabilize interpersonal distance, while keeping in mind the intricacies of the follower-leader relation. May be relevant for designing augmented feedback for the bow rower based on the front rower's bodily information.

Another interactive training concept that involves co-located players is the TacTowers prototype [Ludvigsen et al. 2010]. In this setup, (handball) players are supported in training skills like anticipation, and decision-making in a one-on-one confrontation. TacTowers is described as a sensor-actuator based system that consist of multiple stacked sensors, each of them a larger version of a handball. That when interacted with, provide real-time visual feedback by changing colors. Exercises with TacTowers are especially relevant for handball, as it closely resembles its real-world interactions. Which is also relevant for designing augmented feedback for rowing dyads as well. Evaluations with national level athletes show that the external feedback should be responsive, consistent and perceptible at an unconscious level. The athletes reported that when the system did not detect a hit and no subsequent visual feedback was given, they were temporally interrupted in their flow. In other words, real-time visual feedback should be abstract i.e. simple shapes, colors and forms that are accurate yet easy to (subconciously) interpret for athletes.

An example that uses physical Sports I-Tech to facilitate triadic interpersonal coordination in football is by [Yokoyama et al. 2020] Physical Sports I-Tech that manipulates the interpersonal degrees of freedom. In this study, three football players were tasked with a three-versus-one keeping ball possession game in different conditions and instructed to pass the ball as much as possible. The conditions for the three footballers included a three-elastic-band, one-elastic-band and no band. Respectively representing high to low interpersonal degrees of freedom. The one-elastic band is one band covering all players, whereas the three-elastic-bands consist of three bands connecting each dyad. Interestingly, the study reports that elastic bands provide both augmented visual and haptic feedback e.g. through a slackened band. Particularly, the three-elastic-band as it provides feedback per dyadic connection, promoting the awareness on positional changes and organization. Results indicate that although the elastic bands did not improve the triadic coordination, they still facilitated stable interpersonal coordination. Which is in line with research on mechanically coupled rowers. Similar to [D.B.W. Postma and Ranasinghe 2021], this study also provides an interesting concept on interpersonal distance regulation through the real-time visualization of the dyadic connection, being either slackened or tightened.

Examples of Sports I-Tech that facilitate sports training through interpersonal coordination highlight the importance of real-time augmented feedback that provide an external source of information through easy and intuitive to perceive (e.g. uni-colored, slackened bands). However, do often not focus on the design and effectiveness of augmented feedback (e.g. learning protocols), making it difficult to translate into crew rowing. As this discipline is found to be niche, and unique in the way interpersonal coordination is manifested and considered functional. The next section aims to set out what is required for virtual immersive environments to be successful in the acquisition of sport-specific skills, translated to crew rowing and interpersonal coordination.

3.3 Skill Acquisition in Immersive Environments

Virtual Reality is capable of empowering athletes to train without time and place constrictions while providing compelling immersive sports training activities that approximate its real-life counterpart. However, the effectiveness of a VR application and augmented feedback is often based on retention- and transfer test to real-world situations. [Ruffaldi and Filippeschi 2013] describes design criteria for a multimodal training platform - digital representation, information exchange, training protocols (out of scope for this thesis). Additionally, the review of [Farley et al. 2020] was used to come up with requirements of successful application of VR, and subsequently rephrased to match crew rowing and interpersonal coordination.

First of all, rowers in VR are required to produce the rowing stroke in synchronization similar to real-world rowing. [Ruffaldi and Filippeschi 2013] identified that the main components of the rowing task are the rowers, the boats, oars, water and the air. First of all, the RP3 dynamic ergometer in this study will be used to perform the rowing stroke similar to on-water rowing. Secondly, the synchronization of rowing stroke requires interaction through coupling. Mechanically coupled ergometers allow rowers to mimic movement synchronization as if they are in the same boat (see setup by [Cuijpers 2019]). Furthermore, the intended visual coupling requires a representative virtual performance environment [Araújo and Davids 2016; Davids et al. 2013], segmental information from virtual avatars, and optical flows like water passage [Millar et al. 2013]. If the above are present, the third requirement becomes the ability of the multi-person rowing platform to manage the role division and seating positions of the stroke and bow rower according to the follower-leader relation.

Secondly, ensure that the rowing stroke is performed with a variety of conditions. For indoor rowing, this is limited and likely refers to adaptions and perturbations in the rowing stroke. The setup is limited in directional movements, however rowers are able to row with different movement frequencies and application of force if needed. Additionally, the implementation of time and distance training allow workouts or even simulation of race conditions, which does require a lengthy virtual rowing track. And lastly, the virtual performance environment does not include additional conditions to row in such as weather or daytime changes, which is out of scope for this thesis.

Finally, outcomes of the rowing stroke must be available to rowers including its sensory consequences. As rowing is inherently multi-modal, any information coming from the performed rowing stroke on the RP3 must be respected and translated into the virtual rowing environment if necessary. When performing the rowing stroke on the RP3 without VR, there is already visual, haptic and sound feedback present. A Dutch podcast titled 'the sound of rowing' [NPO Radio 1 2020]mentions the importance of naturally occurring sound feedback from the boat e.g. a moving sliding seat to determine the current state of rowing. This also holds for the RP3, as there is feedback from the sliding seat and flywheel, especially during the drive phase. For crew rowing, it is therefore essential to place the RP3s in a back-to-back alignment similar to the seating positions in the actual boat, not only to have realistic sound feedback, but also to respect the stroke and bow's visual viewpoint relative to each other. Further realisation of this requirement relies mostly on the ability to translate the captured rowing dynamics into the virtual rowing environment. Since mechanical coupling does not require any translation to VR, the focus is on the facilitation of visual coupling between rowers in VR. This consist of ensuring that the aforementioned optical flows and segmental information from virtual avatars are present in the virtual rowing environment (see follower-leader relation). Furthermore, when rowing on the RP3, the same movement must be visually represented in VR. Therefore, they key is to represent the co-located rowers on the RP3 through virtual rower avatars that are seated in a virtual boat able to move on a virtual sliding seat (e.g. to mimic the leg push). Moreover, the performed rowing stroke from multiple rowers has to be real-time translated into virtual boat propulsion to facilitate optical flows like water passage.

The development of virtual rowing in the multi-person rowing platform should be evaluated to ensure behavioural realism[Farley et al. 2020; Faure et al. 2020]. The rower's movement and behaviour in VR must closely resemble real-life rowing, in this case rowing on the RP3 ergometers. Related work emphasize aspects of behaviour realism such as the importance of using first-person viewpoint and real-time motion capture [van Delden et al. 2020]. Another aspect is the preservation of realistic and original sizes e.g. for realistic ball spin effect [Faure et al. 2020], or the user's size [Ruffaldi and Filippeschi 2013]. For the latter, [Varlet et al. 2013] reported the difficulty of participants on following a virtual stroke rower that was too small in size. Similar to the recommendation by [Faure et al. 2020], this thesis evaluated the immersive rowing capabilities of the multi-person rowing platform through evaluations with experienced rowers.

Existing virtual rowing simulators predominantly focus on the training of individual rowers. Like the VR4VRT-system, other systems like the SPRINT, M3 Trainer, and commercial available rowing simulators provide personalized training for rowing technique, other skills like energy management. Only a few use such systems to explore multi-person rowing simulators. This lack of information was consolidated through relevant Sports I-Tech systems that were able to facilitate co-located athletes in sport activities, and subsequently show examples real-time augmented feedback that are easy and intuitive to perceive. However, there is difficulty in the applicability of such results to immersive crew rowing. To cope for this, requirements on skill acquisition in virtual immersive environments were identified and subsequently translated to crew rowing and interpersonal coordination. Despite the limited body of related work on immersive crew rowing, there is still adequate information and opportunities to successfully realize the envisioned expansion upon the VR4VRT-system.

4 MULTI-PERSON ROWING PLATFORM IN VIRTUAL REALITY

The multi-person, mixed reality, rowing platform has been built to provide a unique virtual immersive performance environment capable of hosting multiple (co-located) rowers, allowing them to row together as a crew. As of now, no virtual rowing simulator is capable of providing the required foundation to train interpersonal coordination. Therefore, the multi-person rowing platform was developed to fill in the need to facilitate within-crew interactions while respecting the follower-leader relation in a fully immersive rowing environment. This ex-situ system is designed to be a joint learning system that empowers crews, specifically rowing dyads, to train their synchronization in a setup that mimics on-water rowing dynamics by using RP3 ergometers and the performance environment by using the rowing virtual environment.

This section describes how the the multi-person rowing platform was realised by taking the step to expand upon the extant VR4VRT-system [van Delden et al. 2020] towards virtual crew rowing, specifically aimed at rowing dyads. Which consist of expanding upon the VR4VRT-system's architecture and design to effectively double the capacity to host a co-located rowing dyad. Also, how this was subsequently translated into a joint virtual rowing environment concept. After that, the upcoming section describe the realisation of this multi-person rowing platform. First of all, by describing how the system is able capture the rowing dynamics from motion trackers of multiple (co-located) rowers. Secondly, how such rowing dynamics contributed to the facilitation of within-crew interactions by mapping the alignment of the real to the virtual RP3 including the virtual rower avatar and the transfer to the virtual multi-person boat. Finally, the physical and virtual interactions between the user and the multi-person rowing platform are covered step-by-step to explain how to row together as a virtual crew.

4.1 System Design

The multi-person rowing platform consists of a physical setup and virtual environment that interact through the rowers' movement data (see figure 4). The physical setup is similar to the VR4VRT setup, containing an RP3 ergometer, and motion tracking, except that it is scaled up to accommodate rowing dyads. The virtual environment allows rowers to set up and configure their physical RP3 such that it matches to a virtual appearance of the RP3, making them visually coupled. These layers interact by combining and processing the RP3 flywheel and tracker data of the rowers into virtual rowing dynamics. Making the system capable of providing a realistic and immersive rowing experience with respect to the performance environment. So how does the system function for hosting co-located rowing dyads? As the system is expanded to host rowing dyads, the virtual rowing environment must be capable of facilitating social VR experiences. Effectively changing the setup in terms of required space, hardware, and software. However, on the rower level, its foundations remain largely intact. This section will answer the aforementioned question by describing the expanded system in terms of requirements, components, and physical/virtual setup.

4.1.1 Hardware. The figures 2, 3, 4 respectively show the system setup for co-located rowing dyads, the schematic systematic architecture, and the tracker roles and placement on the RP3 ergometer that will discussed throughout this section.

Requirements. The requirements for setting up the VR system for each ergometer/user are based on maintaining a consistent framerate and latency for co-located rowing dyads in NeosVR (see Software). The core components include VR-capable computers, base station tracked VR kits, and VR motion trackers. Additionally, a mini USB to USB A cable that supports a 2.0-highspeed connection is attached to the RP3. During development and testing, the following requirements were found suitable. First of all, a VR-capable PC with recommended specifications such as a fast CPU, minimum

16GB memory, RTX 2070 or better graphics, and at least 10GB of available storage. Secondly, the Valve Index was preferred over the HTC-Vive Pro Eye (used in VR4VRT) in terms of resolution, wider field of view, and refresh rate. Finally, Tundra trackers were used for tracking abilities of continuous movement and easy attachment to the RP3. Using the recommended hardware, the system can provide the intended immersive rowing experience.

Playspace. The setup of the system needs to be capable of hosting co-located rowing dyads on the RP3 ergometer. Not only increasing the required amount of play space needed but also a double hardware setup. The play space is focused on hosting a co-located rowing dyad and therefore occupied with two back-to-back lined-up RP3 model-T ergometers and 4 base stations (see figure 3). Each RP3 with equipped motion trackers does however require that the motion trackers are clearly visible to the base stations. Also, the RP3 is linked with a mini USB to USB-A data cable of 3m to the computer, which is placed together with the monitor in an adjacent way to avoid cable-pulling issues. In addition, the VR base stations should be placed as high as possible (> 2m), angled downwards at the floor, and cover at least 7.5m x 2.5m play space area, to reliably track both RP3s and equipped motion tracking. This should ensure proper tracking of the VR headset and Tundra trackers placed on the RP3.

Trackers. To capture the rowing dynamics, the RP3 ergometer is equipped with VR motion trackers to map the key points of the rowing movement into the virtual environment, as seen in figure 2. The rower is seated on an RP3 ergometer with the Valve Index Head Mount Display (HMD) and 3-4 Tundra motion trackers. All trackers- Machine, seat, handle, and optionally the backtracker- have their own distinctive role in mapping the dynamics of the rower's movement. Respectively always mapping the front part, sliding seat, and handle of the RP3. Note that the seat tracker is positioned next to the seat to be in sight of the base stations for reliable tracking. Moreover, by combining the seat- and back tracker input, one can calculate the continuous back angle. Which is often named as an important measure [van Delden et al. 2020], even to indicate interpersonal coordination [Millar et al. 2013; Varlet et al. 2013; **?**]. Note that the back tracker is not actively used for the virtual avatar movements. All trackers, except for the handle- and back trackers, were stuck to the RP3's surface. The handle tracker is attached directly onto the RP3 handle through a 3D-printed adapter and velcro strap. Whereas, for the back tracker, rowers wore an EOZ chest strap[7] which tightly secures the back tracker to the rower's body. The described VR tracker setup allows the system to track, map and analyze the rower's dynamics.

4.1.2 Software. NeosVR as 'peer-to-peer Virtual Reality metaverse' [8] was used to develop the multi-person rowing platform (as of now rebranded to Resonite . Based on a recommendation, this social VR platform was evaluated through a latency test with a co-located dyad to ensure low end-to-end latency i.e. the time between physical input from one user to visual change on the screen of the other user., preferably < 25ms. To compute this, both users were recorded by using a 120fps camera. The users were equipped with VR motion trackers, in iterative steps of adding one tracker per user, up to 12 trackers in total. Overall, findings show that NeosVR provided sufficient low end-to-end latency (< 25ms), for which the more abrupt movements would result in a temporary lag. Additionally, during the test NeosVR provided a consistent framerate of 60fps for both computers (also because of the computers and network, but nevertheless consistent). All

---

[7] Tundra tracker and EOZ chest strap found on https://tundra-labs.com/

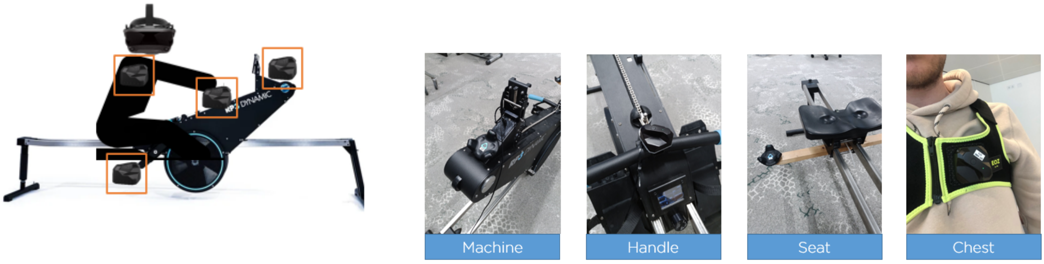


Fig. 2. The VR motion tracker placement on the RP3 ergometer

Fig. 3. The playspace setup used for a co-located rowing dyad (note that for the experiments the entire mirror was covered)

in all, NeosVR as social VR application was found to be well-equipped to develop a multi-person rowing platform on.

Besides NeosVR as social VR platform, the system architecture in figure 4, shows other software programs that are required for the data communication of tracker- and RP3 input, and output log. The SteamVR software is a tool that enables a room-scale VR experience as it allows the computer to connect to the the VR HMD and the trackers, which in turn allows NeosVR to receive the required tracker input in the virtual environment. Secondly, the data communication is established through WebSocket programs. For the RP3 data input, and getting the output log. Looking at the system architecture in figure 4, the RP3 interface program handles the communication from the RP3 to NeosVR and the WebLogger program from NeosVR back to the PC. The RP3 interface constantly reads the wired RP3 input, processes it, and sends its performance output to NeosVR over port

---

[8] NeosVR Metaverse: https://neos.com/

[8] Resonite: https://resonite.com/

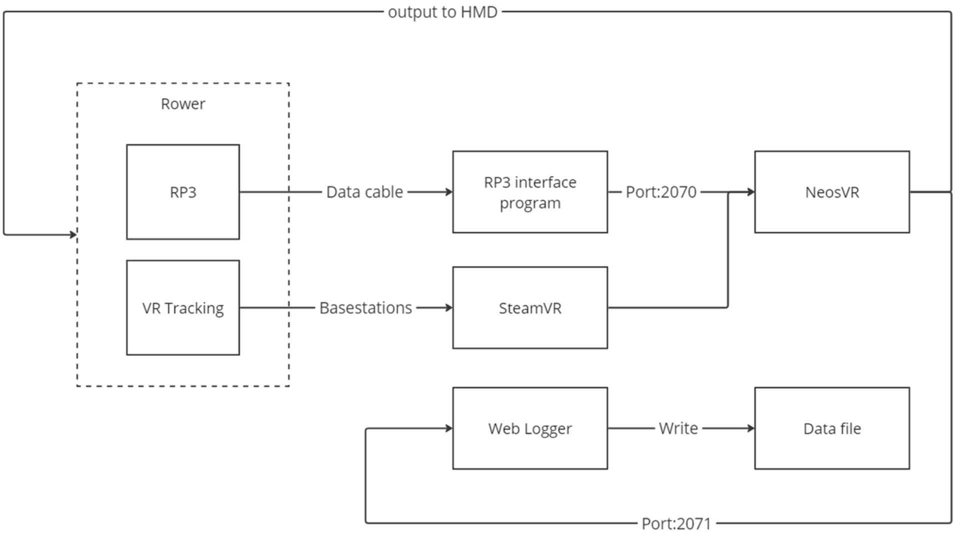


Fig. 4. System Architecture

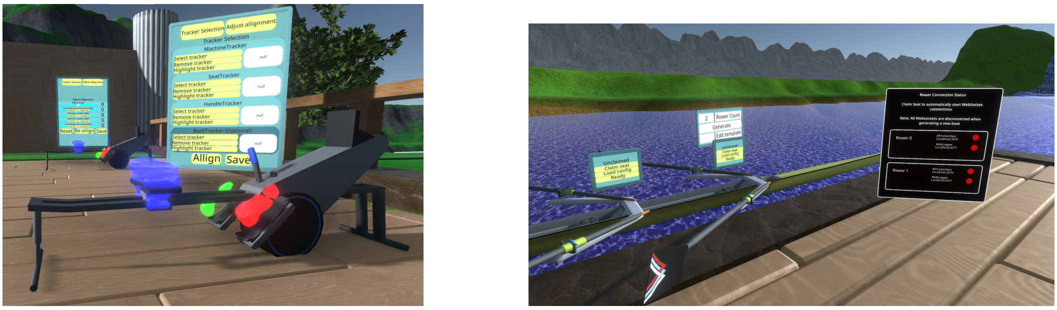


Fig. 5. The virtual Rowing environment consisting of a dock environment to setup the virtual RP3 ergometer (left), and a rowing track with virtual boat setup (right)

2070. Furthermore, the WebLogger runs on port 2071 and receives string typed data transmitted when claiming a seat in the virtual boat (for more details see Websocket Communication) and continuously per frame while rowing in the virtual environment. It then stores the data line-by-line in the log file. When the data communication is active, the rowing dyad is able to setup the virtual configurations in the rowing environment.

4.1.3 Virtual Reality Rowing Environment. The rowing environment is the joint virtual space where rowers are represented by virtual athletes and train together as a crew in a virtual boat. In figure 4 "NeosVR" represents the virtual layer of the system where all the captured rower data input is processed into immersive rowing. When the virtual crew is completed and seated, rowing becomes active and the movement data will be actively used to move the virtual avatars and determine the propulsion of the boat, which is then fed back to the rower's VR HMD, completing the loop in the

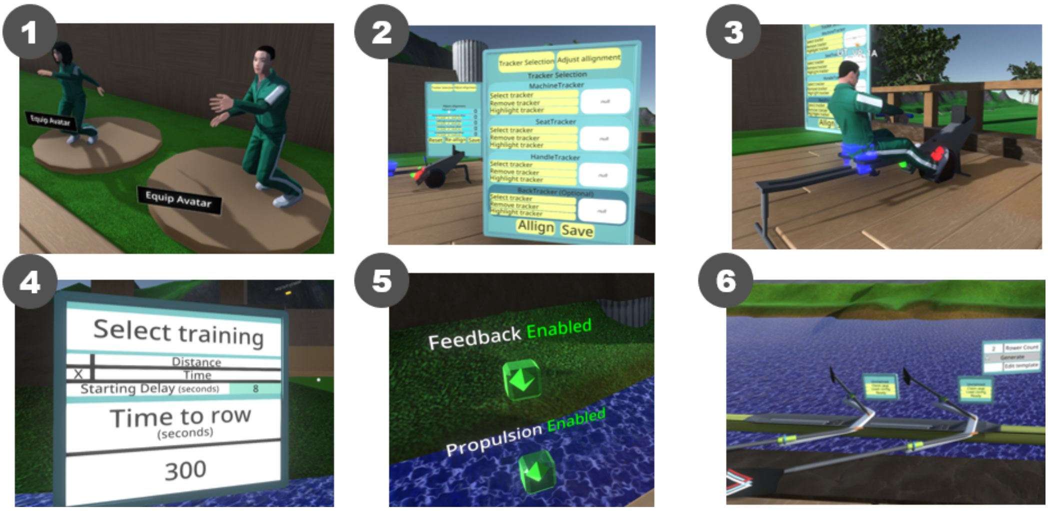


Fig. 6. The required steps to setup your virtual rower counterpart and get ready to row as a crew in VR

system architecture. The virtual rowing environment is designed to distinguish between setup and practice. Rowers first set up their virtual counterparts on the dock environment (see 5), and then move to the rowing track to configure the boat and training. More details on this is are found in the upcoming Implementation and Interaction sections.

4.2 Development Process

This section discusses the development process for the multi-person rowing platform. Providing information on how captured rowing dynamics were processed in order to facilitate within-crew interactions by mapping the alignment of the real RP3 to the virtual RP3 using a virtual avatar rower, and how a multi-person boat system uses this alignment of multiple rowers to keep track of the stroke cycles, and subsequently determines the boat's propulsion. As of now, when a user joins the virtual rowing world, they can configure their virtual rower counterpart by following the steps depicted in figure 6. After the setup of the virtual boat, the crew is ready and can start their rowing practise. Each of the following subsections will correspond to a specific step in the rower setup, which also reflects the order of developments that took place.

Virtual boat generation and anchors. The generation of a real-sized virtual double scull was the first step towards rowing together. To ensure realistic within-crew interactions according to the follower-leader relation, preservation of original sizes and interpersonal distances between virtual rowers and the boat is essential[Faure et al. 2020; Meerhoff et al. 2014; Varlet et al. 2013]. Which means that the double scull including seats, oars, footboard, rigger, and stern require realistic dimensions. Based on Olympic rowing standards [9], the International Rowing, the double scull's average length is 10.4 meter with a minimum weight of 27kg. Also, the oars have to be approximately 3.9 meter long. To realize this, a 3D model of an existing single scull from the VR4VRT-system was re-modeled to a realistic double scull size. From there, the model was divided into the stern, seat, and bow modular parts in order to make the boat modular and allow for different crew sizes. To generate a new boat with x amounts of seats, provide the numerical input in the menu and press 'Generate', the system uses the modular parts as templates i.e. a stern and bow model to form the respective front and end of the boat, then places x amount of seats in between, and subsequently implements the required offsets between the modular parts to eventually form a unified boat model. The next step was to allow seating for each rower in the boat.

In NeosVR, to put a virtual avatar into a seated position requires locomotion through so-called avatar anchors. Anchors can be compared to seat belt as they are virtual placeholders for specific body parts of the avatars e.g. to constraint the hip movement. This placeholder functionality was found suitable to guide the avatar's limb movements. For immersive rowing, the virtual seat anchors consisted of the RP3 seat/hip and feet anchors to virtually represent the hip and legs. To playtest this, users on the RP3 were also seated in the virtual boat and asked to assume rowing stroke positions and move as if they were rowing slowly. Furthermore, the oars were attached to the riggers of the boat, acting as a pivot. After that, the hand anchors were placed on the grip of the oars, and they would follow the hands constrained by the oar pivot. The difference in shape and movement between the RP3 handle and virtual oars, was found to easily result in discrepancies such as floating oars. On the other side, the hip anchor was successful in moving the rower's torso back and forth, while the feet anchor provided sufficient simulation of knee tucks and leg stretches. However, when slightly mismatched, users would struggle to keep the feet in place. If for instance an avatar's shoe was too wide, twitching feet behavior started to occur, also when the anchor was too far the feet would bungle in the air. The first issue was solved by finding a suitable 'Ready Human Player Me' avatar available within NeosVR that included Inverse Kinematics and had to an extent predictable behavior while being anchored. The other issue is discussed later on in the next section. Based on the findings from the playtests with different rowing positions, coupled with the following tracker setup: the machine, seat, and handle tracker to respectively the feet, hip, and hand of the avatar, led to representable virtual rower movements.

Tracker alignment Tool. The alignment of the real and virtual rower is a mixed-reality setup, where rowers realistically map the physical RP3 to its virtual counterpart. First part of this process, described here, is about the development of the tracker alignment tool. The second part of this process, the interaction with this tool and visual alignment /coupling of the real and virtual RP3 is discussed later in the Interaction section.

To avoid a repeating manual process, the tracker alignment menu has been developed as an inventory tool to visually select and align trackers from the real to the virtual RP3. This tool introduces an intermediate step where users can first align their real and virtual ergometer, basically coupling the trackers to the seat anchors, before the rowing activity. It handles the process of assigning roles to trackers e.g. the handle tracker on the RP3 is coupled to the hand anchors placed on the oars. Because of safety concerns in social Virtual Reality, trackers are represented by a random 64-string when spawned in. Therefore, finding the reference of a tracker is not as simple. Assuming the trackers are active and paired to the computer, immersed users can look around, and see floating virtual tracking representations staying relative to their orientation. The alignment menu uses this aspect to let rowers visually select these representations to directly save that specific tracker references in the menu slots.

When all trackers roles are assigned i.e. machine, handle, seat and optionally back tracker, the rowers can visually inspect if the alignment is correct (see Interaction). However, the mapping from the tracker roles to the seat anchors on the virtual RP3 is not straightforward. Looking at figure 2, it can be seen that the seat tracker is next to the seat, and the handle tracker can rotated while attached to the RP3. So how to define the movement direction? Next to the assumptions of the VR4VRT-system on hand and foot placement, another important assumption is that the machine tracker, placed on the front part of the RP3, is consistently in line with the rest of the ergometer.

---

[9] Olympic rowing: Rules, regulations and all you need to know https://olympics.com/en/news/olympic-rowing-rules-regulations-and-all-you-need-to-know

Therefore, the role of the machine tracker is used as reference point for alignment and represents the opposite direction of the boat movement. Since the VR setup cannot be accurate at all times, another sub-menu was developed to manually adjust the alignment in different angles and offsets (see Interaction). Once the alignment is correct, all tracker references including any adjustments are saved into a rower's personal configuration, which eventually is transferred onto a seat in the boat.

4.2.1 Ergometer Physics. The implementation of the ergometer physics is explained to the extent of key metrics and basic stroke detection. For more precise information and math, check out 'the physics behind open rowing monitor' [10]. Due to circumstances, the physics were implemented in a later stage. At that time, a foundation for basic stroke detection and performance variable calculations was already present in the virtual rowing environment. Primarily, the time and distance calculations were based on tracker data, rather than RP3 values. As mentioned before, the RP3 interface program reads the flywheel values, processes these, and outputs them to the virtual rowing environment. For training interpersonal coordination, outcomes of the rowing stroke must be available to rowers i.e. propulsion of the boat. This has been realized by applying ergometer physics and will explained in two steps: First off how to process the RP3 input and secondly the implementation of ergometer physics and the limitations in the current system for rowing dyads.

The RP3 ergometer uses so-called flywheel values to calculate relevant performance variables. During a workout, rowers perform work against air resistance (via the flywheel fans), which increases for higher intensities of rowing. This friction is controlled through a slider that changes the resistance levels from 0 to 10, where a recommended setting of 4-5 is used for experienced rowers in training/on-water (based on expert advice to mimic a double scull). Rowing on the RP3 is about translating the linear force applied on the handle into flywheel rotations. To measure this angular momentum, the flywheel is equipped with four equally spaced sensors. These sensors measure the time between consecutive readings/impulses also known as "flywheel values", which are the basis of all calculated rowing performance variables. In order to calculate the boat's displacement, the flywheel values from all rowers need to be translated into linear velocity.

The implemented ergometer physics provides a robust rotational to linear conversion, which is done in the RP3 interface program. This rotations-to-distance conversion solely depends on calculating a so-called drag factor, based on the flywheel- and boat drag constants, since air resistance is the only force acting on the flywheel, flywheel kinematics can be obtained using fairly straightforward forward-dynamical modeling. Considering the inertia of the flywheel, storing energy in the form of angular momentum, two distinct situations are present. The coupled situation i.e. the drive phase where the rower pulls the handle, and the uncoupled situation i.e. the recovery phase where no force is applied, but the flywheel still rotates (boat still moves). In other words, besides the acceleration/deceleration for stroke detection, the reduction in kinetic energy over the recovery can be used to re-calculate the drag factor. However, the implementation process stumbled upon limitations regarding the exact flywheel kinematics of the RP3. During testing, the drag factor did not match the RP3 performance monitor values. Because most calculations and constants were based on the golden standard of the Concept 2 ergometer and other unknowns on the RP3. It was decided to avoid further systematic errors and adopt a fixed drag factor of 120 [Cuijpers 2019], which resembles resistance level 4 on the RP3. Furthermore, following the robust method as proposed by the 'Open Rowing Monitor'[11]. Effectively estimating the linear velocity by staying close to the measured angular values of the flywheel. It is expected that this method still is suitable for realistic boat movement, but that linear velocity is overestimated for more powerful

---

[10] Open Rowing Monitor - Physics Behind Open Rowing Monitor https://laberning.github.io/openrowingmonitor/physics_openrowingmonitor.html

rowers, and maybe even a slight influence on detecting stroke-related events. To conclude, the RP3 interface program processes the flywheel values by the suggested robust method and outputs the time between impulses, angular velocity, and linear velocity per rower to the virtual rowing environment.

Because of the limitations and unknowns of the RP3 physics, multiple 1000 meter trials were conducted to cope with the systematic errors for single- and double rowing. The goal was to translate the rower's input into a smoothly interpolated non-stuttering movement that is immersive and still approximates real-life rowing. Two coping mechanisms were implemented to accomplish this. First off, to smoothly interpolate the rower's movement input implies a trades-off to responsiveness. A discussion regarding this trade-off was read on the 'Open Rowing Monitor', and a running average is applied to the RP3 input. Secondly, a velocity multiplier was implemented to match the expected travel distance per stroke as a result of testing. As the RP3 has a build-in performance monitor, the travelled distance was used as metric to compare the implemented physics (virtual boat distance in m) to the RP3 physics (RP3 monitor distance in m). Based on the used calculations for the Concept 2, each meter per stroke is calculated by dividing the resistance level by 2. Combined with the experimental settings of rowing trials on 20 spm for 5-minutes means that the approximate travelled distance will be around 1000 meter. With a self-induced threshold of 5% about 50 meters, multiple 1000 meter, and even 2000 meter trials were conducted. It was found that the longer the trial, the more apparent the systematic errors became in the end. Furthermore, note that the velocity multiplier is not an inclusive solution as it tends to deviate for different rowers, particularly rowers that exert more power overall. Eventually for the single rower a multiplier of 4.2, and for rowing dyads a 9.18 was found to more closely match the expected travelled distance per stroke.

4.2.2 Boat System. The boat system refers to the collection of implementations governing the boat's state. It is responsible for the boat's propulsion, host appointment and anchor/release events of the rowers. It is an overarching parent system that holds all other systems, except for the feedback, and manages the state of the seating positions in the boat, and therefore has access to all rower instances like the user- and tracker references. First off, every seat with avatar anchors triggers anchor- and release events that indicate whether or not the seat is occupied by a user. These events are used in both the virtual RP3 and boat to track the current state of a seat including user-specific data. To for instance determine if the boat is fully occupied, or when a user is released to reset the boat to its starting position. Secondly, to avoid syncing issues the collective boat propulsion is calculated by a single designated user, which for practical reasons is the host of the virtual world session and assumed to be the stroke rower. Finally, when rowing is active, the boat system determines the boat's propulsion and updates the boat's position every frame. By looping over the rower instances, the linear velocities are collected, and subsequently averaged over the amount of active rowers to get the boat's linear velocity. Like the physics, this posses a limitation as the rowers are represented equally, despite their individual differences. The linear distance travelled in that frame gets calculated by dividing the linear velocity by the delta time of that frame. During this, it was found that the RP3 ergometer can give signals while being stationary. Therefore, the linear velocity needs to exceed a velocity of 0.7 m/s to be considered as active rowing. Finally, the aforementioned smooth interpolation is applied to this linear distance in order smoothly propel the boat backwards.

4.2.3 Rower Management. Each rower in the boat, through claiming a seat, has their own subsystem that keeps track of the tracker input, anchor movements, stroke cycle status, and performance variables. The stroke cycle management of the rowers is modeled like the finite state machine also used in the VR4VRT-system [van Delden et al. 2020]. In this model, a rower has an idle, drive, and recovery state. Where the idle state refers to an inactive rower and when active resets the performance variables on start and after the rowing practise is finished. When rowing is enabled, a drive phase is assumed and the system awaits the RP3 acceleration in order to start the new stroke cycle. Switching between the drive and recovery phase is based on the acceleration/deceleration of the flywheel indicated by the angular acceleration. When this variable is positive (i.e. above 0.0) informs a drive phase, whereas a deceleration (i.e. lower than -0.1) informs a recovery phase. At this time, the rower also hosts their WebSocket connections to the RP3, Weblogger connection to NeosVR and subsequently calculate and safeguard their own performance variables like time (stroke rate, drive time, recovery time), distances (stroke length, min flexion, and max tension), and back angle values per stroke cycle.

4.2.4 WebSocket Communication. The WebSocket connections are established and handled by the seated user. When a new boat is generated, each seat is equipped with two Web Socket objects to connect and receive/transmit data from the RP3 and to the Weblogger. WebSocket connections in NeosVR are required to be handled solely by the same user that is also referenced as its handling user i.e. the seated rower is responsible for establishing the connection and transmitting data. Assuming the WebSocket software is running on the computer, the connection can be completed from within the virtual rowing environment. To accomplish this without any errors/disconnects, utilize the button for claiming and unclaiming a seat in the boat, which is a user-specific action coupled to connecting/disconnecting a WebSocket. Upon claiming a seat, the reference of the interacting user initializes the WebSocket connections automatically. If done correctly, the rower connection menu visually updates the status to green indicating successful data communication. The rowing dyad can sit in their claimed seat, hold their handles, and be ready to row.

If a situation requires rowers to switch seats, they can simply unclaim their current seat, claim another seat, and load their configuration onto that seat. Effectively disconnecting and then establishing a new WebSocket connection. When a WebSocket is closed, its handling user reference is set to null, which resets the active connection and resets the driven rower-related variables.

Once the rowing starts, RP3 values are received four times each flywheel rotation through a string containing the angular velocity, time between impulses, and linear velocity which are then used to drive the rower's performance variables and directly inform the stroke detection process (see Data acquisition and processing). On the data collection end, the weblogger transmits both continuous and discrete data. The continuous data is sent each frame and includes the current tracker position- and rotation, back angles, phase status, and if applicable feedback variables. Furthermore, after each stroke, discrete data is sent that summarizes the stroke in terms of timing, stroke length, and various min- and max values e.g. back angles. All this outputted data is actively written line-by-line to a log file. If all rowers established both of their WebSocket connections, by claiming a seat, the rowing practise can be setup and started.

4.2.5 Data Acquisition and Processing. For each rower, both continuous and discrete performance variables are computed to facilitate immersive rowing and data logging purposes. As mentioned before, each seat has a subsystem that tracks and computes all rower-related variables. Which also inform the generation of visual augmented feedback. The computed performance variables are based on either the flywheel values from the RP3 or the captured rowing dynamics through the trackers' positional and rotational values. For data acquisition and processing, the flywheel values inform the stroke cycle detection process, whereas the tracker data is used to continuously move the virtual avatar, and compute distance-related variables such as stroke length and the back angle.

The stroke detection process is based on the flywheel values to determine when the rower switches from drive to recovery or vice versa. When a stroke cycle starts it is assumed to be in the drive phase. During this phase, performance variables are computed throughout. (examples include). When a switch to the recovery phase occurs i.e. the finish, variables like stroke length or drive time are computed. Also during the recovery phase, performance variable continue to be computed. However, when a switch occurs to the drive phase i.e. the catch, first all stroke cycle related data is collected and send over to the web logger, referenced as so-called ’end-of-stroke data’. Then before initiating a new stroke cycle, the stroke cycle related data is reset.

The performance variables are categorized as either continuous or discrete in nature, and involve either time or distance related data. For the continuous data, the following time-variables are tracked: time between impulses (RP3), system time, frame-rate, delta time and stroke rate. These persist during the rowing activity, except for the stroke rate, which is a rolling average over 3 consecutive strokes to smooth out variability and improve accuracy (see ’Open Rowing Monitor’). Furthermore, tracker positional an rotational data for the machine, seat, hip and back tracker. For which, the distance between the handle- and machine tracker is used to calculate the stroke length, and the seat- and back tracker are used the inverse of the tangent function to compute the back angle, additionally converted from radians to 0-180 degrees. For discrete data, calculated at either catch or finish position, the following time-variables are tracked: drive time, recovery time, stroke time. For the distance-related variables this includes the back angle and stroke length. In particular the minimum and maximum values during a stroke cycle. For the back angle, there is a continuous check whether or not the min or max values are exceeded and need to be updated. Whereas for the stroke length, it is assumed that the catch and finish position correspond to the minimum and maximum travelled handle distance, by extracting these from each other the stroke length is determined per stroke cycle. Eventually, all the performance variables and logged in a single file to use for data analysis later on.

4.2.6 Training Setup system. The training system enables the rowing activity and keeps track of its progress before, during, and upon completion of the training. By tracking changes regarding the boat’s position, stopwatches, and occupied seat anchors, the system is capable of tracking the training status throughout. Rowers can manually change the training settings in the training menu. Change the type to either distance or time and set the length of the training by providing numerical input in either meters or seconds. The training over distance compares the current boat’s backward position relative to its starting position, and over time uses a stopwatch to keep track of the elapsed time. Furthermore, an initial starting delay can be set that delays the start of the rowing activity. When the boat is at the starting position and all rowers are anchored, rowing is automatically enabled. Allowing for direct RP3 input that results in the propulsion of the virtual boat. It was however found that immersed rowers needed some time to familiarise themselves when they anchored into the rowing seat, often times requiring about ten seconds to mentally prepare themselves. If errors occur during the training, the boat and rowers can be safely teleported back by releasing any user from their seat anchor (space for desktop mode or jump with one of the VR controllers). This automatically also resets the training setup. When the training is completed without issues, it will enter the finishing process. A countdown appears indicating that the training is complete, and that a reset will occur in ten seconds. No more ergometer input is used and the boat effectively slows down without it, since the immediate stoppage of the boat was indicated to occasionally introduce motion sickness. When the timer is depleted, both the boat and rowers are teleported back to the relative starting- and release positions near the start of the rowing track. In summary, the training system is not only responsible for all the start- and stop mechanisms surrounding the training, but also provides timely status feedback before and upon completion of the training to prepare the rowers for what will happen.

4.2.7 Environmental design. To accommodate for all distances, the rowing track itself is designed to be an endless straight river track. In order to create a calm virtual environment for rowing dyads, a few lenses from [Schell 2008] were applied to design world aesthetics and spaces, to set a calm and relaxing atmosphere. Which forms a solid contrast to the active rowers. The lenses of freedom and atmosphere provided insights on how to design the river track. Note that the dock environment is not discussed into detail here. Similar to [van Delden et al. 2020] there is a need for a one-dimensional endless river track for the boat to traverse. Also the river is implemented such append that a new river track gets appended after the previous track is almost completely traversed by the virtual boat.

A 3D riverbed was designed and modelled as a relaxed river track with scope of space and dynamic water in mind. First off, a waterfall has been designed to serve as a visually pleasing vanishing point. Secondly, in comparison to [van Delden et al. 2020], the riverbed hills were lowered to about 3-4m and hills were placed at a distance to provide background. Also the width of the riverbed was doubled in size. Thirdly, available textures in NeosVR were picked based on the nature reserve color palette from [Nat 2024] and applied to the height-based color map (see 5). The chosen textures closely resemble grass, yellow grass, dirt and river bottom. And finally, to create the perception of moving water, an available dynamic water asset was used. It was implemented to provide a steady neutral water flow in a skewed direction opposed to the vertical movement of the boat to enhance the visual perception of travel distance during the drive phase.

4.3 Interaction

This section will describe the interactions a rowing dyad will have with the virtual rowing environment. Up till this point, parts of the interactions are touched upon and described. Therefore the focus will be on how an immersed rowing dyad sets up and experiences a training practice from spawning into the virtual rowing environment up to completing a row training as a crew in the virtual boat. This will be covered into the following sections, namely the virtual rower representation, setup of the Virtual boat and the row training.

The virtual RP3 is a real-sized 3D model of the RP3 ergometer, meaning that if the alignment is set up correctly, one experiences mixed reality (see interaction). Once the configuration is complete and saved, the rower moves to the end of the dock, next to the rowing track.

Reaching out to the virtual RP3 handle also results in grabbing the actual handle. Which also holds for the physical seat and somewhat for moving the legs. As the leg size depends on the chosen model, which is a one-size-fits-all avatar since bodily personalization is out of scope. Reportedly no problem for rowers around approx. 1.70-1.85m.

Aligning the Real and Virtual Rower. Besides the tracker alignment menu, stands a virtual RP3 ergometer that is used to ensure the visual alignment between the real and virtual RP3 is correct (see figure 6 step 3). Before this can be done, rowers have to interact with the tracker alignment menu. As mentioned before, rowers can see the virtual tracker representations staying relative to their orientation. In figure 6 step 2, it can be seen that the tracker alignment menu consists of four sub-menus, each representing an empty inventory slot to save a tracker reference. To align for instance the Handle tracker, click on the 'Select Tracker' button near 'HandleTracker', and a cone-shaped tooltip with a laser pointer will automatically equip on the right hand.. The rower can use the tooltip to point at the virtual tracker corresponding to the actual handle tracker. When it lights up blue, pressing the trigger will select the tracker, and directly updates its reference in the menu slot, which will no longer be 'null'. Once finished, rowers can use the 'align' and 'save' buttons to save the alignment configuration.

Next, rowers have to visually inspect the alignment by checking for responsive movements while being seated on the RP3 ergometer with a virtual avatar body. The virtual RP3 is a real-sized 3D model of the RP3 ergometer, meaning that if the alignment is set up correctly, one can experience mixed reality. Specifically, the rower should notice the hands being attached to the handle, a responsive sliding seat, and moving legs when actually pushing out their own legs. The best indicator of correct visual alignment is to grab the virtual handle while immersed should result in physically grabbing it. Which also holds for the physical seat and to a lesser degree for moving the legs. As the leg size depends on the virtual avatar model, which is a one-size-fits-all avatar since bodily personalization is out of scope. To cope for this or other changes, the adjustment menu allows for real-time adjustments to the rower's viewpoint by changing angles, or by applying offset in different directions. Once done, the virtual rower representation is complete and the rower can move towards the dock environment to setup the virtual boat.

Setup VR Boat and Seat. The virtual boat setup is done by interacting with a boat generator- and seat menu. Looking at figure 6 step 6 shows a double scull with the single menu being the boat generator menu, and the two smaller menu being the seat menus. To create a virtual double scull, the rower can use the boat generator menu, change the 'rower count' to 2 and press generate to get an instant generated double scull with a seat for both the stroke and bow rower. Next to each seat, a menu has appeared that can be used to claim a seating position in the boat. When the rower claims a seat, it automatically provides a visual indication with user name and showcases the seat anchors to indicate its claimed state. However, this does not contain the alignment configuration yet. Rowers have to load the alignment configuration onto the seat before entering. If not done, rowers will experience out-of-body experience due to the virtual body missing guidance from the seat anchors. Again, if any changes are required, rowers can release themselves from the seat anchor, go back to the virtual RP3 and adapt their alignment setup. It frequently occurs that this requires a back-and-forth between the aligning of the virtual RP3 and loading the configuration on the seat. Sometimes this even requires a re-calibration of the VR room setup. Once the alignment is correct and both rowers are anchored, a countdown appears to mentally prepare the rowers for the start of the row training.

Row Training. The virtual crew approximates on-water rowing by capturing their movement dynamics and within-crew interactions. During the training, these are based on mainly visual information, therefore these are best described by reflecting upon the aforementioned requirements for training interpersonal coordination in Virtual Reality [Farley et al. 2020]. First of all, rowers in VR are capable of producing the rowing stroke in synchronization similar to real-world rowing. In this setup, the dynamic RP3 ergometer serves as the input device capable of simulating on-water rowing. Furthermore, correct alignment results in capturing accurate rowing stroke dynamics performed by the virtual avatars through the tracker input. Together these form a solid basis for performing a realistic rowing stroke. A bow rower in a rowing dyad can synchronize based on realistic information from the dynamic stroke avatar. On the other hand, the stroke relies on repetitive environmental landmarks, where for instance the water passage is continuously the same. This leads to the Second requirement of performing the rowing stroke in a variety of conditions. The same reasoning holds here, the only difference lies in the limitation of allowed perturbations. Besides the difference in seating, both rowers can only experience the backward movement of the boat. Similarly, the rowing track repeats itself and does not have distinct landmark features. Rowers interact with each other and the environment in a constrained manner. A side effect of trackers is that unnatural perturbations also occur in the form of drifting avatars and/or oars. When not tracked correctly, this directly impacts the avatar dynamics and sometimes results in avatars sliding forward or backward with their whole body, lowering the immersion. Thirdly, outcomes of the rowing strokes must be available to rowers including sensory consequences. The current setup respects the follower-leader relation for rowing dyads but is limited beyond perceptual coupling. The rowing dyad interacts in VR mainly through visual information, involving the back-and-forth movement of real-sized avatars/objects and optical flows from the virtual environment. Good to note is that the Field Of View (FOV) of the used Valve Index is about 130 degrees... However, limited by mechanical coupling. It was found that immersed users, when mechanically coupled, experienced a more realistic rowing experience but were indicated to be more sensitive to motion sickness when perturbations occurred, especially detrimental when caused by latency. Rowing in the virtual environment is designed to incorporate rowing dynamics and interactions similar to the performance environment. Part of the virtual row training is the option to active feedback, The next section will be the second contribution of this thesis, namely augmented feedback tailored to the roles of the rowing dyad.

5 AUGMENTED FEEDBACK

Visual augmented feedback has been designed and developed to facilitate training of interpersonal coordination by providing real-time personalized visual support for the stroke and bow rowers in their respective roles. Specifically, to guide (and ideally train) them in their perception of time- and movement qualities relevant for maintaining stable and functional interpersonal coordination, which are otherwise intangible. As the system is capable of hosting co-located rowing dyads while respecting the follower-leader relation, the next step is to augment this dynamic through the application of visual augmented feedback, and not to overwhelm rowers.

Importantly, the focus of this thesis is on the application of augmented feedback to facilitate skill acquisition of interpersonal coordination by guiding the rowers' visual perception and inform them about the knowledge of performance (KP) i.e. the quality of the executed movement. Ideally, as [Sigrist et al. 2013] mentions: "Visual concurrent feedback designs are desirable that guide the learner toward the optimal movement without causing a dependency on the feedback". However due to time constraints, feedback schemes for bandwidth feedback are out of scope. Moreover, neither transfer nor retention tests were conducted to investigate the feedback's effectiveness. Despite this, examples of related work with/without similar limitations still reported the positive impact augmented feedback can have on interpersonal skills [van Delden et al. 2020].

Therefore, this section describes how this was realised by the describing the design, development and testing processes that led to the final feedback forms as shown in figure 7, including how rowers interact with the presented augmented feedback.

5.1 Ideation session

An ideation session was conducted with an expert in the Sports Interactive Tech field to tinker about what, when and how to provide augmented feedback within the scope of promoting interpersonal coordination for immersed rowing dyads. Both the researcher and expert had first-hand experience with rowing in the multi-person rowing setup with and without VR. The session was divided into the following parts: 1) recall the rowing experience in VR through videos showcasing the stroke and bow perspectives, 2) how to design augmented feedback to make optical flows visually tangible for immersive rowing including a mix-and-match on various feedback forms, and 3) the application of feedback schemes, particularly focused on creating/avoiding dependency. The following paragraphs will focus on highlighting the most relevant findings for each part.

The immersive rowing experience

By recalling the immersive rowing experience from the rower's perspective, the difference in visual stimuli between stroke and bow was once more underlined. In the rowing setup, both rowers are limited in directional movements while seated. Unlike the stroke, the bow rower was found to embrace a more thrilling experience that has a myriad of visual stimuli to act upon (also noted by [Millar et al. 2013]). Leading to a more immersive experience and togetherness. The overall impression was that the stroke rower is isolated and leading based on limited access to feedback, whereas the bow rower has access to more visual support like segmental information from the front rower's virtual body.

Personalized visual augmented feedback

The most prevalent ideas to suit both rowers were based on guidance through abstract visual feedback forms. To be more precise, for the stroke rower, tasked with setting an easy and intuitive to follow stroke rate, the visual handle trajectory feedback already present in the VR4VRT-system was found suitable to augment the stroke rower's role by providing guidance on maintaining a consistent drive-to-recovery ratio throughout the rowing activity. For more details on this feedback see [Bergsma 2020].

For the bow rower, feedback forms involved visual augmentation of the bodily information from the stroke rower and the interpersonal distance between the rowers. From the bow's perspective, the stroke's upper back was found a relevant source of information to coordinate upon for non-VR rowing [Millar et al. 2013; van Delden et al. 2020]. In particular, the upper back as pendulum and the scapula movement during the drive when exerting power. Furthermore, the concept of puppeteering, related to 'connecting' the stroke and bow rower by visually augmenting the interpersonal distance as a 'wired' connection between rowers, was considered beneficial for the bow rower. With a similar function to the augmented feedback from the elastic bands by [Yokoyama et al. 2020], making the interpersonal coordination tangible as a 'wired' connection between rowers to indicate a real-time synchronization status. Using attributes like color, intensity to indicate the 'tightness' of the connection.

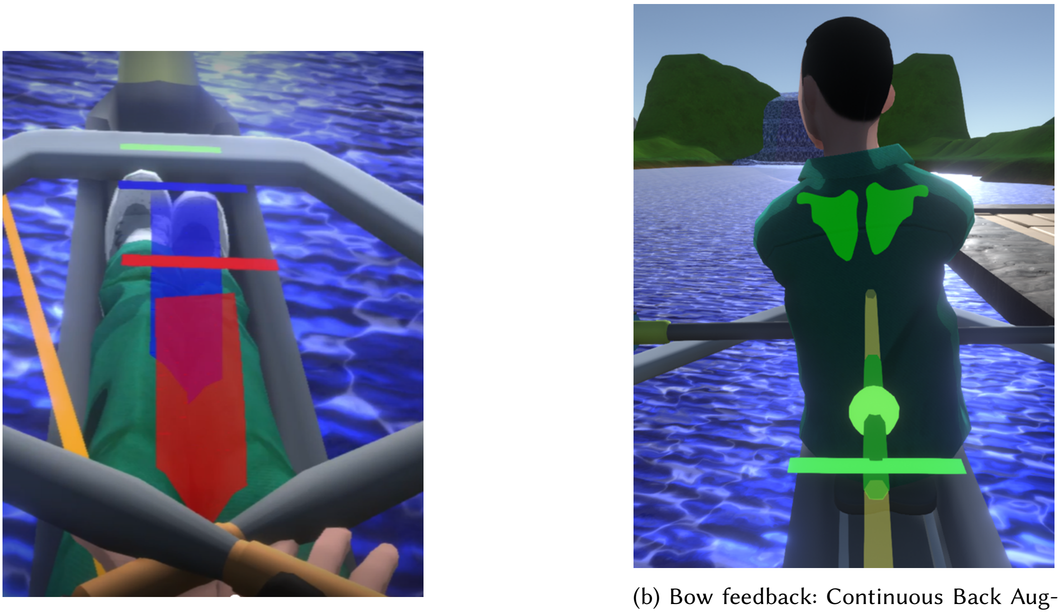
Finally, both feedback forms were ideated to move along a constrained linear trajectory because of the rowing setup. Furthermore, both forms augment existing optical flows also found in real-life rowing within the Field Of View (FOV) of the rowers. Therefore, when made tangible through abstract visualisations, is considered to potentially help rowers in training their interpersonal coordination as it is intended as an external source of information aimed at complementing the rowers in their visual perception.

Dependency

An external focus in the form of visual feedback to promote interpersonal coordination can be beneficial, but only if the rowers are not overwhelmed and feedback is not permanent [Sigrist et al. 2013]. Due to time constraints, the design and implementation of fitting feedback schemes is out of scope. Nevertheless, permanent or 100% frequency feedback causes dependency on the learner. But how to design feedback in such a way to avoid this? Especially when there are no clear-cut guidelines as the effectiveness of augmented feedback cannot be drawn from most related work. However, by reversing the question into how to deliberately design for dependency, new insights were gained to avoid potential pitfalls.

Not respecting the follower-leader relation was considered having the most impact for inducing dependency on rowers. By tampering with the inherent access to perceptual information, the premise is that rowing behaviour becomes dependent on the feedback. First of all, by providing the stroke rower with the bow's segmental information that is otherwise not perceivable. For instance, continuously offering a side-view visual of both rowers' posture to the stroke. Secondly, the augmentation of non-functional optical flows is expected to deceive learners into using irrelevant information to incorrectly coordinate upon. Thirdly, overwhelming the rowers by introducing visual clutter that can also block the rower's field of view while rowing. And finally, introducing unintended effects by not preserving the real-size of avatars and objects as noted by [Faure et al. 2020; Ruffaldi and Filippeschi 2013; Varlet et al. 2013]. By for instance making the feedback too small-sized, disproportional or out of position to directly steer the external focus of attention in non-meaningful ways.

To avoid dependency, feedback should only augment optical flows that are relevant in real-life rowing by making them visually tangible and guide rowers in learning how to perceive them. Eventually the personalized augmented feedback should lead to improved unison of the collective rowing behaviour towards more stable and functional interpersonal coordination.



(a) Stroke feedback: Handle trajectory feedback during the recovery phase based on an adaptive Drive-to-Recovery ratio

(b) Bow feedback: Continuous Back Augmentation through scapula movement and Centre of Mass visualization inspired by rope pulling

Fig. 7. Augmented feedback through abstract visual forms

5.2 Final Feedback Designs

The concurrent visual augmented feedback forms have been designed to support the stroke and bow rower in their respective roles. In order to support rowing crews in training the skill of interpersonal coordination, real-time augmented feedback should guide the rowers in perceiving the quality of the movement execution. In this case, augmented feedback has to promote functional and stable interpersonal coordination [Poel, de et al. 2016], including a margin of error to allow for functional adaptations as the follower-leader dynamic is flexible [Hill 2002; Seifert et al. 2017]. On top of that, the augmented feedback has to augment optical flows such that it supplements the rower's perceptual attunement to the desired movement execution that resembles real-life rowing behaviour within rowing dyads [Farley et al. 2020]. To reiterate, the stroke rower sets the stroke rate and rhythm, whereas the bow rower follows this lead and is responsible for the stability by steering the boat. The latter is not possible in this setup and limited to follow and adapt to the stroke's lead. From the ideation phase, it became clear that feedback should respect the follower-leader relation by augmenting existing optical flows. For which the augmentation itself should not overwhelm the rowers to avoid dependency. As seen in figure 7, the augmented feedback forms consist of abstract visuals that augment optical flows to guide rowers in an intuitive way. Feedback for the stroke is aimed at maintaining a consistent stroke rate by visualizing the drive-to-recovery ratio. Whereas feedback for the bow focuses on back augmentation and the center of mass. Feedback is coupled to a specific seat in the double scull and gets triggered by events and performance variables from the rower management system. In other words, visual augmented feedback makes interpersonal coordination tangible by generating abstract visuals based on rower dynamics and stroke cycle data.

To maintain a consistent stroke rate, the stroke rower receives feedback on the ideal velocity trajectory of the handle during the recovery phase (see figure 7a). This feedback was recreated based on the autonomous handle trajectory feedback used in VR4VRT-system ([van Delden et al. 2020]), specifically [Bergsma 2020]. As recommended, the drive-to-recovery ratio should not follow the 'standard' 2:1 ratio, but be adaptive on the stroke rate. Therefore, the drive-to-recovery ratio is adapted for either 'Training' or 'Race' pace (2.06 below or 2.85 for over 30 spm). Which is based on the rates in table 9.2 'Time to Reach criteria of the Force Curve in %' in [Kleshnev 2020] for rowing. Based on the drive time and adaptive drive-to-recovery ratio, the ideal constant velocity for the handle trajectory is determined and subsequently visualized.

Feedback for the bow rower, as shown in figure 7b, consist of visual augmentation of the upper back and the interpersonal distance between the rowers inspired by thug-of-war. The scapula feedback augments the upper back movement by accentuating the in-and-outward movement of the rower's scapulae. From ideation, the upper back as pendulum and particularly the movement of the shoulder blades was found to represent the drive and recovery phase well. In addition, the center of mass feedback visualizes the (center of) interpersonal distance within the rowing dyad. Based on the ideation, the feedback was modelled like 'Tug of war'. In this sport, both teams test their strengths by pulling at the end of a rope and win by bringing it at a certain distance. At all times, it is relatively straightforward to understand the current state of the game, as the rope is marked in the middle and the distance is marked by a line. When putting this into the perspective, similar to [Yokoyama et al. 2020], on coordination and visual augmented feedback, these principles can also be applied to visualize the center of mass between two lined-up rowers. Additionally, the scapula can help determine when a rower 'pulls' on the center of mass. The final augmented feedback form, as seen in figure 7b, visualizes the interpersonal distance as a wired 'connection' between the stroke and bow rower and communicates the current state of synchronization through color and intensity.

The visual augmented feedback forms are generated based on real-time comparison of the rowing dynamics and stroke cycle data. Therefore, within a rowing dyad, both the stroke and bow have access to personalized feedback supporting them in their respective roles by augmenting "intangible" visual information. Next section will detail how these visuals are actually generated.

5.3 Development Process

The development of augmented feedback, as seen in figure 7, consist of dynamically driven abstract visuals informed by performance variables and stroke cycle events. At the start of the rowing activity, the feedback is not shown immediately as it requires three consecutive strokes for not only the rowers to get into rhythm, but also to initialize a baseline for some performance variables e.g. the stroke rate is calculated over an rolling average. Otherwise, visual feedback would lead to provide unusable information to coordinate upon. Other methods to account for unrealistic feedback involve around preventing feedback overlap and range of motion/thresholds. Normally when feedback is enabled, often its position, color and intensity are driven i.e. continuously controlled as long as a specific event or state remains unchanged. Like the bow's feedback being active for the entire stroke cycle. Whereas the stroke's feedback is only active during the recovery phase. After which, the feedback is reset and disabled during the drive phase. However, due to inaccuracies in data such as the occasional tracker drifting, the visual feedback can become uncontrollable and meaningless e.g. the bow feedback visuals ends up in the stroke's Field of View like the orange line (centre of mass feedback) in figure 7a. To counter this, prevention of feedback overlap was implemented by a built-in override component that renders feedback visuals inactive for the other rower based on the seating position. Furthermore, ranges of motion were implemented by mapping and clamping performance variables between specific ranges found through testing. One of such examples is the allowed offset for the handle height when tracker drift occurs. All feedback forms are coupled to a specific seat in the virtual boat and gets triggered by events, state- and performance variables from the aforementioned rower management system. The next paragraphs will discuss further implementation of the stroke and bow feedback separately.

The Stroke rower receives feedback during the recovery phase on the trajectory of the handle. With the goal of making the stroke rate more consistent throughout the rowing cycle. This feedback is recreated based on the autonomous handle trajectory feedback used in VR4VRT-system ([van Delden et al. 2020]). As seen in figure 7a, the feedback consists of a blue and red line that shows the respective ideal and erroneous handle trajectory during the recovery. These lines will always move forward at the current handle height, clamped within the height range of the seat and the avatar's upper chest, to take into account potential tracker drift and ensure that feedback moves within Field Of View (FOV). The transparent trail behind the lines indicates the margin of deviation, the same as used for the VR4VRT-system [Bergsma 2020]. To mimic these deviations, the trials were recreated by using a Particle System that emits ribbon particles at a high rate. Unfortunately, it was not possible to directly adjust the length of these trials, which eventually was done by changing the lifetime to a fixed 0.5 seconds, which had the most representative effect. Furthermore, two lines placed near the catch and finish position, represent the virtual hand position for the minimum and maximum achieved stroke length. These lines form the trajectory that the feedback moves over during the recovery. The drive time, trajectory length, and drive-to-recovery ratio were used to calculate the feedback's constant velocity. As mentioned above, the drive-to-recovery ratio is adapted for either 'Training' or 'Race' pace (2.06 below or 2.85 for over 30 spm). When the feedback is not active, the lines are replaced by another single transparent line visual that follows the handle position during the drive. By implementing and slightly adjusting the velocity feedback from [van Delden et al. 2020], which was reported to be intuitive, a simple yet effective feedback form for the stroke was implemented.

The bow rower receives feedback based on the visual augmentation of the stroke's upper back and the interpersonal distance between the rowers inspired by Tug of war. Looking at the figure 7b, aside from the scapula highlight, the other visual elements belong to the 'center of mass' feedback visualization and indicates the state of interpersonal coordination through interpersonal distance between rowers based on comparisons of the relative stroke length from both rowers (see Testing). By combining the back augmentation and center of mass visualization, the aim is to train the bow rower in reading the interpersonal distance. The implementation of the visualization went as follows:

First of all, the scapula is visualized in an abstract manner and highlights the movement of the stroke's back, in this case as if the upper body is a pendulum relative to the seat/rower's hip. A 3D model of a scapula outline was created in Blender for this. This model was placed slightly outside the left- and right shoulder of the avatar. The drive and recovery are visualized by moving the left- and right-scapula towards and away from its center by applying an offset. Which is calculated by mapping the stroke length from 0-100 percent based on min and max values against a manually determined maximum offset. During the drive phase, the shoulder lock is accentuated by making the offset positive and moving the scapula outwards and vice versa for the shoulder 'release' during the recovery phase. Also, a color change from light to dark green accentuates this movement.

Secondly, the center of mass feedback visually connects and augments the interpersonal distance between the bow and stroke rower. The feedback consist of a centred (green) area, sphere and a horizontal line visual. Which consecutively represent the desirable range of interpersonal distance, ideal interpersonal distance and current difference in interpersonal distance between rowers. The line connections are generated by using segment meshes, which dynamically interpolate a line between points A and B, in this case, the respective avatar's upper chest nodes. Furthermore, the desirable distance range introduces a margin for deviations from the ideal center. This offset was eventually made 20% to allow for functional adaptations after receiving feedback from testing. Next, the sphere indicates the ideal center i.e. ideal interpersonal distance related to in-phase coordination, and the horizontal line informs the bow on the relative difference from the bow to the stroke. Rather than the stroke pulling away this line, the opposite has been implemented. In this way, if the line moves towards the stroke and away from the middle, it indicates the bow rower lags behind and should 'pull' the line back to the center. On the other hand, if the line comes closer to the bow, it can be 'pushed' away by slowing down to the stroke's lead.

By mapping the stroke lengths and their min/max values between 0 and 1, the relative phase as a percentage value is determined. By further subtracting the bow from the stroke's phase divided by two, the current intepersonal distance can be calculated continuously updating the horizontal line's position. As seen in 7b, the colors are all green for correct in-phase coordination. When the coordination is not considered in-phase: the sphere becomes yellow, the desirable range orange, and the horizontal lines also become orange. To indicate to the rower that the horizontal line should be guided back within the desirable range, and ideally on par with the 'ideal in-phase coordination' sphere. Note that these feedback form are generated and moved based on real-time tracker data. Meaning that unlike the stroke feedback, it is more sensitive to tracker inaccuracies.

Where the stroke feedback is a closed feedback loop, using visual handle trajectory only during the recovery phase based on the stroke's drive time and stroke rate. The bow feedback is continuously adapted based on both the stroke and bow's segmental information and distance measures such as the stroke length. In summary, the development of concurrent augmented feedback was focused on actively managing the orientations and visual properties of the abstract visuals within realistic ranges of motions to represent real-life rowing behaviour.

5.4 Playtesting

The implemented augmented feedback forms were evaluated through playtesting [Schell 2008], in order to evaluate the design decisions and fine-tune the feedback based on the user experiences. Specifically, to get insights on the (bow) feedback's responsiveness, intended behaviour, and intuitiveness. Both non-rower and rower users were explicitly instructed about the role and function of the feedback (also done in the experiment). Most of the results from the playtests and subsequent changes were already discussed in earlier subsections. Except for the bow's perspective and the feedback's positioning, for which separate testing was done for the center of mass feedback as shown in figure 7b. As mentioned before, the visual line connections that visualize the interpersonal distance between the stroke and bow rower were drawn from segment A to segment B. However, the virtual rower avatar has a lot of body segments, from which the following options were considered from stroke-to-bow: chest-to-chest, neck-to-neck, and back-to-seat. However, each of these has implications for how the perception of this feedback. Therefore, this was playtested in a 3x2 minutes format to evaluate all options.

Feedback from users indicated that they experienced more stability with the neck-to-neck and chest-to-chest perspectives. However, the neck-to-neck form was too sensitive in stuttering and also the skewed bow's perspective on the feedback made it harder to interpret as it was deemed accurate but not precise. Similarly, the chest-to-chest was found to be accurate but more precise and stable during the drive. Most likely due to the inverse kinematics of the virtual upper body. Lastly, the back-to-seat perspective was interesting as it showed a more vertical form of the center of mass feedback and was found intuitive to follow. But again was found to be very sensitive in movement and overlapping with the visual upper back augmentation. Taken together, the chest-to-chest visual connection, as seen in figure 7b, offered the preferred perspective for interpreting the feedback.

Like [Sigrist et al. 2013] mentions, the design of augmented feedback is both a science and an art. During testing, many visual properties, positions, offset, options, and dynamics were discussed that potentially affect the feedback's design and its ability to augment optical flows. The feedback seemed to have sensitivity issues acting on the rowing dynamics based of tracker input, again indicating the trade-off between responsive or smoother motions. Most importantly, the general consensus was that the feedback forms were found to intuitive to follow for immersive rowing.

5.5 Pilot Testing

Two pilot tests were conducted to test the experimental rowing setup, as depicted in figure 3 and 4, with experienced co-located rowing dyads (as suggested by [Faure et al. 2020]). Following the empirical study procedure, the rowing dyads were instructed to synchronize for 5 minutes on a pace of 20 spm in all conditions. Furthermore, the WebSocket communication was active to check for proper data acquisition for both rowers. Moreover, the pilot tests were conducted with mechanical coupling.

Based on the pilot tests, important changes have been made to the rowing setup, data collection and augmented feedback. The most important change has been to omit mechanical coupling altogether, not only because the major focus is on visual coupling, but also because of the potential to cause coordination breakdowns, potentially even inducing motion sickness. From earlier testing, the discrepancy between the mechanical coupling and virtual rowing was already pointed out. As the haptic feedback from mechanical coupling cannot be turned off [Cuijpers et al. 2019], and the visual feedback can be disturbed not only the user but also by the virtual rowing simulation, especially disruptive when there is a perceivable framerate drop or tracker drift from multiple trackers. Secondly, the collected data files were found accurate and reliable in the data acquisition, but has an added initial data header containing rower-related data and fixed variables values to better identify the rower and the possibility to re-compute all variables if needed. Last of all, the augmented feedback visuals were adapted to unlit materials and color gradient instead of instant color changes. As colors and materials types should be clear to interpret, the unlit materials is not affected by environmental lighting, and even allows for emissive colors for extra emphasis. Furthermore, when the interpersonal distance is outside the desirable range, instead of the instant color change, to smooth interpolation between colors.

In summary, the pilot tests show that the multi-person rowing platform (with the presence of augmented feedback) was able to successfully host co-located rowing dyads while maintaining reliable data communication and acquisition throughout the experiment, including correct switching between conditions. Furthermore, the implemented changes based on input from the experienced rowers puts additional emphasis on the trade-off between responsive feedback and smooth/robust movements for immersive rowing. The next section describes the used empirical study and procedures in more detail.

5.6 Interaction

The augmented feedback visually interacts with the rowers based on their movement input. Relevant parts of the interaction already were described in the Development section. Therefore, this section will provide a brief summary of the feedback interactions for both stroke and bow rowers. Again, for the feedback to show, both rowers individually require three consecutive strokes for activation.

When enabled for stroke, two white lines at the min/max positions are placed indicating the edges of the handle trial. When a minimum or maximum value is exceeded, this line turns green and follows the handle position as long as a new min/max value is registered. As mentioned before, during the drive, a transparent target visual follows the handle position, becoming fully visible before the finish position is reached. When the recovery phase starts, the horizontal blue- and red line visuals move from the position where a maximum stroke length has been achieved. The recovery feedback autonomously moves back with a constant velocity over the trial, only being affected by the handle height within the set range of motion. The feedback includes particles and therefore also highlights the difference in handle height. While the stroke rower is moving, it directly impacts the bow feedback through the avatar's upper chest movement on the center of mass and moving back scapula.

In turn, when enabled for the bow, both the back augmentation and center of mass feedback become continuously active and does not change over different rowing phases. Therefore, the interaction is best described in different situations: the bow lags behind the stroke and the stroke lags behind the bow. The implementation already described the correct in-phase as shown in figure 7b. When either of these situations occurs, the color of the feedback elements changes immediately as mentioned before. When the bow lags behind the stroke, the horizontal relative phase line moves away from the bow's perspective. Indicating a need for the bow to push more. When the stroke lags behind, the horizontal lines move closer to the bow rower. If the bow slows down a bit, the horizontal line will eventually move back to the center indicating proper in-phase coordination. Again changing the colors as shown in 7b. The interactions are straightforward and based on back-and-forth movements and changes in visual attributes.

6 EMPIRICAL STUDY

To assess whether the rowing platform is capable of facilitating interpersonal coordination, a within-subject design was applied to compare interpersonal coordination for different conditions within the same rowing dyad. The interest of this study lies in the ability of the multi-person rowing platform, and augmented feedback to incorporate crew rowing dynamics to facilitate and train interactions within a rowing crew, specifically aimed at the skill of interpersonal coordination. During the experiments, experienced rowing dyads participated in the rowing activity consisting of 3x5 minutes rowing in conditions that involved no immersive rowing (Non-VR), immersive rowing (VR), and immersive rowing including the presence of Augmented Feedback (AF). For all conditions, real-time quantitative data was collected through the RP3 ergometer and applied VR motion tracking. In addition, qualitative data was collected by intermediate questionnaires between conditions and post-hoc semi-structured interviews. Details of this empirical study including participants, measures and procedure, along with the data- and statistical analysis are given below.

6.1 Participants

The participants for this study consisted of rowing dyads from the local rowing association D.R.V Euros [12]. In total 8 rowing dyads were recruited and tested for the experiments. These rowing dyads consisted of 14 male and 5 female participants (aged 22.5 ± 2.5 years; height 1.83 ± 0.08m; weight 78.6 ± 11 kg), they had at least 1 year of rowing experience (3.4 ± 1 year), practiced 3 ± 2 times a week, and were in the age range of 22.5 ± 2.5 years. Furthermore, all participants were still active in rowing practise at different levels. 2 row at recreational level, 10 at the club level, 4 at the competition level, and 1 national junior. Furthermore, they were not self-identified participants sensitive to motion sickness and/or prone to get/with injuries that could be aggravated by rowing (e.g. back injuries). Of which 7 participants had previous VR experiences and 12 did not. Most rowing dyads indicated to have rowed together on-water before and were almost all considered similar in terms of length and weight classes. All participants signed an informed consent before the experiment. Finally, every participant was assigned either the stroke or bow role based on their given rowing experience.

6.2 Measures

This section describes the collected measures and provides a detailed overview of how these were collected during the experiments.

The measures for the data analysis are written to a textual log file per rower when rowing in the virtual rowing environment. Also for the NVR condition, data collection is the same for all rowing conditions. The collected quantitative data consists of RP3 flywheel data, tracker positions and calculated performance variables. if a rower claims a seat, initial session-related data about the seated user, constants, and boolean states are collected to double-check the data communication and correct settings. When rowing is enabled and both rowers start rowing, their movements are captured by the trackers and the RP3 ergometer and subsequently transmitted over to the virtual environment (see Software and Websocket Connection). The movement data informs the rowing cycle and dynamics, at the same time other performance variables are calculated in the environment. All this quantitative data is written to each rower's log file for each update frame and after each completed stroke.

The log file consists of line-by-line data consisting of both continuous rowing data and discrete 'end-of-stroke' data. The continuous data consists of time-and phase data including the system clock (hours, minutes, seconds, milliseconds format), the current rowing phase (idle, drive or recovery)

---

[12] Homepage of D.R.V. Euros : https://www.drv-euros.utwente.nl/nl/

and the delta time of the frame. Tracker data is represented by the handle, seat, machine, and back position in all axes. The ergometer values are the time between impulses, angular velocity, and linear velocity. The main measure, the back angle (from 0 to 180 degrees) is calculated by the inverse tangent function on both the seat and back height- and backward position. Furthermore, the stroke length is based on 'the handle and machine tracker distance' difference between the catch and finish position. Lastly, the boat's position can be determined by its current position relative to the starting position.

At the end of each stroke, the cycle is summarized by time and distance values. Time-related data include the drive- and recovery times and stroke rates and are determined by stopwatches, which are started, stopped, and reset based on boolean state switches. Also for the stroke rate, where additionally 60 is divided by the average time of the last 3 strokes. Finally, the minimum and maximum back angle are tracked for feedback purposes. At the end of the training, no more data is written to the log file and is ready to be analyzed.

6.2.1 Continuous Relative Phase. The independent variable to quantify interpersonal coordination is the continuous relative phase difference between rowers calculated relative to the stroke rower. In this case, the trunk movement of both rowers (i.e. the back angles ranging from 0-180 degrees) were used to calculate the relative phase in degrees (0-360). By subtracting the relative phases of the stroke and bow rower, the phase difference within a rowing dyad can be determined at any given point in time. To compute the relative phase per rower, the amplitude-centered Hilbert transform as proposed in the future application section by [Lamb and Stöckl 2014] was applied. Before the amplitude of the relative phases within a rowing dyad can be centered around the x-axis, the data required manual cleaning. Visual inspection and manual ranges of the back angle were determined and used to remove outliers caused by tracker drifting (e.g. unrealistic back angles of 160 degrees). When plotting the back angles for all rowers, sudden peak and unrealistic back angle degrees were easily identified over time. The best-found way to deal with these outliers was to identify a 'natural' back angle range per rower and remove the data points outside this range. Removing strokes based on the presence of any outlier resulted in the loss of a lot of valuable data. If not done, the problem arises that the signal contains 'Not a Number' (NaN) values and cannot be processed. Therefore, the data points are marked as outliers and the back angle is set at 90 degrees for the rower. In this way, signal processing of the back angles continued. By applying the Hilbert transform an analytical signal is created, from which the real part forms the phase angle per rower. By then subtracting the relative phases of the stroke and bow, the continuous relative phase is calculated. Plotting the continuous relative phase shows a signal ranging from 0 to 180, ideally, portrayed at 0 indicating in-phase coordination.

6.2.2 Confounding Variables. The confounding variables for this study include factors related to individual rower differences and tracker-related data inaccuracies, that potentially disrupt the CRP measurement. Moreover, these influences cannot be avoided. However, with precautions be controlled up to a certain degree. As the individual rower differences, training's burden and tracker inaccuracies like calibration and drift were already covered in previous sections or found in the Procedure section, the remaining confounding variables are latency-related. Not to be confused with end-to-end latency (see Software).

Framerate. The framerate is considered a potential cause for disruptions as it impacts the visual coupling within the rowing dyad. The general advice on VR application is to at least have 60 fps[13], whereas other even suggest at least 90 fps for dynamic VR applications [14]. Higher framerates means that the visual quality is high and the displayed rowing motions are smooth, important for the manifestation of interpersonal coordination that requires real-time responsiveness.When the framerate is low or drops for a brief moment, even for one rower, it is almost guaranteed to result in a (temporal) loss of visual coupling between the rowers. Therefore, the framerate/latency was tracked for both the stroke and bow rower seat as reported in the Results section.

6.2.3 Questionnaires. The questionnaires provide qualitative data on the subjective measures of interpersonal closeness, enjoyment, and shared flow of the rowing training within rowing dyads. The first one is asked before and after the experiment, whereas the other two related to multi-dimensional constructs are used as intermediate questionnaires.

First of all, the rowing dyad is asked to indicate their interpersonal closeness by the IOS scale ([Aron et al. 1992]). The Inclusion of Other in Self (IOS) scale provides a highly reliable measure of interpersonal closeness. [Seifert et al. 2017] mentions that team relation relates to closer and tighter synchronization, where both the stroke and bow rower adapted their stroke and style over time to match each other. The scale itself is a single-item pictorial that consists of 7 circles describing the relation between the other in self as overlapping circles, from no overlap to almost complete overlap. Both rowers as "self" will be asked to describe their relation with the "other" in terms of rowing together as a crew. Providing a simple and direct insight into their perceived connectedness and closeness. The other two questionnaires regarding enjoyment and shared flow are filled in after each completed condition.

Secondly, the ENJOY scale is a validated instrument to measure enjoyment across any activity based on empirical evidence. It is a multi-dimensional model by [Davidson 2018], and will be used to capture the subjective positive experiences and account for participation motivation for each rowing condition. The scale itself is comprised of 25 items across 5 dimensions with reported CFA and EFA above 0.90 on the Cronbach's Alpha. Enjoyment consist of the dimensions: pleasure, relatedness, competence, challenge/improvement and engagement. Furthermore, the definition of enjoyment as “a positive feeling, when engaged in a pleasurable and challenging activity, which allows for skill improvement, makes you feel connected to others, and makes you feel proficient with the activity” suits very well with the objective of training interpersonal coordination.

Lastly, the Shared Flow State scale (SFS scale) used in [Zumeta et al. 2016] measures the shared flow to provide an idea about collective sensations in the sports context for each condition per rowing dyad. The scale is an adapted version of the Jackson and Marsh Dispositional Flow Scale (DFS-2) and reformulated to explore the optimal shared group experiences and found in the paper [Zumeta et al. 2013]. Within the sports context, the shared flow is viewed as a multifaceted experience and will be used as a one-dimensional construct that scores 0.95 for Cronbach's Alpha. It comprises of 27 items distributed in 9 dimensions: Balance- challenge and skill, Clear goals, Feedback, Action awareness, Concentration, Sense of control, Loss of self, Distortion of time and Autotelic experience. The items are asked from the perspective of the team rather than the individual. [Zumeta et al. 2016] concludes that quote "shared flow involves optimal collective experiences during physical and sports activities, where all members of the group experience the same sensation of being absorbed by the activity, while the synchrony of movements and shared emotions increase the perceived collective efficacy." In other words, shared flow within rowing dyads involves interpersonal coordination that besides synchronizing efforts, contributes to a sense of unity and shared experiences among rowers (see Follower-leader relation, particularly on [Seifert et al. 2017]).

The qualitative data consist of 7-point Likert scale responses and was analyzed at the ordinal level. Except the IOS scale responses, for which there was no observed difference before and after all experiments in interpersonal closeness within rowing dyads. The analysis of the validated

---

[14] Linde Virtual Academy - Framerate and experience: https://vr.linde.com/2022/10/06/is-your-frame-rate-affecting-your-vr-experience/

[14] Varjo article on framerate: https://varjo.com/learning-hub/frame-rate/

multi-dimensional questionnaires was done by calculating subscale and composite scores. All item responses consist of a 7-point Likert scale ranging from strongly disagree to Strongly Agree, where the ENJOY additionally allowed for a statement to not be applicable (N/A) and were not counted as such. The ratings (1-7) of all items belonging to the same dimensions should be averaged to obtain a subscale score. These were summed to calculate the respective composite scores. For enjoyment, the achieved score is between 5-35 and for shared flow ranges from 9-63 per rower. Because of the construct validity, subscales cannot be used for inferential statistics but will be touched upon in descriptive statistics. The collected responses per participant, additionally labeled for condition and rowing dyad, are put into a single data frame for statistical analysis.

6.3 Experimental Design

The interest for this thesis is to evaluate the ability of the multi-person rowing platform to facilitate and elicit realistic movement behaviour and interactions within an immersed rowing crew, specifically rowing dyads. On top of that, to investigate if the application of personalized visual augmented feedback is able to support rowers in their roles, and has potential to train them in reducing the variance of interpersonal coordination. The hypothesis for this study is therefore as follows:

(1) Crew rowing in the virtual rowing environment is able to facilitate functional and stable interpersonal coordination.
(2) The personalized support of concurrent augmented feedback towards the stroke and bow roles, eventually reduces the variance in crew synchronization as interpersonal coordination becomes more stable.
(3) Both subjective flow constructs enjoyment and shared flow are positively correlated for immersive rowing, from which the shared flow is expected to be particularly influential in the Augmented Feedback condition (AF).

By collecting measures like the continuous relative phase (CRP) and other time-related variables, insights can be gained into how rowing dyads behave and coordinate themselves during different conditions. Since the study involves multiple conditions and rowing dyads, the within-subject design is found suitable as it reduces the amount of sample size needed and accounts for individual rower differences ([Hill 2002]).

To assess whether the multi-person rowing platform and augmented feedback are capable of facilitating potential training of interpersonal coordination, a within-subject design was applied to evaluate this over 3 conditions: Non-Virtual Reality (NVR), Virtual Reality(VR), and Augmented Feedback(AF), where each source consecutively introduces another layer of visual information. As the name suggests, NVR is the only condition without immersion that serves as a baseline where the dyads row in the static research environment with the previously described physical setup. The other conditions both involve immersion and a dynamically changing environment in VR. In both VR and AF the dyads will row together in the virtual double scull propulsed by the RP3 input while being immersed in virtual avatars whose dynamics are adjusted based on tracker input. AF differentiates itself by introducing an additional layer of perceptual information in the form of real-time personalized visual augmented feedback. Also, the assigned stroke and bow roles within a dyad were maintained throughout the experiment. The next section will provide more detail on the experimental design by describing the used procedure.

6.4 Procedure

All experiments were conducted at the local rowing association D.R.V. Euros, where an indoor playspace was made available to set up the virtual rowing platform. A playspace of approximately 8m by 3m was occupied with two back-to-back lined-up RP3 model-T ergometers on a non-slip floor surrounded by 2 base stations positioned in a diagonal manner within 5 meters and setup at a height of 2 meters. The computers had a wired internet connection with low latency and were placed adjacent to the RP3s in order to avoid cable-pulling issues. Additionally, dark canvases were used to prevent lighting issues caused by mirrors and direct daylight.

Before every experiment, the setup was prepared in 30-45 minutes as described in the system overview. Attach the data cables, row several strokes to activate the RP3 monitor, and start/check the RP3 interface program, equip the RP3s with machine, handle, and seat trackers while the back trackers were placed loose on the RP3. The rest of the preparation time went into ensuring optimal tracking and alignment between the RP3 and its virtual representation. In practice, most rules of thumb for quick calibration, physical grab check, and feet offset were present for each preparation. Also the stroke rower setup, as world session host, was first completed before moving on. No further discrepancies relative to the system overview were found. Once the setup was ready and both rowers signed an informed consent, the procedure continued.

Before testing, the participants received information and an explanation about the rowing session. First of all, a screener was conducted to ensure all participants were considered suitable. Meaning they had at least 1 year of rowing experience and were not self-identified participants sensitive to motion sickness and/or injury-prone. Secondly, demographic data was collected on age, weight, length, rowing experience in years, level, weight category, training burden, and training frequency per week. Based on that, participants were assigned either the stroke or bow role and maintained this role throughout the entire experiment. In most cases, they suggested the role division themselves. Finally, information was given about the session, order of conditions, and what to expect from immersive rowing.

To account for potential time-related effects like learning and exhaustion over time, rowing dyads were asked not to train before the experiment and instructed to row for 5 minutes in 3 randomized conditions and maintain a pace of 20 spm. This ensures a sufficient amount of stroke data samples per rower (30) aimed at a more endurance type of training, as the task is to focus on maintaining interpersonal coordination rather than performance.

The rowing dyad received instructions and guidance on the rowing task. Rowers were explicitly instructed to coordinate their rowing movements and maintain a stroke rate of 20 spm for every condition for 5 minutes. In case of "irreversible" coordinative breakdown i.e. no way back to stable rowing; the researcher would instruct the stroke to continue rowing, and the bow to wait and follow up accordingly. If rowers felt motion sick or were not able to continue for whatever reason they were instructed to raise one hand, use that hand to take off the HMD without issues, or verbally indicate to stop the session. Furthermore, if the upcoming conditions was AF (see Feedback Design), the rowing dyad was reminded of their role divisions and that the concurrent feedback was personally constructed based on their tracker's orientation and time measures. The stroke was instructed to follow the "ideal" handle position guided by the colored lines. Whereas the bow had to row by looking at the visualized center-of-mass. At last, the rowers equipped their chest straps with tightened trackers which concludes the tracking setup.

A 2-minute warming-up prepared rowers for the upcoming rowing activity on the RP3. A distinction is made between warming up with and without immersion. First off, a physical warming-up was done without VR before the rowing activity started. If the upcoming condition involved immersion, an additional VR warming-up was put in place, where rowers were on-boarded in VR and explored the world without controllers at their own pace to become comfortable in the virtual avatar and rowing environment while being seated on the RP3. Assuming the virtual world settings were ready for the condition at hand, the running programs were checked for valid data input and logging.

The rowing activity for each condition consists of rowing for 5 minutes followed by a 2-minute break and time for filling in questionnaires. The activity started when the researcher manually anchored all virtual avatars in the virtual double scull. Before the countdown began, instructions were quickly repeated and the 5-minute rowing session commenced. During the break, the researcher prepared for the upcoming conditions and saved the data files. After the break, rowers filled in the ENJOY scale [Davidson 2018] and Shared Flow State scale [Zumeta et al. 2013]. Once all conditions were completed, a semi-structured interview was conducted.

The interview consisted of a mix of standard questions and observations made during the rowing activity e.g. a specific evoked reaction caused by drifting avatars. The standard questions asked about the experienced interpersonal coordination per condition, focus of attention, augmented feedback, and realism while rowing (see Appendix A1). After that, the rowers were thanked for participation and the session was terminated. Lastly, all the data was saved, notes were completed, the world was closed off, and the VR equipment including the goggles and chest straps were cleaned. In total, the experiment takes approximately 45-60 minutes including screening, rowing in 3 conditions (3x5 min), breaks (3x2 min), intermediate questionnaires, and closing interview to complete.

6.5 Thematic Analysis

To get a comprehensive and more structured understanding of the participants' experiences, the qualitative data from observations and interviews were analyzed using a thematic analysis. Over the course of multiple experiments with rowing dyads, it became clear that the rowers' experiences were similar and themes started to naturally emerge from both observations and interviews. To explore this, an inductive approach was taken in which themes were identified, analyzed and subsequently reported to provide an overview of the rowers' virtual experiences.

6.6 Missing Data

Looking at the data profiles in the data frames, different issues with different log files required detection- and handling of exceptions. The errors could be categorized as either fatal or retrieval. Most issues were found among the bow rowers, presumably caused by failing user handling events. Fatal issues refer to the missing data that cannot be recovered. These include either missing/frozen tracker data i.e. no tracker data was updated or remained unchanged throughout the log, or missing RP3 ergometer input which remained 0 for the entirety of the log. As both tracker data and RP3 data form the foundation of all rower dynamics and performance variables, the files for RD2-NVR, RD3-VR, RD6 (anti-phase coordination), RD8, RD9 were omitted. Attempts were also made to recover for instance the back angle when tracker data was partially missing and the unique amount of values was not zero, however, this was not successful. Other missing data, such as incorrect phase indication i.e. idle and missing stroke cycle times could be re-calculated and categorized as retrieval. The correct phase indication in continuous data could be re-calculated based on the 'end-of-stroke' timestamp, which indicates the catch, and then within that particular stroke was searched for the finish timestamp by looking at the switch of the RP3 angular velocity sign from positive to negative. Similarly, missing stroke cycle times (e.g. drive, recovery and stroke rate) were re-calculated based on the timestamps of the phase indicators in the continuous data.

6.7 Data Analysis

The logged movement data was preprocessed to allow for comparison and merging of rower data. All the log files were named by combining the rowing dyad number, participant number, and condition. A script was written to find files by this naming convention and subsequently structure, wrangle, clean, and transform the logged rower data. These files contained string-type data and required correct column typing in order for time-related and numerical values to be in a suitable format. Furthermore, the tracker data had to be unpacked into x, y and z-floats by using regular expressions. Furthermore, there was a mismatch between the stroke and bow registered system times (UTC). However, this was no issue as the initial connection data served as a starting point when rowing was enabled. The system times were changed into a seconds format from 0-300. After that, the file was split between continuous and discrete 'end-of-stroke' data based on the '/' character. The remaining cleaning process consisted of removing redundant data.

First of all, the now redundant connection data was removed as it no longer served a purpose. Furthermore, the first 3 strokes were removed as the startup of the rowers included unrealistic values and feedback not being active yet. Other data removal methods included removing missing data (NA) and stroke rates outside the 10 to 40 spm range, which were related to incorrect rowing cycle detection. The result is that each rower is represented by two data frames, one containing the continuous 'time series' data and the other the discrete 'end-of-stroke' data. Finally, the time-series data was interpolated to effectively compare and combine data over time. Specifically, periodic spline interpolation, which is suitable for cyclic data [Poel, de et al. 2016]. The average latency over all rowing dyads was about 45 fps (see latency), meaning that the time-series data could be safely interpolated over 40 fps without the need for downsampling. All time-series data was interpolated between 0 to 300 seconds with 40 data points per second. With that, the preprocessing of time-series and stroke cycle data was completed.

A stroke profile was generated for every condition, and refers to the interpolated mean of all valid strokes within a condition. First of all, the time-series data was sliced into stroke samples. This was done by using the timestamps of the end-of-stroke data to split all strokes, labelled per rowing dyad and condition. Secondly, stroke cycle data was not immediately removed when outliers were present. Recall that before computing the CRP signal, outliers were marked accordingly. To avoid the immediate removal of rich stroke data, strokes were only discarded when a 25% outlier threshold was exceeded. Which was based on visual inspection of the stroke profiles. Thirdly, the strokes were resampled to a 3-second duration i.e. 20 spm, and subsequently interpolated to 100 data points per stroke sample. The resampled strokes are represented by percentage (0-100 percent), drive time, recovery time, stroke length, stroke rate (spm) and CRP in a data frame per condition (also used as input for the Generalized Additive Models). Finally, the stroke profile was generated based on all valid individual strokes per condition. All strokes per conditions were averaged per percentage point. Consecutively, confidence bands were constructed per percentage point by calculating the lower- and upper bounds of a 95% Confidence Interval. The stroke profiles, as shown in the results, were used to visualize and compare the dyadic coordination patterns between conditions.

6.8 Statistical Analysis

To investigate the pairwise differences between the conditions, the measures were used for descriptive analysis to summarize attributes of the time-series data a Friedman Test post-hoc analysis of composite scores for enjoyment and shared flow, and the Continuous Relative Phase was analysed at the level of individual strokes between conditions using Generalised Additive Modelling. In addition, visual inspection of plots helped in the analysis of dyadic coordination patterns.

Descriptive Analysis. The descriptive analysis of time-series data per condition was done by visual inspection. As the generated stroke profiles are resampled and interpolated to the duration of 3 seconds, the time-series plot shows the CRP for all 3 conditions over 0-100 percent progress. For each percentage point, a 95 percent confidence interval is calculated and visualized as confidence bands. For completion, the finish position is pointed out based on the average drive times.

The collected responses were visually inspected in different stacked bar plots for subscale and composite scores. For subscale scores, separate histograms for enjoyment and shared flow visualize the average ratings (1-7) over the dimensions, showing a weighted subscale profile of the responses per condition. Similarly, for the composite scores, composite scores per condition were shown. To make the different score ranges visually comparable, they were changed into percentages. Because of the construct validity, the weight profiles of composite scores are limited for statistical analysis. Measures of distinct components can provide a better understanding of underlying differences. However, besides visual inspection, cannot be used as both questionnaires are used as one-dimensional constructs. On the other hand, this does not hold for composite scores.

Non-parametric tests. Non-parametric tests were done to identify significant differences among the conditions. There is an ongoing debate about whether or not the Likert scale can be interpreted as interval data i.e. continuous numerical data. In fact, Likert scale data in this case is more between numerical boundaries, and no exact pinpoint of what participants mean. Moreover, a reflection during questionnaires serves more as a useful indicator of enjoyment- and flow constructs [Davidson 2018; Zumeta et al. 2013]. Add in the limited generalizability of the collected data (18 participants in 9 dyads) for assuming the underlying distribution makes using non-parametric tests the best option. These tests can perform well with non-normal continuous data if you have a sufficiently large sample size (generally 15-20 items in each group). Because of the mentioned generalizability, data was tested for the assumption of Equal Variance of condition groups by Bartlett's and Levene's Test. The Friedman test, the non-parametric variant of the Repeated Measures on-way ANOVA, uses sign ranks to test the ordinal dependent data against the hypothesis of any significant difference between the conditions. The tests will be performed on a participant basis, as averaging the data for rowing dyads, representing different roles, not only impacts the integrity of underlying dimensions but is also a blocking factor to account for. If a significant result is found, a post-hoc Friedman Nemenyi test is conducted to reveal which of the pairwise group comparisons is significant. Taking the rowing dyad indicator as a blocking factor. As this test already controls for familywise error i.e. type I errors when performing multiple pairwise comparisons does not require additional p-value adjustment like bonferroni. In summary, a Friedman Test post-hoc analysis of composite scores identifies what pairwise groups show significant differences.

Non-parametric tests, in this case a Friedman Test post-hoc analysis was performed to identify pairwise difference between conditions based on composite scores from the subjective constructs enjoyment and shared flow.

Generalized Additive Models. The Continuous Relative Phase was analysed at the level of individual strokes between conditions using Generalised Additive Modelling (GAM). GAMs is a non-linear extension of mixed effects regression that allows for non-linearities in fitting the data. Using GAMs, it is possible to identify the time-domains for which time-series data from different conditions are significantly different - see Figure 9. The GAM analysis has been performed in collaboration with the main supervisor of this thesis, following the approach detailed in [Analyzing dynamic phonetic data using generalized additive mixed modeling: a tutorial focusing on articulatory differences between L1 and L2 speakers of English]. For more information on Generalised Additive Modelling, the reader is referred to [Wieling 2018].

For this thesis, the collected rowing data involved multi-level time-series data and interaction effects. For example, the effect of stroke length can vary depending on the back angle and/or stroke rate. Besides the rhythmic nature of the collected rowing movement data, the notions of force pattern similarities, functional adaptations, and natural drive/recovery time difference [Cuijpers 2019; Hill 2002] highlight the need to account for complex interaction effects within a rowing dyad. In addition, there is nestedness to the data as many strokes were performed in a condition, from which three conditions can also be attributed to a specific rowing dyad. Which relates to random effects. Therefore, GAMs are suitable as they can account for both random- and interaction effects.

The generated GAMs resulted in visualizations of the pairwise differences between the conditions. As the aim is to understand and explain the differences between the conditions NVR, VR, and AF in facilitating interpersonal coordination proxied by CRP, the GAMs exclude random effects. The resulting plots visualize the difference between a pair of (non-linear) smooth functions. When this plot is significantly different from zero, indicating no pairwise difference, a red shaded significant band overlaps the x-axis (including vertical dotted lines).

7 RESULTS

All rowing dyads were able to successfully row on the instructed 20 spm for a 5-minute duration and complete the NVR, VR and AF conditions. Also, all questionnaire responses regarding the interpersonal closeness, enjoyment and shared flow have been collected. Because of missing data issues, time-series data was collected for only 6 out of the 9 rowing dyads. Furthermore, the collected amount of stroke data was not equally distributed over the rowing dyads, especially in the first few experiments.

This section describes how the collected measures were used for analysis. First of all, the collected stroke was used for descriptives to summarize time-series data like framerate. Furthermore, the CRP stroke profile visualizes the dyadic coordination patterns through phase difference between stroke and bow rower. Next, the questionnaire responses were visually analysed on subscale level, and statistically analysed by performing non-parametric tests. Finally, based on observations and conducted semi-structured interviews, relevant themes were identified and described in detail.

7.1 Collected stroke data

In total, 1063 rowing strokes were collected from 6 rowing dyads. Because of missing data issues, time-series data was collected for only 6 out of the 9 rowing dyads. Table 1 shows that for each Rowing Dyad (RD), the following amount of completed rowing stroke (cycles) were collected: RD1: 86, RD2: 92, RD3: 164, RD4: 275, RD5: 286, RD7: 252. Meaning that for each condition, a total of 328 (NVR), 381(VR), and 354(AF) strokes were collected. Given the instructed stroke rate of 20 spm for a 5-minute duration for each rowing activity, around and near 100 strokes were performed by/could be collected from each rowing dyad per condition. However, this is not case when looking the at the missing data, also reflected by the percentage of stroke contributions per rowing dyad.

Table 1. Overview of stroke counts and contribution per rowing dyad for all conditions

Rowing Dyad	NVR	VR	AF	Total	Contribution in %
RD1	7	44	35	86	7.45
RD2	-	47	45	92	7.98
RD3	75	-	89	164	14.20
RD4	95	94	86	275	23.81
RD5	101	103	87	286	24.76
RD7	50	90	112	252	21.80
Total	328	381	354	1063	100.00

For the total amount of strokes used for analysis, it is observed in table 1 that the contribution of completed rowing strokes is not spread equally over all the rowing dyads. More than 2/3 of the rowing stroke contribution belongs to RD4, RD5 and RD7 (respectively 23.81%, 24.75%, and 21.80%). Considering that RD6 tested for antiphase rowing and is therefore not included, the rest belongs to the other 6 dyads, which should ideally be about 16-17% per dyad. The missing data is characterized by the aforementioned fatal data errors, as mentioned in *Missing Data*, which results in unusable stroke data. As shown in1, these were most prevalent for the rowing dyads RD8/ RD9, and conditions RD2-NVR/ RD3-VR, which contrary to their zero contribution completed the entire experiment as intended. Furthermore, the sessions of RD1 and RD2 had serious tracker-related issues which are reflected in the relatively low amount of contributed strokes. Most likely caused by incoming sun light and mirror reflections during the experimental setup.

Despite these data-related issues, the discrete 'end of stroke' cycle data in table4 reflect that on average the intended stroke rate was followed consequently. Only notable differences are the relatively higher spm variance in the VR condition and lower recovery time and higher average spm for the AF condition. Still the differences of these dependent measures overlap between all conditions.

7.2 Framerate

As mentioned before, framerate is considered a potential cause for disruptions since it directly impacts the visual coupling between the rowing dyads as it determines the visual quality and the smoothness of movements. Participant dyads indicated that disruptions of flow occur when parts of the virtual experience do not match the expected rowing behavior. If either the stroke or bow experienced serious latency disruptions, a temporal loss of interpersonal coordination followed, after which a period of re-stabilization was first needed to get back into functional interpersonal coordination. To investigate this, the framerate over time was plotted per participant, seat and condition to see if and where in time potential disruptions occur, and if they could explain the aforementioned stroke contributions.

The descriptive statistics of the framerate measure show moderate differences between the stroke and bow role, and higher overall fps in the Non-VR condition. Overall, the bow rower had a considerably higher mean and variable framerate (51.42 ± 1.62 fps) compared to the stroke rower (45.03 ± 0.95 fps). Furthermore, a comparison between conditions is looked at for each seat/role. For the conditions Non-VR, VR, and AF, the consecutive Stroke framerates in frames per second were 45.08 ± 1.26; 45.14 ± 1.25, and 45.03 ± 0.48 fps, and the bow framerates were 53.44 ± 1.84, 48.28 ± 1.28, and 44.86 ± 1.26 fps,

Finally, the minimal values for rowing dyads RD1, RD2, RD3, and RD7 temporarily crossed a threshold of 40 fps but was not considered detrimental. Most framerate drops i.e. minimal values remained in the high 34-37 range and did not prevail long enough to explain the low contribution of strokes.

Table 2. Latency measurements per rowing dyad

		Mean	SD	Min	Max
RD1	Stroke	45.0	0.15	43.0	48.0
	Bow	42.6	1.41	34.0	52.0
RD2	Stroke	46.96	3.88	43.0	68.0
	Bow	44.35	1.27	36.0	52.0
RD3	Stroke	44.86	1.09	30.0	48.0
	Bow	51.26	2.34	40.0	61.0
RD4	Stroke	45.03	0.29	42.0	48.0
	Bow	53.51	1.45	45.0	60.0
RD5	Stroke	45.17	0.58	41.0	52.0
	Bow	55.02	1.79	43.0	63.0
RD7	Stroke	44.86	0.87	35.0	50.0
	Bow	55.45	1.8	42.0	61.0
RD8	Stroke	45.09	0.69	41.0	56.0
	Bow	54.4	1.77	44.0	60.0
RD9	Stroke	45.24	1.09	40.0	56.0
	Bow	53.92	1.87	43.0	60.0

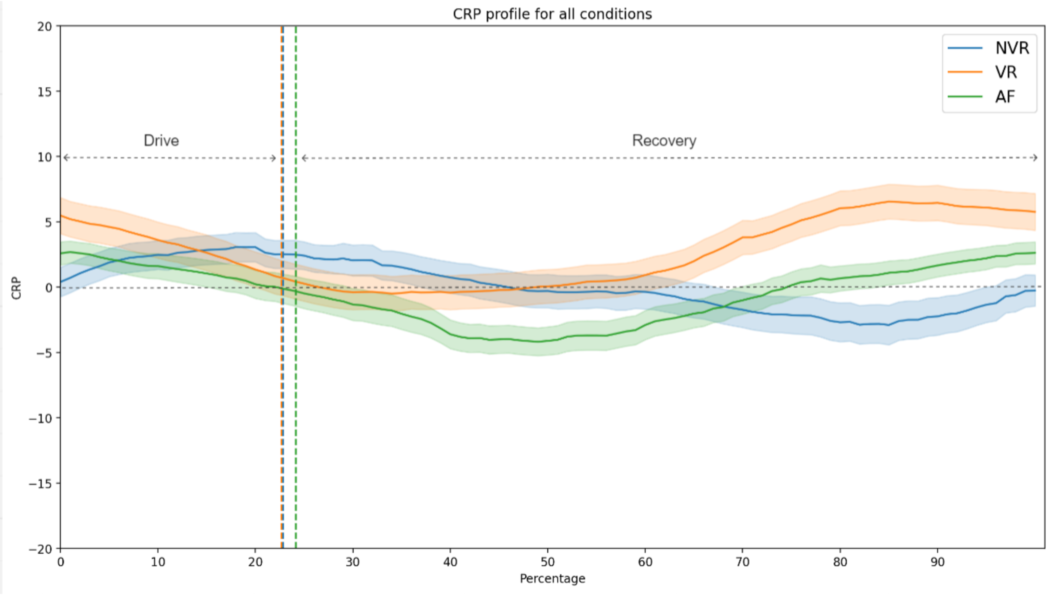


Fig. 8. CRP stroke profiles

7.3 Stroke profiles per condition

The CRP stroke profiles as observed in figure 8 summarizes the follower-leader dynamic (bow-stroke) between the stroke and bow per condition by visualizing the interpersonal coordination through the phase differences over an average normalized stroke cycle. The plot consist of horizontal and vertical dotted lines. The vertical dashed lines were added to indicate the relative finish position per condition based on the mean drive- and recovery times. Furthermore, the horizontal dashed line represents the perfect in-phase coordination at CRP = 0. On the positive CRP side the stroke rower is leading the movement within the stroke cycle and vice versa. To put the CRP values in perspective, the visualized stroke from 0-100% represents a 3-second duration, by mapping this to the CRP range (0-180), a difference of 5 CRP implies that the stroke is about 0.014 seconds ahead of the bow at a specific point within the stroke cycle. The interpersonal dyadic coordination patterns can be visually compared to compare the average follower-leader dynamic between conditions.

All conditions show dyadic coordination patterns in the form of sine shaped profiles with similarities in their one-wave cycles. Sharing similar periods and amplitudes, which occur within similar CRP ranged but different vertical baselines compared to NVR. Such similarities are also reported in **??**, where differences in drive times are negligible and only the recovery times differ but within a 0.2 seconds margin. As expected in the follower-leader relation and depicted by NVR, the stroke leads during the drive, but the immersive conditions deviate during the recovery phase.

The shape differences between the immersive conditions and NVR are observed as horizontal and vertical shifts. A vertical shift between a pair of conditions means that either the stroke or bow rower (i.e. higher or lower amplitude) is more dominant in leading the stroke cycle. Whereas a horizontal shift indicates a phase shift or time lag between the pair of patterns. Looking at the CRP profile, a phase shift can be observed between NVR and the immersive conditions VR and AF, especially near catch. Compared to maximum CRP of NVR around the finish position at approx. 23 percent, both immersive conditions cross the CRP ≈ 0 threshold. Similarly, NVR crosses this threshold later near 50 percent. Effectively showing a phase shift of approx. 20-30 percent. Showing that the immersive conditions is phase shifted compared to the expected stroke-bow dynamic of the NVR baseline, explained as either a dominant stroke lead or lagging bow rower.

Secondly, the vertical shift on the VR is most notable, as it indicates a more dominant lead from the stroke rower, unlike the other conditions that show a clear takeover from the bow rower after the finish. VR and AF overlap each other during the drive, but significantly start to differ at 40 percent, as confidence intervals do not overlap anymore, from which the profiles move in somewhat parallel fashion during the rest of the recovery phase.

Towards the catch, there is a difference between NVR and the immersive conditions in the second half of the recovery phase. After the finish, NVR is the only condition where the stroke and bow alternate evenly during the recovery phase, where the stroke eventually catches up getting in-sync towards the catch. Whereas for the immersive conditions, the stroke already takes a preliminary lead during the second half of the recovery. This becomes apparent comparing the positive parabolas of NVR and AF in the respective first- and second half of the recovery phase. On the contrary, the VR condition does not seem to have a catching up phase as the stroke rower keeps in constant lead besides the temporary perfect sync after the finish. Interestingly, all conditions appear to somewhat converge near the catch and overlap during the drive. The observed differences in phase shift and in the second half of the recovery show that the immersive conditions get in-sync at the finish, whereas the expected NVR gets in-sync towards the catch. This suggests that the stroke-bow dynamic of the immersive conditions lags behind the expected non-VR rowing baseline. Which is confirmed looking at the pairwise comparison of the Generalized Additive Models in the next section.

7.4 Generalised Additive Modelling

The Generalized Additive Models (GAMs) provide graphs that show the pairwise additive difference between the conditions (1=NVR, 2=VR, 3=AF) as seen in 9. Each graph compares a pair of conditions e.g. '1v2' is 'NVR v VR' and highlights the significant percentage window by the red line on the x-axis. The patterns shows the additive difference between the condition pairs. Besides the aforementioned observations in the 8 plot, these additive differences directly capture the pairwise comparison in a visual manner. Note that the absolute CRP ranges differ per plot. NVR v AF is less volatile compared to NVR v VR, even when sharing similar difference pattern. This becomes apparent looking at the underlying differences between VR v AF where after the finish, where the stroke in VR has a more dominant role in the higher percentage window. Interestingly, the relevance of the catch is underlined by the visible turning points as the pattern makes a clear change of direction near the CRP 0 line from 85% to the upcoming catch.

Looking at the significant percentage windows of the generalised additive models (9), the majority of the recovery phase and drive onset are significantly different, especially compared to the VR condition. The drive onset, which for all comparisons is significant at catch indicated by 0 % up to 5 or 9 percent in when compared to AF condition, and even 12 % between NVR and VR. Interestingly, this only holds for the small portion after the catch as it not significant near the finish position as the curves tends towards a CRP of 0 for all graphs. On top of that, all significant windows in the recovery phase go to 100%, especially compared to VR from 35.35 % to 91.92/100% respectively. The least significant difference is observed in NVR v AF, where notably the recovery is 'only' significant between 63.64 to 100%.

7.5 Questionnaire responses

The responses from all participants on the inclusion of other in self (IOS-scale [Aron et al. 1992]), enjoyment construct (ENJOY-scale [Davidson 2018]) and shared flow construct (SFS-scale [Zumeta et al. 2013]) were analysed. Not missing any responses. The rating of the Likert scale responses

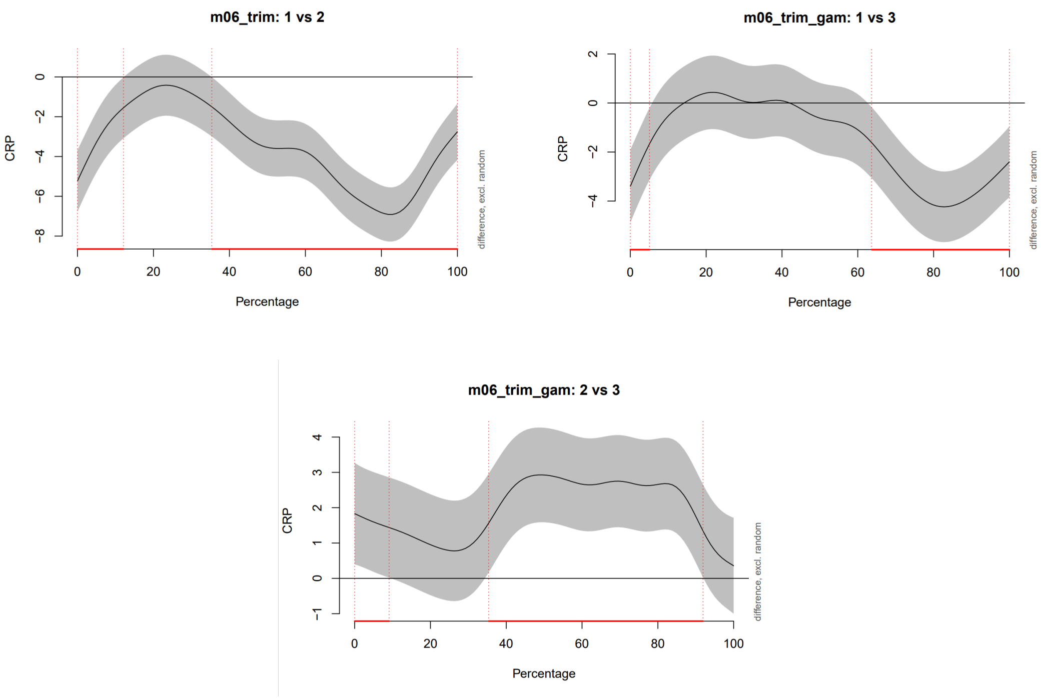


Fig. 9. GAM plots

Table 3. Percentage Windows of Statistical Significant Difference

Condition Pair	Lower Percentage Window	Higher Percentage Window
NVR v VR	0.00% - 12.12%	35.35% - 100.00%
NVR v AF	0.00% - 5.05%	63.64% - 100.00%
VR v AF	0.00% - 9.09%	35.35% - 91.92%

Table 4. The Time-related variables of normalized stroke per condition

Condition	Drive time	Recovery time	SPM	SPM variance	Stroke length
NVR	0.64	2.16	21.44	1.85	0.94
VR	0.66	2.26	21.04	3.44	0.97
AF	0.65	2.04	22.36	1.98	1.01

(1-7) was used to calculate subscale scores per dimension and composite scores for both Enjoyment and shared flow constructs. Except for the IOS scale responses, for which the rowing dyads clearly indicated that the rowing activity did not change the perceived interpersonal closeness before or after the experiment.

In the Enjoy scale a total of 25 N/A responses occurred. Most of them in the questions E1, E10, E11 related to the rowing activity and skill development. Most notable, 6 N/A responses for E10 'I improved my skills the last time I did the activity' and 4 N/A responses for E22 'I felt like I did a good job the last time I did the activity'. Also, E16 and E19 both with 3 N/A responses regarding cooperation and shared effort.

The bar chart distribution of all questionnaire items and response range underline themes found in the thematic analysis. Rowers did agree on the questionnaire items regarding being 'focused, concentrated and absorbed in the rowing activity' (SFS 11, 12, 13, 14, 15). on top of that, rowers indicated to lose track of time and what happens outside of the activity for the immersive VR and AF conditions (E3, 13, 20). Providing additional evidence for the themes 'Time/distance perception' and 'Focus of Attention'.

For the IOS-scale, rowing dyads on average indicated to have strong degree of overlap (4.9±1.45) in their interpersonal relation as rowing partners. Most dyads indicated to have either equal or strong overlap (4/5). From which RD5 indicated small overlap (2), RD2 and RD7 very strong overlap (6) and RD4 even most overlap (7). Interestingly, RD6 indicated a strong overlap (5), but interpreted the degree of interpersonal closeness also to their collective rowing performance. It is no surprise that, questionnaire items regarding 'perceived abilities and skills related to the activity/challenge' scored relatively high (SFS 1, 2, 3).

Because of the construct validity, subscales cannot be used for inferential statistics but will be touched upon by visual inspection. The collected responses per participant, additionally labeled for condition and rowing dyad, were put into a single data frame for statistical analysis.

7.5.1 Subscale profiles per condition. Because of construct validity, the subscale profiles for enjoyment and shared flow averaged over all conditions are only visually inspected the figure below (10). The underlying components show different weighted profiles and will be discussed as part of their respective construct measurement - enjoyment and shared flow. By visual inspection, noticeable patterns can be observed between the sequence NVR-VR-AF.

For the enjoyment subscales, a potential significance difference between the NVR-VR and NVR-AF pairs can be explained by the relatively higher average ratings of pleasure and particularly engagement for the immersive VR and AF conditions compared to NVR. At the same time, the challenge/improvement does not seem to affect this as there is little difference in Challenge/improvement, which is also observed in the aforementioned 'perceived abilities and skills related to the rowing activity' (SFS 1, 2, 3). Furthermore, the slight decline in competence and a higher score of relatedness in the VR condition is interesting considering the reported potential of the application of VR for rowing practise.

For the shared flow subscales, a difference between NVR and AF is shown by NVR having a seemingly higher average overall rating than AF, except for the sense of control and feedback dimensions. Other notable observations include, higher action awareness in the NVR condition and no seeming difference in the concentration scores. Lastly, there is a suggested inverted correlation between a sense of control and loss of self. Sense of control has a relatively low baseline and a slight decrease in rating over time, whereas the loss of self shows an increase in rating. Making it seem that the idea of control comes at the cost of self-loss. This can also be due to the NVR condition not having a virtual performance environment, and augmented feedback that reacts to the rower's movement input.

Besides the subscale scores being limited to visual inspection, making the observations and suggested relations between dimensions suggestive, they can still serve as a possible interpretation significant differences between pairwise conditions for enjoyment and/or shared flow.

7.5.2 Statistical Analysis. The composite scores for both the enjoyment and shared flow constructs were subjected to a Friedman Test post-hoc analysis. The sample data consisting of composite scores per rowing participant passed the assumption of equal variance as both the Levene and

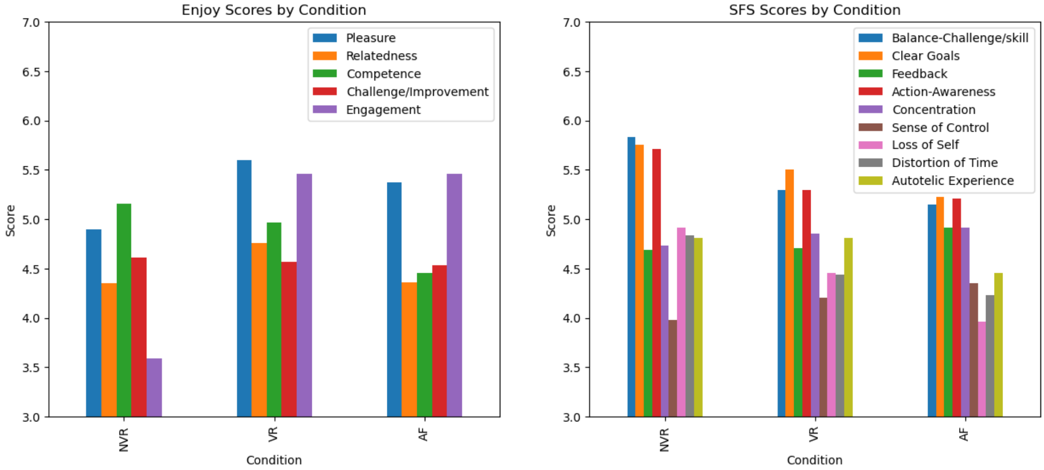


Fig. 10. Average subscale scores per condition

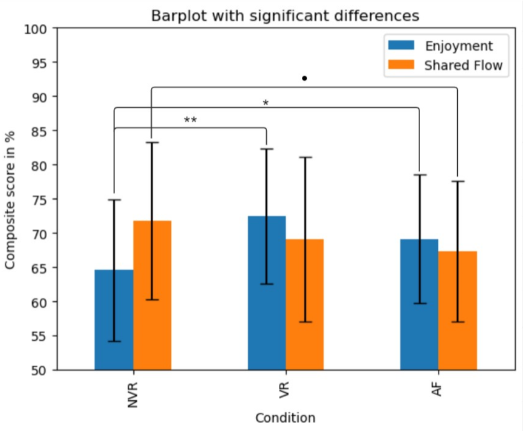


Fig. 11. Barplot with significant differences on pairwise comparisons

Bartlett tests failed to reject the null hypothesis of equal variance ($p < 0.05$) between the condition groups for both the enjoyment and shared flow constructs.

For the enjoyment construct, the Friedman chi-square test revealed a statistically significant difference among the conditions $\chi^2 = 9.13, p = 0.010$, $p < 0.05$). A post-hoc Nemenyi test demonstrated significant differences in favor of the immersive conditions ($p < 0.05$). For both the NVR and VR pair ($p = 0.001$), and the NVR and AF pair ($p = 0.04$). Within the immersive conditions VR and AF, no significance was found ($p = 0.50$).

For the shared flow construct, the Friedman chi-square test only yield a marginally significant difference ($\chi^2 = 5.38, p = 0.07$, $p < 0.05$). This indicated trend towards significance between NVR and AF was also expected based on the observations and interviews reported in the next section: Thematic Analysis.

The statistical significance for the composite scores is visualized in a horizontal bar plot with error bars. The figure11 shows the composite scores in % per condition while at the same time providing the statistical significance based on the results from the post-hoc Friedman tests. The error bars are used to represent the variability in the data, in this case the standard deviation is a reliable error propagation for smaller sample sizes and highlights the dispersion of the composite scores per construct and condition. In the plot, it can be observed that for enjoyment the immersive conditions scored overall higher for enjoyment, with slightly lower standard deviation (NVR:10.33, VR:9.83, AF:9.41) and this difference is highly statistically significant for the NVR/VR pair and statistically significant for NVR/AF pair. On the other hand, the marginally significance in shared flow for the NVR/AF pair, which is somewhat highlighted by the lower composite score and standard deviation for the AF condition (NVR:11.47, AF:10.31). In general, showing significant higher scores of enjoyment for the immersive rowing conditions VR and AF, while similarly showing a decreasing trend of shared flow scores towards the immersive conditions.

7.6 Thematic Analysis

A thematic analysis of the observations and conducted semi-structured interviews identified relevant themes. These will be highlighted and described below:

Segmental information. Segmental information is reported to be crucial in the facilitation of interpersonal coordination. All rowers mention this topic as it makes or breaks the immersive rowing experience. The virtual bodily information was found to have potential for synchronization within a rowing dyad, especially for the bow rower. When the setup was correct and immersion was free of perturbations, the leg drive and the rower's seat/hip position was found to be useful. Compared to the NVR condition, the segmental information missed sophistication, mostly involving the avatar's back, arms and oar movement. Examples given the lack of oar movement in the catch and extraction of the water, and the feather of the oar. Also, three bow rowers (RD1, RD5, and RD7) were looking at the elbow, stretching of the arms and back angle to synchronize upon. On the other hand, occurring perturbations in the avatar's bodily information, oars, handle, and feet pull away the rowers' attention or in some cases even resulted in out-of-body experiences. Effectively causing a temporal loss of coupling. When segmental information (used for synchronization) matches the rower's expectation, which may differ based on the training regime, has been indicated to have potential to make immersive rowing suitable for training practises. To conclude, stable segmental information is deemed essential in maintaining stable synchronization within the virtual rowing environment.

Time/distance perception. RD1, RD7 This theme refers to the rower's perception on the current state of training. It was reported that immersed rowers had little idea of the training progression in terms of time and distance, especially the stroke. Rowing dyads RD1, RD2 and RD7 even reported to perceive shorter rowing times when immersed. Although this can refer to the enjoyment of immersive rowing, it was also pointed out that rowers missed a purpose while rowing. As most rowing dyads indicated the need for having information about performance variables like stroke rate or split time per 500m, to aid their perception while immersed. Furthermore, the virtual rowing environment should include (recognizable) landmarks to focus on, which was also mentioned in [van Delden et al. 2020]. Taken together, rowers should be informed within the virtual environment about traveled distance or time through performance variables and/or virtual landmarks.

Augmented feedback. RD3 like, RD4/RD5/RD6/RD8/RD9 not like- have in common that the avatar was also found glitchy The effectiveness and clarity were the most important key words in summarizing the AF condition. With augmented feedback, the stroke feedback became confusing over time as a result of a positive reinforcement loop constantly increasing the set stroke rate. The stroke rowers liked the clarity of the feedback and understood the purpose of it, following the visual feedback at the seeming cost of their own intuition. However, it can be considered effective in the wrong way, as it introduced a positive reinforcement loop on the stroke rate. On a side note, stroke rowers did pay attention to the subtle 'charge effect' during the drive phase and indicated that the min/max lines was a nice addition, but did not understand why it disappeared during the drive. Whereas the bow rowers generally understood the feedback purpose, especially the scapula feedback, but were overwhelmed by the presence of the other dynamic visuals aimed at visualizing the interpersonal distance. Which oftentimes were also considered too sensitive and stuttering, as they are directly influenced by the tracker input as denoted by rowing dyads RD4, RD5, RD6, RD8, RD9. One of the bows, RD3, mentioned to like the concept of a dynamic sphere, and suggested to make the sphere's color also the main focus and indicator of correct synchronization. As of now, the the color only changes when it leaves the desirable range of interpersonal distance. Augmented feedback is a worthwhile addition for immersive rowing as it is capable of actively influence the rower's behaviour, also in unintended ways if not designed carefully.

Focus of attention. The focus of attention directs the attention of the learner away from the movement itself [Postma et al. 2022], which was found to differ for all conditions. Overall, the rowers used the present visual information and the RP3 sound for synchronization. Furthermore, rowing dyads indicated miss specific sound cues like the oars entering the water. Also compared to the bow, the stroke rowers felt less part of the crew and act more in solitary. One example of this one stroke attempting to get additional information by looking at the bow's oar. In the NVR condition, the performance monitor was used and reported to have a positive effect on maintaining a consistent stroke rate. Also, as mentioned before, the bow rowers had access to realistic segmental information from the elbow, arms and back angle. Moreover, in the VR condition this information was not present in the same way, which made the stroke's back and seat important information sources. Similarly, in the AF condition, the stroke's avatar back augmentation was found reliable to synchronize upon. On the other hand, the bow was often overwhelmed by the amount and sensitivity of moving visuals. In combination with theme of 'time/distance perception', it can be argued that immersive rowing requires an additional external focus of attention directly from the virtual rowing environment.

Boat propulsion. The real-time boat displacement, or boat propulsion did not match the rowers' expectations compared to the applied effort on the RP3. The boat's movement was found to be smooth and non-stuttering. Simultaneously, the propulsion did not entirely match the rower's expectation in terms of responsiveness found in on-water rowing. Effectively missing the result of their drive phase when power was exerted. This implies that the aforementioned trade-off between smooth and/or responsive movement requires additional tweaking.

In summary, it was reported that immersive rowing shows potential for training purposes, but requires a more stable and synchronized experience. Particularly focused on stable segmental information and environmental landmarks serving as information cues. Moreover, rowers emphasized the need for a clear focus of attention and the lack of mechanical coupling. Improvements in virtual avatars, landmarks, and simpler visual augmented feedback can improve the immersive experience immensely.

8 GENERAL DISCUSSION

The objective of this thesis was to investigate the potential of Virtual Reality in facilitating the training of interpersonal coordination in sports, particularly for crew rowing. To research this, two contributions were realized: 1) a multi-person VR rowing platform capable of hosting (co-located) crews, extending upon the extant VR4VRT-system [van Delden et al. 2020], and 2) the application of visual augmented feedback that is tailored towards rowing dyads to facilitate functional interpersonal coordination. Subsequently, these were studied in a within-subject design consisting of 3 rowing conditions related to different levels of visual coupling: Non-VR (NVR), VR and Augmented Feedback (AF).

The results show that the multi-person rowing platform has been able to successfully host co-located rowing dyads, elicit realistic crew rowing behaviour, and facilitated rowing interactions in the first ever steps towards training the skill of interpersonal coordination. In addition, the presence of augmented feedback showed potential in supporting rowers in their roles by visually guiding their movement patterns towards more stable and functional interpersonal coordination. However, comparing to non-VR rowing, there is a strong need for more sophistication in order to elicit more realistic rowing behaviour within VR.

8.1 Multi-person rowing platform

The multi-person rowing platform was found to facilitate interpersonal coordination within rowing dyads, although not entirely functional. For all conditions, the CRP stroke profiles share overlapping characteristics in their average stroke cycles. However, the GAMs show significant pairwise differences, especially near catch. First of all, the NVR stroke profile is in line with the expected stroke and bow dynamics, as the plot matches the shape of the one-wave sinus cycle as depicted in the 'computed differences between force patterns' figure from [Hill 2002], meaning that the stroke and bow interaction as shown by the force patterns is also seen in the CRP profiles. Additionally, The CRP stroke profiles of the immersive conditions share overlap in periods and amplitudes with the NVR baseline. Meaning that the average stroke cycle was completed within the same amount of time (see table 4), and the degree to which either stroke or bow is ahead in the stroke cycle is similar to NVR. In other words, the rowing dyad interactions occur within the same domain for all conditions.

Despite this, significant phase shifts between NVR and the immersive conditions were found. Looking at the GAMs of pairs NVR-VR and NVR-AF, the drive onset and second half of the recovery phase are significantly different. The significance percentages windows cover the second half of the recovery up to and including the catch (0%-5% and 63.6%-100%). This coverage is explained by a constant phase shift of the immersive conditions compared to NVR, which is also emphasized by the crossing CRP profiles during the drive- and recovery phase. At the catch, the immersed stroke rowers were already ahead in their lead at the maximum CRP amplitude. Looking at the complete CRP profiles plot, the NVR profile can be interpreted as the bow compensating the initial lag after the finish. Aside from being immersed, when considering the stroke rower as a constant factor, there is no difference in perceptual information for the conditions NVR and VR presented to the bow. Therefore, it can be argued that the bow initiated the stroke cycle too late, effectively indicating an unnatural adaptation near the catch. Moreover, the GAMs show that this preparation for the catch comes as a sudden converge towards the catch around 85% for both VR and AF. Given the similarity in trajectory and later on parallel movement of these CRP profiles, it can be suggested that the bow rower is constantly lagging behind and does not manage to compensate this lag throughout the stroke cycle.

The framerate is considered a confounding factor for facilitating interpersonal coordination since it directly impacts the visual coupling between the rowing dyads. Recall that the framerate for dynamic VR applications is preferred to be at least 90 fps, whereas the more static applications this is at least 60 fps. The descriptive statistics of the framerate showed that the framerate standards were not met, while also showing interesting differences between the rower roles and conditions, especially for the bow. The seating position of the bow (51.42 ± 1.62 fps) compared to stroke (45.03 ± 0.95 fps) indicates that the bow rower experienced more latency. Moreover, looking at the framerate on condition level for the bow seat (NVR: 53.44 ± 1.84, VR: 48.28 ± 1.28, and AF: 44.86 ± 1.26 fps) shows that each additional step of presenting visual information results in lower framerate. On the other hand, the minimal framerate values temporarily crossed the 40 fps threshold, but cannot be considered detrimental. Most framerate drops i.e. minimal values remained in the high 34-37 fps range and did not prevail long enough to explain the low contribution of strokes. In general, the framerate is not up to the standard, for which it can be considered a confounding factor in this study. However, even when a temporary drop can be sufficient to destabilize interpersonal coordination, framerate does not explicitly explain the significant phase shifts.

Taken together, the multi-rowing person platform has shown the potential to facilitate interpersonal coordination. The immersive CRP profiles occur in the expected CRP ranges for expected stroke and bow dynamics in non-VR. However, immersive rowing did not support this skill in a functional manner. In terms of distance regulation, like [Varlet et al. 2013], rowers were deemed capable of coordinating their movement and behaviour with their virtual rower representations. At the same time, significant phase shifts occurred where the stroke is oftentimes ahead in the lead, especially near catch. Like the study of [Varlet et al. 2013], the results indicate a movement lag and variability of coordination for immersed rowing. Likely also a result of an agency effect. However, they displayed prerecorded movements of an expert stroke on screen rather than having a fully immersed rowing dyad with real-time tracking data. Therefore, this platform shows the potential to facilitate interpersonal coordination for fully immersed rowing dyads while respecting the inherent follower-leader relation. This potential can be further realized beyond facilitation when lowering the phase shifts and effectively closing the gap to the Non-VR rowing CRP pattern.

8.2 Personalized Augmented Feedback

Real-time augmented feedback shows a stabilizing effect on the immersive coordination patterns. Looking at the immersive CRP profiles, VR and AF overlap during the drive phase, but start to move in parallel during the recovery. Moreover, the VR stroke is leading significantly compared to AF. The GAMs pairwise differences reveal that AF is significantly more stable than VR, especially during the recovery phase. Also AF tends more towards the 0 CRP line and is less volatile in the CRP range than VR compared to the NVR baseline. Aside from the finish, the VR condition shows an unintended effect with a dominant stroke lead, unlike the other conditions. Specifically in the drive phase and second half of the recovery. Interestingly, the presence of AF seems to stabilize this effect.

The augmented feedback consisting of personalized stroke and bow feedback is capable of influencing the rower's behaviour in positive but also unintended ways. In general, the rowers response to feedback was mixed. Depending on the preference or interpretation, the feedback was able to guide or overwhelm the rowing dyads, as rowers have a preference in their perceptual information needs (as the coaches noted in [Millar et al. 2013]). Additionally, rowers indicated using both the RP3 sound and visual stimuli presented, hinting at a multi-modal use of feedback.

For the stroke, AF was reported to be intuitive feedback to follow. Most strokes liked the feedback form as a visual guidance of the adaptive drive-to-recovery ratio. Table x reflects this by a SPM variance equal to NVR, and an average drive-to-recovery rate closer to the intended ratio. However, in some cases the feedback induced a positive reinforcement loop on the stroke rate. Similar to VR4VRT,-system [van Delden et al. 2020], this lead to higher stroke rates only reduced by instructing the stroke to focus on the instructed pace. Probably also caused by a low initial minimum handle trajectory threshold, for which the feedback disappears.

For the bow, the dynamic visuals were found overwhelming and sometimes difficult to interpret. In contrast to the stroke, this concurrent feedback is based on the tracker input, making it sensitive to inaccuracies. Overall, the bow rowers appreciated the simplicity of the back augmentation for the scapula forms, some even indicated it to be their sole focus point. The more dynamic visuals covering the centre-of-mass was reported to be overwhelming and difficult to interpret at times. As the feedback moves away from the rower, the depth perception in VR makes it likely harder to interpret its current state. Furthermore, the status indication through color was not always clear, as multiple visuals were coupled to colored status indicators. Interestingly, the rowers seemed to adopt a strategy to focus on limited visuals to cope with being overwhelmed.

As extensively covered in ‘Augmented Feedback – Implementation’, there is a trade-off between responsiveness and inaccuracies for presenting real-time feedback directly based on tracker input. Other implications for feedback design include the personal preference, colored status indicators and the direction of motion. Taken together, AF is not straightforward to design and implement for as it requires multiple design iterations, and one cannot directly measure its effectiveness. However, concurrent visual augmented feedback is a promising tool in making optical flows tangible to guide towards positive rowing behaviour. (with the addition of bandwidth feedback, the dependency hypothesis can tackled, and training rowers in naturally using the inherently present optical flow).

8.3 Enjoyment and Shared Flow

The subjective flow states enjoyment and shared flow can be considered relevant indicators for the multi-person rowing platform as potential training tool (enjoyment) and facilitator of collective crew experiences (shared flow).

First of all, the enjoyment construct statistically highlight the added value of immersion for enjoyment in the rowing practise for conditions VR and AF. The used definition of by [Davidson 2018] hints at enjoyment as indicator for skill improvement, connectedness, and proficiency. Compared to NVR, the immersive conditions showed high average scores of the subscales pleasure and engagement. Moreover, a high score of relatedness in the VR condition. At the same time, the subscale challenge/improvement did not change over the conditions. Visual inspection of the underlying dimensions suggest that immersion has an positive effect on enjoyment and therefore also hint at the multi-person rowing platform as potential training tool for skill acquisition.

Secondly, the shared flow construct provide context on the visual coupling between rowers and their environment. Recall that the presence of shared flow is relevant for collective experiences and sensations as underlined by [Millar et al. 2013]. The marginal significance between the NVR-AF pair goes alongside the observation that NVR scored higher on action awareness, loss of self and slightly lower sense of control and distortion of time. Which most likely is related to the theme ’time/distance perception’. Furthermore, there is a suggested inverted correlation between sense of control and loss of self. Moreover, the loss of self difference for the pair NVR-AF is relatively high. Although the themes ’focus of attention’ and ’augmented feedback’ provide some explanations for this, it can be argued that overall the immersive rowing is not on par with Non-VR rowing, especially considering the theme of ’segmental information’, in which the virtual rower avatar misses sophistication for the facilitation of interpersonal coordination.

Despite the limitations of flow constructs for analysis, the analysed responses from the enjoyment and shared flow states point towards the multi-person rowing platform as training tool to facilitate interpersonal coordination, but only if the shared experiences and sensations are also present in immersive rowing.

8.4 Behavioural Realism in Virtual Rowing

Despite the potential as training tool for interpersonal coordination, the multi-person rowing platform did not facilitate the expected rowing movement patterns and behaviour for real-life rowing. Even when AF seemingly stabilizes the immersive movement patterns, the GAMs still shows significant differences during the second half of the recovery and the catch. Compared to the NVR condition, there are significant shifts in movement lag that persist throughout the CRP profile as shown in figure 8. In the related study of [Varlet et al. 2013] it was stated that a decrease in movement predictability is related to the rowers adopting a "reactive rather than adoptive" approach, which imply a change in behavioural realism. From a systematic point of view, the measurement and data handling is the same for all conditions. Meaning that NVR is the only condition to not directly act upon the real-time measured data, since the rower dynamics are based on the actual rowers themselves. When considering the stroke rower as a constant factor, since there is little difference in the presented visual information between NVR/VR in this setup (except for boat propulsion), it can be argued that the bow rower is lagging behind and this would indeed hint towards a more reactive behaviour adaptation. Taken together, the significant phase shifts imply that the multi-person rowing platform consist of systematic errors that lead to a decrease in behavioural realism.

The simplification of the rowers and their movement patterns is considered to impact the ’behavioural realism in virtual rowing’, as it directly affects the visual coupling within the rowing dyad. This is the case for most virtual rowing simulators that mentions aspects like virtual teammate dynamics [Varlet et al. 2013] or other aspects of realism e.g. preservation of original size [Farley et al. 2020; Ruffaldi and Filippeschi 2013] as limitations in their studies. The identified themes made it clear that there is a need for sophistication to match the rowers´ expectations. The themes ’focus of attention’ and ’time/distance perception’ highlight the rower’s need for reliable information to not only coordinate upon, but also to understand the training progress. This is most likely related to theme ’boat propulsion’, in which rowers indicated that the boat propulsion was not perceived as realistic during the drive phase. Moreover, the theme of ’segmental information’ shows that the avatar’s bodily information was not always stable and prone to perturbations, especially for the bow rower. The simplification of visual information has implications for the system’s ability to facilitate skill acquisition of interpersonal coordination, because the outcome of the performed rowing stroke(s) on the RP3 ergometer(s) is not completely (visually) present in the virtual rowing environment. Therefore, the next paragraphs will discuss the themes boat propulsion and segmental information.

The boat propulsion was perceived as being not realistic, because it was not responsive to the rower’s performed effort during the drive phase. Based on the applied power on the RP3 handle, rowers expected that by looking at the water passage, a more responsive and higher amount of boat displacement. Which was especially prevalent for rowers that exerted more power. Given the importance of the paradigm "row with the boat" [Millar et al. 2013] that states that rowers match their velocity to that of the boat, implies that both rowers were not entirely able coordinate their action based on the boat’s displacement. Due to unknowns in the RP3 physics, the adopted robust physics model from the ’Open Rowing Monitor’ is limited in the power/force related calculations. Taken together, the implemented ergometer physics were not able to accurately approximate the boat movement, and therefore likely led to variability in interpersonal coordination.

Stable segmental information was reported to be crucial for interpersonal coordination in virtual rowing, especially for the bow rower. When the virtual bodily information was displayed correctly, the bow rowers indicated to be able to coordinate their movement with that of the virtual stroke. However, at the same time, it was found to be a source of perturbations. Examples include floating oars, handle, feet offset issues and in some cases even out of body experiences. These issues can be explained by the calibration and tracker inaccuracies. First of all, there is no calibration of the virtual avatar. A one-size-fits-all type of avatar is used, which unlike the SPRINT-system [Ruffaldi and Filippeschi 2013] does not taken the user's size into account. The mismatch between physical and virtual body was reported to introduce feet offset issues, where feet would not stay on the footboard, especially near the finish position. Secondly, the avatar movements are based on the real-time tracker input, even when inaccurate. Rowers reported that the virtual body movements were (temporally) out of sync to the actual rower, freezing their own movement in the process. In case of tracker drift, the virtual body movements became unrealistic and immediately disruptive to the visual coupling between rowers. The resulting deficit in visual information from segmental information can explain the lagging bow rower, since the stroke is less impacted by pertuberations of segmental information, but for the bow there is a clear decrease in movement predictability, which is related to reactive behaviour adaptations [Varlet et al. 2013].

The simplification of virtual rowing compared to its real-life counterpart is considered a systematic error that lead to a decrease in behavioural realism. Because the virtual rower is represented as a simplification in terms of rowing dynamics and segmental information. These systematic errors affect both rowers, but expected to influence the stroke rower to a lesser degree. Since the bow rower is more dependent on visual information like stable segmental information, it is more likely and also suggested that the significant phase shift is explained as the bow rower lagging behind the stroke.

8.5 Future Research

To further explore the potential of the mixed reality multi-person rowing platform as potential training tool for crew rowing, future research should focus on the facilitation of more realistic rowing behaviour and interpersonal interactions. As this thesis show the first-ever steps towards a virtual rowing simulator that facilitates both interpersonal interactions and personalized augmented support for rowing dyads. However, compared to real-life rowing, there is a strong need for sophistication. Therefore, the next steps to empower rowing crews in training (interpersonal skills) without time- and place constraints, is to improve upon the behavioural realism of virtual rowing.

Similar to the VR4VRT-system [van Delden et al. 2020], the follow-up developments include the integration of power curves, calibrations of the virtual avatar size, and bandwidth feedback. Furthermore, reducing the tracker inaccuracies or dependency altogether must be considered, as it immediately resulted in perturbations of segmental information leading to temporal loss of visual coupling. For instance by letting the oar movement follow a predefined animation path instead of the handle tracker movement. Finally, the virtual rowing environment can benefit from the inclusion of landmarks, more realistic water animation and visualizing performance variables like time- or distance metrics.

The integration of power curves directly from the RP3, would allow for real-time visualizations of how rowers apply force during the rowing stroke, which is often present in rowing-related research and analysis. Like [Hill 2002], crew analysis is preferably also done by including the overlap/comparison of different force patterns from all individual rowers into an overall rowing crew profile. When done correctly, would contribute to more realistic boat propulsion and other research possibilities like real-time augmented feedback that acts upon the force patterns. Unfortunately, this has been a limitation of the VR4VRT-system [van Delden et al. 2020] for multiple iterations, because the RP3 app does not fulfill the need of real-time available data in the virtual rowing world. As of now, improvements have been made in reading out the flywheel values of the RP3 into a robust physics model that approximates the boat's displacement, but it still lacking in force/power-related calculations.

On top of the alignment process, the virtual avatar's size has to also be calibrated to match the user's size. In this thesis, steps have been made in providing a more standard way of calibration through the newly implemented alignment process. However, this is about enabling the mixed reality by aligning the real- and virtual RP3 ergometer and does not go beyond the avatar anchors, as to adapt the avatar's dimensions itself. Instead, like the SPRINT-system, the multi-person rowing platform should opt to use improve the existing calibration system to account for the user's size [Ruffaldi and Filippeschi 2013].

Instead of the augmented feedback being active all the time, bandwidth feedback should be implemented to only provide feedback when the collective crew behaviour is not stable in their interpersonal coordination As of now, the augmented feedback is 100% active, which creates a dependency on the rowers [Sigrist et al. 2013]. An example of bandwidth feedback related to this thesis is by [Bergsma 2020], in which feedback became more intense depending on the error size. However, the bandwidth feedback should take the follower-leader relation into account. As studies on crew phenomenology by [Seifert et al. 2017] and [Feigean et al. 2017] revealed that experiences and rowing adaptations occur on both collective- and individual level, making case for a smart algorithm that can distinguish not only when to provide feedback, but who to provide feedback for and in what form.

Future research on the multi-person rowing platform includes a myriad of research directions and opportunities. Some of which are already being explored as of now. Examples include rowing over distance, virtual teammates/opponents, virtual coaches. For this thesis, aiming to facilitate the training of interpersonal coordination, the following research steps are most valuable and discussed below.

First and foremost, conducting transfer- and retention tests to measure the transfer of training from the simulated environment to the real environment. Also as a means to investigate the effectiveness of the applied augmented feedback designs. Look at for instance the experimental design and learning protocols of [Varlet et al. 2013] or [Seifert et al. 2017]. As of now, the experimental design provides a 5-minute snapshot for each condition and is not sufficient to make inferences on the training/learning effect related to actual row training.

Secondly, research on real-time augmented feedback to promote interpersonal coordination within rowing crews. This can be research on identifying new forms of concurrent augmented feedback, improving upon existing feedback, or work towards a combination thereof that for instance offer rowers different types or combinations of augmented feedback. Also, personalising feedback by preferences or location may be useful to look into, since not all feedback is useful for each rower, also because of the way they have been trained. Another direction is that of multi-modal feedback, which can offer distinct advantages to immersive row training. [Sigrist et al. 2013] even states that "Designs of augmented multi-modal feedback should exploit the modality-specific advantages". Rowers even indicated the need for multi-modal feedback by reportedly using audio-visual information to coordinate upon, including the sound from the RP3 ergometer. Given the decision to omit mechanical coupling, one can argue that the system must work towards a audio-visual-haptic feedback system. Despite the limitations of this study in providing evidence on the feedback's effectiveness, evaluations through empirical results and subjective flow states do highlight the benefit of real-time personalized augmented feedback, specifically it's suggested potential to provide more stability in synchronization for immersive rowing. Further research in this direction can turn the multi-person rowing platform into the envisioned training tool for interpersonal coordination, or even other related skills.

9 CONCLUSION

This thesis shows the potential of a mixed-reality, multi-person rowing platform in its first-ever steps to facilitate the training of interpersonal coordination within crew rowing, specifically co-located rowing dyads. By expanding upon the extant VR4VRT-system, the platform was able to host co-located rowing dyads and provide personalized augmented feedback to support the stroke and bow rower in their respective roles that visualizes, the otherwise intangible, interpersonal coordination.

Nevertheless, the Continuous Relative Phase (CRP) and Generalised Additive Models (GAMs) graphs indicates a significant phase shift with respect to non-VR rowing, especially near the relevant catch timing, where the bow seemingly lags behind the stroke's lead. A within-subject design consisting of 3 rowing conditions related to different levels of visual coupling: Non-VR (NVR), VR and Augmented Feedback (AF) was conducted. 8 rowing dyads participated and indicated a significantly positive rowing experience regarding enjoyment, especially while immersed. Interesting is that they tried to automatically synchronize based on the RP3 sound and visual information presented in VR, but were easily perturbed if realism was missing, especially regarding the boat propulsion and segmental information from virtual rower avatars. The CRP-profiles for the immersive conditions VR and AF occured in the CRP range/domain related to the stroke and bow dynamics from the non-VR baseline, but also included a persistent phase shift throughout the stroke cycle. Because the virtual rower is represented as a simplification in terms of rowing dynamics and segmental information, it is suggested that the bow rower adopts rather reactive instead of anticipatory behaviour to the visual stimuli.

To conclude, the preliminary results show that the multi-person rowing platform is promising as it offers a virtual rowing environment that empowers rowing crews to practise without time- and place constraints, while being able to simulate real-life rowing dyad interactions according to the follower-leader relation, even augmenting this relation as personalized augmented feedback seemingly stabilized interpersonal coordination for immersive rowing. Despite its limitations, and strong need for more sophistication on behavioural realism, the multi-person rowing platform has shown to be able to facilitate interpersonal interactions within a visually coupled co-located rowing dyad, which is the first step towards training the skill of interpersonal coordination.

BIBLIOGRAPHY

2024. Nature Reserve Wilderness Color Palette. https://colorpalette.org/nature-reserve-wilderness-color-palette/. Accessed: July, 2022.

Duarte Araújo and Keith Davids. 2016. Team synergies in sport: theory and measures. *Frontiers in psychology* 7 (2016), 1449.

Arthur Aron, Elaine N Aron, and Danny Smollan. 1992. Inclusion of other in the self scale and the structure of interpersonal closeness. *Journal of personality and social psychology* 63, 4 (1992), 596.

Sascha Bergsma. 2020. Virtual Rowing Coach.

Yohann Cardin, Cyril Bossard, Cédric Buche, and Gilles Kermarrec. 2013. Investigate Naturalistic Decision-Making of Football Players in Virtual Environment: Influence of Viewpoints in Recognition. In *NDM11, the 11th International Conference on Naturalistic Decision Making*. 109–117.

Laura Suzanne Cuijpers. 2019. *Coordination dynamics in crew rowing*. Ph. D. Dissertation. University of Groningen. https://doi.org/10.33612/diss.94906482

Laura S. Cuijpers, Ruud J. R. den Hartigh, Frank T. J. M. Zaal, and Harjo J. de Poel. 2019. Rowing together: Interpersonal coordination dynamics with and without mechanical coupling. *Human Movement Science* 64 (April 2019), 38–46. https://doi.org/10.1016/j.humov.2018.12.008 Copyright © 2019 Elsevier B.V. All rights reserved..

Laura S. Cuijpers, Frank T. J. M. Zaal, and Harjo J. de Poel. 2015. Rowing Crew Coordination Dynamics at Increasing Stroke Rates. *PLOS-One* 10, 7 (17 July 2015). https://doi.org/10.1371/journal.pone.0133527

Keith Davids, Duarte Araújo, Vanda Correia, and Luís Vilar. 2013. How small-sided and conditioned games enhance acquisition of movement and decision-making skills. *Exercise and sport sciences reviews* 41, 3 (2013), 154–161.

Shayn Davidson. 2018. *A Multi-dimensional model of enjoyment: Development and validation of an enjoyment scale (ENJOY)*. Embry-Riddle Aeronautical University.

Dennis Reidsma D.B.W. Postma, Annabelle de Ruiter and Champika Ranasinghe. 2021. SixFeet: An Interactive, Corona-Safe, Multiplayer Sports Platform. (2021).

Oliver RL Farley, Kirsten Spencer, and Livvie Baudinet. 2020. Virtual reality in sports coaching, skill acquisition and application to surfing: A review. (2020).

Charles Faure, Annabelle Limballe, Benoit Bideau, and Richard Kulpa. 2020. Virtual reality to assess and train team ball sports performance: A scoping review. *Journal of sports Sciences* 38, 2 (2020), 192–205.

Mathieu Feigean, Mehdi R'Kiouak, Reinoud J. Bootsma, and Jérôme Bourbousson. 2017. Effects of Intensive Crew Training on Individual and Collective Characteristics of Oar Movement in Rowing as a Coxless Pair. *Frontiers in Psychology* 8 (2017), 1139. https://doi.org/10.3389/fpsyg.2017.01139

Nicolas Gerig, Peter Wolf, Roland Sigrist, Robert Riener, and Georg Rauter. 2017. Automated feedback selection for robot-assisted training. *International Journal of Computer Science in Sport* 138 (2017).

James J Gibson. 2014. *The ecological approach to visual perception: classic edition*. Psychology Press.

Holger Hill. 2002. Dynamics of coordination within elite rowing crews: Evidence from force pattern analysis. *Journal of sports sciences* 20 (03 2002), 101–17. https://doi.org/10.1080/026404102317200819

C. Hoffmann, Alessandro Filippeschi, E. Ruffaldi, and B. Bardy. 2014. Energy management using virtual reality improves 2000-m rowing performance. *Journal of Sports Sciences* 32 (2014), 501 – 509. https://doi.org/10.1080/02640414.2013.835435

Ivan Hooper. 2009. A discussion of fixed vs. dynamic ergometers.

Yuki Kamaya, Takatoshi Naka, Masashi Yamada, and Shinya Miyazaki. 2018. Information visualization for virtual martial arts training. In *2018 Nicograph International (NicoInt)*. IEEE, 66–69.

Gilles Kermarrec, Yohann Cardin, and Cyril Bossard. 2014. Shared Understanding and Coordination in Team Sports-Contribution of Viewpoints Changes and Shared Information Displays for Team Situation Awareness Training. In *International Congress on Sport Sciences Research and Technology Support*, Vol. 2. SCITEPRESS, 89–96.

Valery Kleshnev. 2020. *Biomechanics of Rowing: A unique insight into the technical and tactical aspects of elite rowing*. The Crowood Press.

Kai Krabben, Dominic Orth, and John van der Kamp. 2019. Combat as an interpersonal synergy: An ecological dynamics approach to combat sports. *Sports medicine* 49, 12 (2019), 1825–1836.

Peter F Lamb and Michael Stöckl. 2014. On the use of continuous relative phase: Review of current approaches and outline for a new standard. *Clinical biomechanics (Bristol, Avon)* 29, 5 (2014), 484–493.

Martin Ludvigsen, Maiken Hillerup Fogtmann, and Kaj Grønbæk. 2010. TacTowers: an interactive training equipment for elite athletes. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. 412–415.

L Rens A Meerhoff, Harjo J. de Poel, and Chris Button. 2014. How visual information influences coordination dynamics when following the leader. *Neuroscience Letters* 582 (2014), 12–15.

Sarah-Kate Millar, Anthony Oldham, and Ian Renshaw. 2013. Interpersonal, Intrapersonal, Extrapersonal? Qualitatively Investigating Coordinative Couplings between Rowers in Olympic Sculling. *Nonlinear dynamics, psychology, and life sciences* 17 (07 2013), 425–43.

NPO Radio 1. 2020. Het Geluid van Roeien. https://www.nporadio1.nl/podcasts/het-geluid-van-sport/30146/1-het-geluid-van-roeien. Accessed: July, 2022.

Harjo Poel, de, A.J. De Brouwer, and Laura Cuijpers. 2016. *Crew rowing: an archetype of interpersonal coordination dynamics.* (1 ed.). Routledge, 140–153.

Dees B.W. Postma, Robby W. van Delden, Jeroen H. Koekoek, Wytse W. Walinga, Ivo M. van Hilvoorde, Bert Jan F. van Beijnum, Fahim A. Salim, and Dennis Reidsma. 2022. A Design Space of Sports Interaction Technology. *Foundations and Trends in Human-Computer Interaction* 15, 2-3 (25 Aug. 2022), 132–316. https://doi.org/10.1561/1100000087

G. Rauter, R. Sigrist, K. Baur, L. Baumgartner, R. Riener, and P. Wolf. 2011. A virtual trainer concept for robot-assisted human motor learning in rowing. 1 (2011), 00072. https://doi.org/10.1051/BIOCONF/20110100072

Emanuele Ruffaldi and Alessandro Filippeschi. 2013. Structuring a virtual environment for sport training: A case study on rowing technique. *Robotics and Autonomous Systems* 61, 4 (2013), 390–397.

E. Ruffaldi, Alessandro Filippeschi, C. Avizzano, B. Bardy, D. Gopher, and M. Bergamasco. 2011. Feedback, Affordances, and Accelerators for Training Sports in Virtual Environments. *PRESENCE: Teleoperators and Virtual Environments* 20 (2011), 33–46. https://doi.org/10.1162/pres_a_00034

Jesse Schell. 2008. *The Art of Game Design: A book of lenses.* CRC press.

Marianne Schmid Mast, Emmanuelle P Kleinlogel, Benjamin Tur, and Manuel Bachmann. 2018. The future of interpersonal skills development: Immersive virtual reality training with virtual humans. *Human Resource Development Quarterly* 29, 2 (2018), 125–141.

Ludovic Seifert, Julien Lardy, Jérôme Bourbousson, David Adé, Antoine Nordez, Régis Thouvarecq, and Jacques Saury. 2017. Interpersonal Coordination and Individual Organization Combined with Shared Phenomenological Experience in Rowing Performance: Two Case Studies. *Frontiers in Psychology* 8 (2017), 75. https://doi.org/10.3389/fpsyg.2017.00075

Jaehyuk Shim, Youngnoh Goh, Hyejin Kim, Seungchan Lim, and Daseong Han. 2018. A Rowing Game Based on Motion Similarity of Two Players *(CASA 2018)*. Association for Computing Machinery, New York, NY, USA, 83–85. https://doi.org/10.1145/3205326.3205362

Roland Sigrist, Georg Rauter, Robert Riener, and Peter Wolf. 2013. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic bulletin & review* 20 (2013), 21–53.

Silvan Steiner, Anne-Claire Macquet, and Roland Seiler. 2017. An integrative perspective on interpersonal coordination in interactive team sports. *Frontiers in psychology* 8 (2017), 1440.

C. Sève, A. Nordez, G. Poizat, and J. Saury. 2013. Performance analysis in sport: Contributions from a joint analysis of athletes' experience and biomechanical indicators. *Scandinavian Journal of Medicine & Science in Sports* 23, 5 (2013), 576–584. https://doi.org/10.1111/j.1600-0838.2011.01421.x arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2011.01421.x

Wan-Lun Tsai, Li-wen Su, Tsai-Yen Ko, Cheng-Ta Yang, and Min-Chun Hu. 2019. Improve the decision-making skill of basketball players by an action-aware VR training system. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 1193–1194.

Annefie Tuinstra. 2021. *Virtual Reality Rowing.* B.S. thesis. University of Twente.

Robby van Delden, Sascha Bergsma, Koen Vogel, Dees Postma, Randy Klaassen, and Dennis Reidsma. 2020. VR4VRT: Virtual Reality for Virtual Rowing Training. In *Extended Abstracts of the 2020 Annual Symposium on Computer-Human Interaction in Play*. 388–392.

Manuel Varlet, Alessandro Filippeschi, Grégory Ben-sadoun, Mickael Ratto, Ludovic Marin, Emanuele Ruffaldi, and Benoît G. Bardy. 2013. Virtual Reality as a Tool to Learn Interpersonal Coordination: Example of Team Rowing. *PRESENCE: Teleoperators and Virtual Environments* 22 (2013), 202–215.

Joachim von Zitzewitz, Peter Wolf, Vladimir Novaković, Mathias Wellner, Georg Rauter, Andreas Brunschweiler, and Robert Riener. 2008. Real-time rowing simulator with multimodal feedback. *Sports Technology* 1, 6 (2008), 257–266.

Martijn Wieling. 2018. Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics* 70 (2018), 86–116.

Keiko Yokoyama, Noriyuki Tabuchi, Duarte Araujo, and Yuji Yamamoto. 2020. How Training Tools Physically Linking Soccer Players Improve Interpersonal Coordination. *Journal of sports science medicine* 19 (05 2020), 245–255.

Zeng Yuqing, Cao Mingliang, Zhang Haoyang, and Zhong Yong. 2021. VR Technology and Application in Martial Arts. In *2021 IEEE 7th International Conference on Virtual Reality (ICVR)*. IEEE, 240–245.

L Zumeta, A Wlodarczyk, N Basabe, S Telletxea, D Alves, and A Puente. 2013. Shared flow and emotional communion in collective activities. *Poster on 12th ECPA.(Donostia/San Sebastián;).[Google Scholar]* (2013).

Larraitz N Zumeta, Xavier Oriol, Saioa Telletxea, Alberto Amutio, and Nekane Basabe. 2016. Collective efficacy in sports and physical activities: Perceived emotional synchrony and shared flow. *Frontiers in psychology* 6 (2016), 1960.

APPENDIX

A1: Rowing Reimagined GitHub

The GitHub page for the Rowing Reimagined project contains information and guides for the first time setup and general setup of the multi-person rowing platform. This information is available with the following link: https://github.com/marsmaantje/RowingReimagined

Note: the information on here is last updated during 2023, and is focused on NeosVR as platform (as of now rebranded to Resonite).

A2: Post-Assesment Interview Questions

1) When thinking about matching your movement with your teammate, was there any difference between the conditions?
2) What condition did you feel had the best team synchronization?
3) Where did you focus your attention during the different conditions, and how did it differ? if any difference at all.
4) Did the feedback provide you with relevant information about your rowing movement?
4a) Did the feedback support you in your respective role as stroke or bow rower?
4b) Did you feel like following the feedback?
5) Did the virtual rowing environment provide you with a realistic rowing experience?
6) Do you think this virtual rowing environment can facilitate your actual training practise, in this case for interpersonal coordination?
7) Imagine having such a setup here, would you consider using it for team practise?
8) Any other thoughts you think are worth sharing regarding this experiment?