Trial-and-Mirror

Enabling climbing movement exploration with interactive puppetry design to enhance out-of-action perceptual motor skill acquisition.

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Preface

"Behind the visible movement there is another movement, one which cannot be seen, which is very strong, on which the outer movement depends."

– Jeanne de Salzmann, French-Swiss dance teacher.

At the beginning of my student time, my roommates took me along to the bouldergym. Right away I was mesmerised by the sport and everything it entails. As a beginner climber, I felt very motivated by watching other climbers from the ground, from chatting with peers about "figuring out routes" and cheering each other up. In the bouldergym, there is no real competition between climbers: everyone just wants to have fun and climb as many interesting routes as possible.

The reoccuring struggle for me, and many of my peers, is the growing exhausion of the muscles over the course of the training session. Once your body is fatigued, your training session ends. However, you still would like to explore new movements ideas. Bouldering routes, often referred to as 'problems' or 'projects', are technically challenging and it usually takes multiple attempts before you reach the top. Therefore, you can see climbers sitting in front of the wall, previewing their 'project' route and imagine themselves climb up there to prepare for the ascend. It is fascinating to see that climbers move their arms, hips and sometimes even their legs during route reading on the ground. Additionally, they communicate strategies, share experiences or give advice through words supplemented by body gestures.

From the described scenario that I experience myself every week, I am pleased to have worked on the topic of *route reading*. Three years ago I chose to combine the master studies *Industrial Design Engineering (IDE)* and *Interaction Technology (I-Tech)*. My vision was to obtain as much knowledge and skills as possible to create relevant human-computer interaction designs. I am more than happy with this decision and with the unique opportunity to apply both expertise into one big research project. For me, this graduation project embodies all the knowledge that I have obtained during my master studies I-Tech and IDE.

Everything I have learned so far came together in the making of this. I am grateful with the opportunity that I got to explore my interests, having the freedom to follow my intuition and receiving tutoring, love and support from people around me. Therefore, I wish to thank those who have been involved in the execution of this graduation project. Without your valuable knowledge, critical feedback, and guidance it would not have been possible to reach such results.

The biggest gratitude goes to Dennis Reidsma. You provided incredible guidance throughout the whole journey and gave me the opportunity and freedom to work on this amazing project. When I got stuck in my head, you lightened up the space. After every meeting, I was always left with positive energy and a head full of ideas. First, I got to know your enthusiasm for everything that comes with research and design through our project for the Ethics Committee. And although, most of our meetings were online, they were always a delight.

Next, Jelle van Dijk, thank you for being there when I needed you. Your expertise on Embodied Interaction and Participatory Design methods was very helpful and inspiring. Also, I would like to thank Robby van Delden, Dees Postma and everyone from Sport, Data & Interaction for your incredible insightful feedback during our meetings. Furthermore, I would like to thank all my climbing friends and participants of the co-design sessions and user study. Especially Herman Engbers for giving me the opportunity to execute experiments, test out prototypes and facilitate everything bouldering related.

Special thanks go out to all of my friends and family. Especially Roel, I am beyond grateful for having you in my life. You are not only my ultimate climbing buddy but also my motivator, flatmate and partner in crime. We have both simultaneously worked on our master thesis and I am excited for the next phase of our lives.

I hope you enjoy reading my thesis!

Amy de Lange

Enschede, October 2022

Summary

The perceptual motor skill is crucial for individuals to execute physical motor behaviour in their environments. In sports training, the focal point of (perceptual) motor skill learning is mainly physical practice. However, *mental practice* has proven to be also beneficial for (perceptual) motor skill development. The out-of-action cognitive rehearsal of a physical skill through *motor imagery*, helps athletes to reflect upon their actions and prepare for upcoming ones.

In bouldering, *mental practice* is embedded in the training by climbers and referred to as *'route reading'* on the ground. Climbers prepare themselves for the ascend in between attempts through visual inspection and motor imagery. Bouldering routes do not rise above 4.5 meters above the safety mat and this makes them shorter and more technically challenging than traditional sport climbing routes. *Route reading* is therefore an essential part of bouldering training since it enables climbers to perceive affordances and to investigate, choreograph and make an action plan. Route reading *out-of-action* (i.e., on the ground) is necessary since doing so in-action (i.e., on the wall) is physically fatiguing. However, there is still a gap between the 'lived' experience (in-action) and the 'imagined' experience (out-of-action). On the wall climbers receive immediate motor feedback on their actions, but when in-action the muscles are also fatiguing. On the ground the body can rest, and climbers have an overview of the whole route but it is challenging to imagine oneself on the wall.

This thesis investigates the design space of utilising tangible and embodied interactive technology to bridge the gap between in-action and out-of-action *route reading* practice. By applying an iterative Research-through-Design (RtD) methodology, the design space was further developed and enriched by incorporating knowledge throughout the process.

The outcome of this thesis is the investigated design space and the final design concept that embodies the knowledge from the design space. The hi-fi prototype of the final design concept (Trial-and-Mirror) consists out of a tangible puppetry system where users can perform out-of-action *route reading* through manipulating their 'surrogate' (the puppet) and receiving visual motor feedback on top of this external representation. The tangible interactive puppetry system has demonstrated its potential during a final user test. It enhanced both ('functional') affordance perception and exploratory behaviour. Especially, for less experienced climbers the Trial-and-Mirror system has shown to stimulate the sensemaking of climbing poses by providing additional visual feedback, containing spatial and motor information. These aspects are known to be beneficial for athletes' perceptual motor skill acquisition over time. To underpin the statements and explore the design space further, more future research is needed.

Contents

Acronyms & Terminology

List of Acronyms

GUI	Graphical User Interface
HCI	Human Computer Interaction
hi-fi	High fidelity
lo-fi	Low fidelity
MI	Motor Imagery
TEI	Tangible and Embodied Interaction
TUI	Tangible User Interface

Glossary of Terms

beta	Climbing jargon which entails information on the sequence of movements performed in order to finish a 'route'. The description could be something as simple as the general type of holds, like "just trusted the feet", to something more complex, like "pinch the hold on the right corner, then match it, and swing to the other side".
drop knee	Climbing footwork technique that involves heavily weighting the outside of one foot in order to generate body tension in order to shift the hip towards the wall and torquing the knee downwards.
2.5-dimensional (2.5D)	Two-and-a-half dimensional, alternatively pseudo-3D, is a technique of a two-dimensional (2D) graphical projection that simulate the appearance of a three-dimensional. It appears to the viewer as three-dimensional (3D) when in fact it is technically speaking 2D.

Clarification on climbing and bouldering term:

Throughout the thesis the context of bouldering is often referred to as 'climbing'. Although 'climbing' is the overarching term of all forms of climbing-related sport practice, and bouldering is only one type of them. Still, 'climbing' is used to refer to the bouldering practice as well as the act of physical executing performed on the wall during bouldering practice. When we talk about other forms of 'climbing', it will be mentioned.

Clarification on ‘lived’, ‘imagined’ and ‘surrogated’ experience:

Throughout the thesis three terms are defined to distinguish experiences in the context of *route reading* and the design space is discussed. With the ‘lived’ experience, we refer to the in-action activity that in the context of bouldering takes place on the climbing wall. The climbers then performs physical execution of climbing movements and therefore receives feedback from the environment, which all contribute to the ‘lived’ experience. The ‘imagined’ experience is situated out-of-action when someone re-lives or imagines themselves in-action through motor imagery. The ‘surrogated’ experience is a newly introduced experience that users interacting with the Trial-and-Mirror system will encounter. The tangible puppet can be manipulated into climbing movements which enable the user to enact exploratory behaviour through their ‘surrogate’ (the puppet).

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Chapter 1

Introduction

Climbing is a popular sport that occurs outdoors at rock formations and indoors at specially built facilities. Bouldering is a derivative of sport climbing in which there is no use of ropes and other safety gear. Traditionally climbers would try to climb on top of large boulders in nature. Bouldering has since moved indoors where artificial boulder walls with holds are constructed that rise up to 4.5 meters above a safety mat. Climbing routes are built by routesetters and they are always unique and vary widely in difficulty level depending on the shape of the holds and the wall. Due to the relatively short length of the routes in bouldering, they are generally known to be technical challenging and physical demanding.

Climbers intensively use their whole body and muscular system to ascend the given climbing routes [13]. Climbers cannot endlessly execute motor actions on the wall as their body will eventually reach a state of fatigue. Therefore, climbers aim to climb routes as efficient as possible. While climbing on the wall, climbers' physical and cognitive abilities have to work together to perceive their action possibilities and correctly act upon them. Once back on the ground, this process continues by inventing climbing movements and plan for the next attempt through *motor imagery*. In both situations, on the wall and on the ground, the perceptual motor activity is referred to as *route reading*.

The out-of-action part of *route reading*, happening on the ground, is crucial within bouldering since it can reduce unnecessary time and (muscular) effort on the wall. Climbers have to develop the *perceptual motor skill* to perform *route reading* in order to climb more efficiently and overall finish more routes (i.e. reach the top hold). From the ecological theory of Gibson (1966) [14], *route reading*

Figure 1.1: Picture of two climbers performing route reading on the ground with the act of 'marking' to prepare themselves for their next attempt [1].

can be described as a continuous perception-action cycle between the individual and the environment through their performed activities. The relevant information picked up from the environment in relation to one's own capabilities lead to the perception of *affordances* (i.e. action possibilities).

Route reading on the wall enables climbers to receive instant motor feedback on their actions. The possibility to touch the surfaces of the holds allows climbers to obtain more spatial information. Next to that, to evaluate the feasibility of their motor plan climbers might perform *exploratory behaviour*, by for example changing their body orientation on change the position of their hands on the holds. On the ground, climbers rely on the visual inspection of the wall and *motor imagery* to imagine themselves executing their motor plan on the wall. This out-of-action part of *route reading* is often enhanced by *'marking'* [15] which is seen in Figure 1.1 where climbers move their arms to support their *route reading* on the ground. Still, *route reading* on the ground remains a challenging task since crucial aspects (e.g., proprioceptive and motor feedback) for perception-action coupling are missing.

Research in cognitive sciences and Human Computer Interaction (HCI) are increasingly acknowledging the importance of mental practice as an effective activity for (perceptual) motor skill acquisition [16]. However, the focal point in (bouldering and) sport practice is often physical training. By bringing the in-action and out-of-action experiences of sports training closer together, athletes can be supported in their cognitive tasks (e.g. *route reading*) to enhance their perceptual-action coupling. Over time, a learning environment that enhances the visual inspection on the ground and facilitate exploratory behaviour out-of-action can enrich the *route reading* process. This will presumably be beneficial for perceptual motor skill acquisition of climbers. Interactive technology can facilitate such a rich learning environment and/or experiences for athletes to support their skill acquisition. The practice of *route reading* can be advanced by including movement-based interactive design embedding (currently missing) aspects that are beneficial for the learning process of climbers.

1.1 Motivation

The gap between the in-action and out-of-action experience in bouldering makes an interesting case for exploring the potential of interactive technology. By incorporating movement-based interaction design, we aim to create a more meaningful experience on top of the current *situated practice*. Existing HCI research has investigated technological usage in the field of sports with movement analysis, performance tracking, enhancing collaboration, augmenting feedback and more. Most sport-HCI is positioned in the in-action training situation or out-of-action reporting on the performed actions. However, facilitating the *sensemaking* process during mental practice through *movement-based interaction design* remains relatively unexplored.

Implementing a technological artifact into a situated practice, such as bouldering, comes with its challenges. It is important for designers of these artifacts to think about the potential positive and negative influences on the cultural, social and physical context. For example, it would be a loss when a technological device would cause climbers to disconnect from the situated practice in the bouldergym. Taking the perspective of the embodied cognition theory, and by acknowledging the importance of the 'lived' experience, it can seem contradictory to design for the out-of-action scenario. However, we argue that the out-of-action practice, by complementing it with an embodied interaction, can enrich the athlete's sport training. The embodied interaction would not be as physical demanding as the in-action context (in this case: on the wall). By promoting the physicality of interaction design, technology could actually enrich the current *route reading* practice overall. By investigating the skill acquisition through technology-enhanced mental practice, we aim to bring the in-action and out-of-action parts of sport practice closer together.

1.2 Objective

This thesis aims to bridge the gap between the experience on the wall (in-action) and the experience on the ground (out-of-action) through interaction design. By bringing interactive technology in the situated practice of *route reading* on the ground, we can facilitate an enriched learning environment where climbers can explore movements while their physical body is resting. By enriching the out-of-action *route reading* practice, technology could enhance climbers' perception-action coupling and motor imagery. This would contribute to the climbers' perceptual motor skill acquisition by facilitation their exploratory behaviour to investigate, invent, choreograph and evaluate action possibilities on the ground.

The goal of this thesis is to investigate and expand upon the design space that was described above. The complex challenge of facilitating climbers' sensemaking and their design *of* movement, demands for an interactive system that allows *for* movement. Therefore, to explore the design space of movement-based interaction design for *route reading* we aim to work with a method that facilitates design activities *with* movement. The enriched and refined design space will be the main outcome of this research where the interactive design proposals (with their prototypes) will be the embodiment of the knowledge present in the design space.

Throughout the design-research process, design activities will be held to empathise with the situated practice and define and refine the design space while ideating, prototyping and testing solution directions. By involving the user, and their bodies in movement, various perspectives can be adopted to retrieve a deeper understanding of *route reading*. Specifically, on the gap between *route reading* on the wall and on the ground and how to close it through interaction design.

1.3 Research Questions & Thesis Outline

This thesis aims to deepen the design space through an iterative research process. The research process consists of three design phases in which five reoccurring steps are taken: Empathise, Define, Ideate, Prototype & Test, see Figure 1.2. This thesis determines the design space to be a dynamic asset that evolves over the course of the research process. After every design phase, the design space will be evaluated, refined and enriched with the knowledge obtained during the design activities in that phase.

At the beginning of the thesis, existing literature will be analysed as part of preliminary research (Chapter 2) in order to construct the initial design space. The main research question resulted from the preliminary research once the research opportunity was identified. The main research question guides the whole thesis towards the final conclusion.

> **Main research question:**
> *How to design a tangible interactive system for out-of-action route reading to enhance perception-action coupling?*

The design activities that correspond to the five steps of the Design Thinking approach will be constructed according to the demands of that research stage. Overall, the research question will be answered following a Research-through-Design methodology. This means that the design process and the material output (e.g. prototypes) can aid the investigation of the topic itself. This approach is further described in Chapter 3.

To facilitate the refinement of the design space throughout the design phases, sub-questions were incrementally articulated. The following sections will briefly introduce the sub-questions developed within each design phase. The process towards composing the sub-questions is shortly described as well. This hints at what can be expected in the rest of the thesis.

1.3.1 Design phase 1

From initial design space, based on preliminary research, it became evident that climbers perform out-of-action *route reading* through their mental representation and motor imagery. The mental representation in climbers' minds can be distributed to a visual external representation by interactive technology. A co-design session, design ideation and self-observation was executed to obtain more information about the current *route reading* experiences of climbers and potential solution directions using an external representation. The objective of this first design phase was supported by the first sub-question.

> **Sub-question 1:**
> *What visual representation of bouldering movements can accommodate route reading on the ground?*

1.3.2 Design phase 2

At the end of design phase 1, a solution direction was determined to have a *2.5-dimensional* graphical representation of climbing poses in reference to the bouldering route. The goal of the second design phase was to investigate what tangible and embodied user interface could allows for pose manipulation and exploration. The second sub-question supports the objective to explore tangible and embodied user interaction design to enhance athlete's out-of-action sensemaking process.

> **Sub-question 2:**
> *What tangible and embodied user interaction can enable 2.5D pose manipulation to enhance climbers' route reading on the ground?*

1.3.3 Design phase 3

The second design space resulted in a digital puppetry system that allows the user to represent their invented climbing poses through a tangible interaction. The Low fidelity (lo-fi) prototype, that represents the design space up till this stage, is still lacking motor feedback that is beneficial to the sensemaking process. The goal of the final design phase was therefore to explore how the 'lived' experience (on the wall) with its motor feedback and spatial information can be translated into a visual abstraction to enhance the situation on the ground. The third sub-question therefore accommodates this investigation, together with the evaluation of the technological feasibility of materialising the design possibilities.

> **Sub-question 3:**
> *What visual feedback can be augmented on a 2.5D representation of climbing poses to enhance climbers' route reading on the ground?*

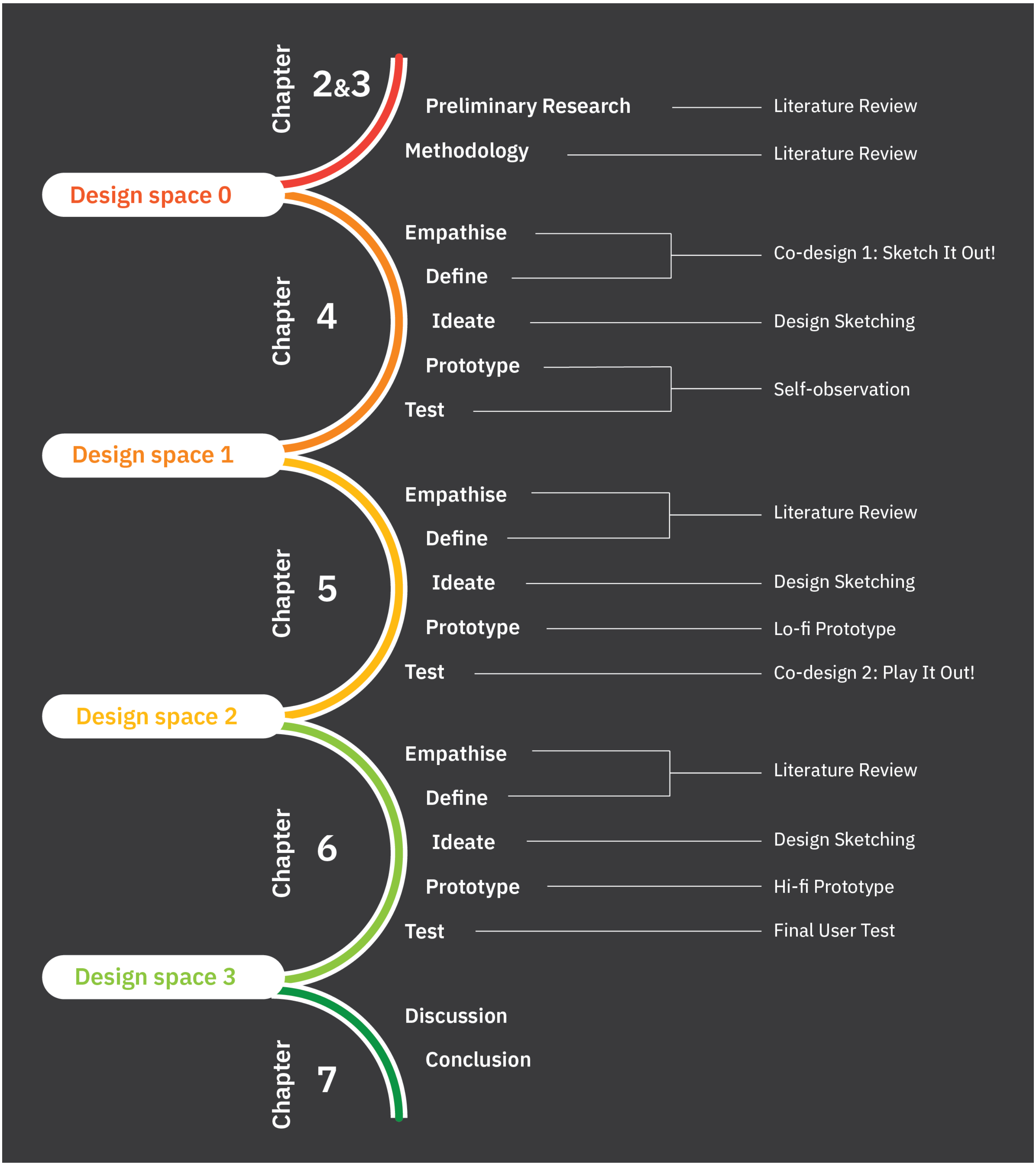

Figure 1.2: Iterative Research-through-Design process of this thesis.
The initial design space (nr. 0) is constructed after preliminary research and is based on literature. The following three arcs represent the three design iterations made where in each phase the five steps of Design Thinking are performed in various design activities. The three arcs correspond to Chapters 4-6 and each chapter end with an extension of the design space. At the end of the thesis, the outcome is reflected upon in the Chapter 7 including the discussion and final conclusion.

Chapter

02&03

Preliminary Research & Methodology

Design space 0

Chapter 2

Preliminary Research

The research objective derived from a literature reviewing process. In this chapter, the state-of-the-art research in areas of bouldering practice, perceptual motor learning and human computer interaction (HCI) pave the way towards the formulation of the design space. The underlying principles, phenomena and researched case studies are considered to identify opportunities and trends.

Part of the content of this chapter was written for the research proposal (i.e., research topics) as part of the thesis preparation phase. After the official start of the master thesis, more literature has been investigated during the Research-through-Design iterations (described in Chapter 3). This chapter introduces all related fundamentals to the thesis objective. However, some topics and literature are further elaborated on within the design phase chapter it corresponds to. For instance, during the second iteration the idea of a digital puppetry system emerged. This led to a more literature investigation into this topic. Digital puppetry as a form of embodied interaction is presented in this chapter, but described in more detail in Section 5.1 in Design Phase 2.

This chapter is divided into the following sections:

- **Section 2.1 Bouldering Practice**
  The sport practice explained with its goals, activities, environment and other related aspects.
- **Section 2.2 Perceptual Motor Learning**
  The skill acquisition investigated through the cognitive and ecological lens, with the focus on climbing and out-of-action skill acquisition. Followed by literature on learning environments that can aid the perceptual motor development.
- **Section 2.3 Related Work on Human-Computer Interaction for Climbing**
  Related work and trends on movement-based HCI with the focus on embodied interaction, augmented feedback and sensing of movement in the context of climbing.
- **Section 2.4 Design Space 0**
  From preliminary research, we can identify challenges, opportunities and gaps in the domain of interest. This results in the initial design space.

2.1 Bouldering Practice

Sport climbing has sparked interest in the past years and has made its debut in the Olympic Games in Tokyo 2020. Where it used to be a sport for a few outliers in the mountains, climbing has now expanded to numerous variants including bouldering, speed climbing and sport climbing. Bouldering leaves ropes and harnesses behind and makes use of climbing shoes, a bag of chalk and safety mats. Because there is no use of ropes, the top of bouldering routes never exceeds approximately 4.5 meters above the safety mat. Bouldering routes are often referred to as boulder “problems” as the routes short and very technical. The way to the top is generally not obvious and thus requires the climber to have physical strength, balance and technique as well as the ability to visualise him/herself on the wall and choreograph movements. One usually tries to figure out a way to “top” (= finishing) the route when they are resting on the ground in between attempts. Depending on the individual’s body dimensions and climbing preferences, multiple ‘*beta*’s’ are possible. If you are tall, you probably benefit from the ability to reach far, but in some routes you can find yourself cramped into the nooks of the wall.

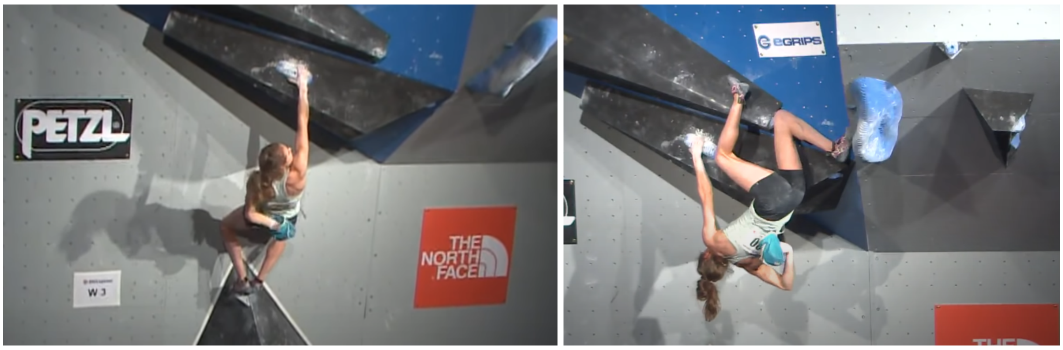

Figure 2.1: Margo Hayes in resting positions during the final round of the 2017 Bouldering Open National Championship [2]

Bouldering competitions vary slightly in the way the climbers are judged. However, there are overarching objectives that determine the scores. The highest score is achieved by the number of completed boulders and the attempts needed to do so. Climbers that “flash” (= completing a boulder problem on their first try) usually receive bonus points. In order to achieve the top score, athletes have to both read the route correctly, determine the most effective sequence of moves, and execute their sequence successfully. Considering the fact that time is not the most important component, climbers makes use of the possibility to rest in position in the wall to shake out their limbs and re-evaluate their sequence. One of the masters in this game is Margo Hayes. During the final round of the 2017 Bouldering Open National Championship, she clamped herself on different parts of the route to grab chalk, shake out her arms, and re-evaluate the remaining part of the climb, see Figure 2.1. The goal for non-professional climbers is mostly to top as many routes within a training session as possible. Bouldering routes are known for their technical difficulty which requires lots of physical load. Therefore, climbers need to be cautious to prevent early fatigue which stops the training session.

Indoor bouldergyms, routes are constructed by routesetters by the mounting of artificial holds and additional wall extensions (also called “modules”) on a fixed wall. The holds are not placed randomly, the routesetter rather plans out a sequence of moves to create the route in a sophisticated manner. Each routesetters operates differently: some start screwing interesting holds on the wall and tinkers with it, while others have a specific sequence of movements in mind and find holds that facilitates for them. Different aspects have to be considered: think of the theme of the route (e.g., balance or powerful moves) and differences in climbers such as length, strength and experience. The finest details of hold placement matters: think of the structure, form, angle and in relation to the other placed holds. Since routesetters start with a blank canvas, they have to rely on their imagery skills to set a route that will work out as one had in mind. However, after testing the route by climbing it, many (small) adjustments can still be made to improve the route.

Once the route is finished, routesetters assess the difficulty level. The vast majority of bouldergyms use the French numerical system to rate the routes to their technical difficulty and physical strenuousness. The system starts at 1 being 'easy' and end around 9 being 'extremely difficult'. For every level is also subdivided by adding a letter (a, b, c) and plus sign on top of the letter. The assessment of bouldering routes is subjective and either done by routesetters and climbers themselves. Therefore, not every 6a is experienced the same in different gyms and by different climbers.

Thanks to the absence of any ropes, climbers can easy step in and out routes trying to solve the problem. This is not only done individually but mostly together with peers. Several people often work together to figure out how to complete the route. Aside from the social aspect, it is beneficial to everyone's individual performance. Every attempt to top the route does not have to be executed by a single person which results in preserving energy. Moreover, watching the climb from the ground leads to different insights than from the wall and vice versa. Both experiences can be exchanged verbally to help each other.

Bouldering lessons for beginners start with the basics of body position, hand and feet placement, balancing of your body and working with one's center of gravity. The purpose of the basic techniques are to climb as efficiently and effectively as possible. During climbing lessons, trainers guide their students by giving verbal feedback from the ground and by showing them proper techniques while students are watching from the ground. Unfortunately, one cannot climb the route simultaneously to the received instructions. More advanced climbing techniques are movement guidelines intended to efficiently climb specific reoccurring parts of boulders. An example of a climbing technique is the *drop knee*. The purpose is to place oneself closer and slightly lower to the wall (see Figure 2.2). Placing oneself closer to the wall reduces the strength required to hold on.

Figure 2.2: The *dropknee* technique to shift the center of gravity for balance and better foot and hand grip.

Figure 2.3 gives an overview of all the activities during a bouldering session and highlights the typical activities in order. Typically, a boulder session starts by arriving at the bouldergym, followed by a warming up with either exercises on the floor or by climbing easy routes. Afterwards, the first route has to be chosen which can be a new route based on the level of the climber, a route that has not been completed in last session or something else based other personal motives. Once the route is selected, the climber will take a glance at the wall and try to imagine themselves climbing the route in the most optimal way. This activity is the *mental practice* part of the overall *route reading* and is situated on the ground. In Section 2.2 we will further elaborate on the process of *route reading*. From the moment the climber feels prepared enough, the climbing on the wall begins. Climbing is a constant interplay between the physical part of moving their body on the wall from hold to hold,

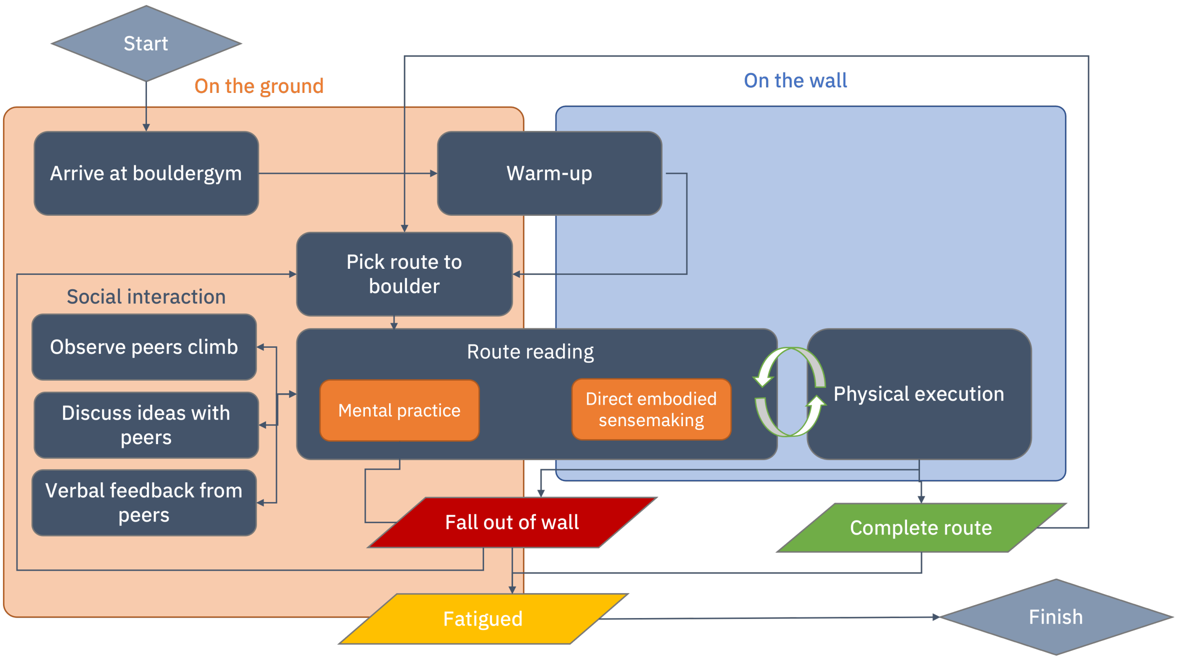

Figure 2.3: The activity flow diagram of a bouldering session.
The last paragraph of section 2.1 describes all the activities and relations.

while reconsidering and adjusting their movements on the go. This continual process stops when the climber falls, steps out of the wall or has reached the end of the route. When the end of the route was not reached, the climbers feel either motivated to continue working on the route or another route will be chosen. As they continue solving the boulder problem, climbers often work together by discussing ideas, exchanging feedback and watching each other climb. After a while, the climber will inevitably become physically exhausted, the training session will come to an end.

2.2 Perceptual Motor Learning

The acquisition and improvement of movements skills is often referred to as motor learning. Through the execution of movements, sensory information is perceived by the mover which can be analysed to reflect upon and plan for upcoming actions. This continuous cycle, between the cognitive process and performed actions, is an ongoing process during daily interactions. From the moment we step into this world, we interact with our surroundings to develop the necessary motor skills to navigate ourselves. During sport training, athletes are usually motivated to perform activities that promotes and enhances motor learning.

2.2.1 Theoretical Approaches

On the subject of motor learning, multiple theories have been formulated over the years. They all boil down to two main opposing theoretical frameworks: the cognitive based approach and the ecological dynamics approach. Traditionally, physical activity and sport practice have utilised cognitive based activities to set up a scripted learning environment. Students are stimulated to perform receptively particular fragments of movement to focus on the precision of execution. On the contrary, the ecological dynamics approach takes another perspective on physical activity and motor learning puts more emphasis on how people deal with the world in-action. Following this approach, learners are provided with an environment aiming for the freedom to explore a variety of movements. The ecological dynamics theory put the whole body more central and integrates the environment into the equation. The classical model (i.e., cognitive based approach) provides a different picture in which cognition is solely located in the head, detached from the environment. It states that actions are first internally reasoned in the individual's mind before being acted out in the world.

The following sub-sections will further elaborate upon both approaches and ends with an evaluation. By analysing the differences and how they affect our (research towards) understanding of bouldering and *route reading*, the goal is to find a fitting viewpoint of the research objective.

Cognitive Based Approach

In the cognitive based theories, the central nervous system is placed at the centre of an individual's motor learning process and understood as separate from an individual's environment. The cognitive based approaches perceive a human being in movement as a series of motor programs [17] that can be activated by complex commands in their minds. For improvements of performance and to provoke motor learning, enforceability and repetition of execution is the basis of cognitive-based training programs.

The cognitive based approach rests on the hypothesis of the *Cartesian Split* in which the mind and body are distinguished. Researcher taking the traditional cognitive position argue that knowledge is stored in representation in one's mind. This internal representational model in the brain received input from the outside world but it is not depended on it. This idea stems from Cognitivism [18] [19] in which the mind is essentially perceived as a computer where information is processed. From the perspective of Cognitivism, scientists argue that for an individual to obtain new motor skills, they depend on their natural ability to process information [20]. This implies that human beings are born with skillness in (motor) information processes instead of evolving over the course of human-world interactions.

Ecological Dynamics Approach

The ecological dynamics approach rejects the paradigm of the cognitive based approaches by shifting the focus towards human beings making sense of the world while interacting with the world. The theoretical viewpoint removes the Cartesian split between the individuals' 'inner' process and the 'outer' world. The ecological theory of Gibson (1966) describes the cognitive process as a continuous perception-action cycle between the individual and the environment through performed activities [14]. The individual relates relevant information for actions from the environment to their own action capabilities which enables them to perceive opportunities for action, also called *affordances* [21]. Affordances can be described as action possibilities provided by the environment that relate to the observer. For instance, affordances we perceive in the human environment are that stairs can be walked to move to a different floor and that a cup affords for grasping and holding a liquid. The information is picked up through *exploratory activity* by the perceptual systems through changes in body orientation, having a glance on the environment, touching surfaces and so on [14]. Thus, learning motor skills effectively requires adequate exploratory action and differentiating between relevant and irrelevant information streams [22].

> *"Perhaps the composition and layout of surfaces constitute what they afford. If so, to perceive them is to perceive what they afford. This is a radical hypothesis, for it implies that the "values" and "meanings" of things in the environment can be directly perceived. Moreover, it would explain the sense in which values and meanings are external to the perceiver." -James J. Gibson (1979, p. 127) [23]*

Appropriate Framework for Design Space

The design space of this thesis revolves around the sport practice of bouldering. As described in Section 2.1, the bouldering routes that climbers come across during training are always unique. Therefore, bouldering training does not aim to isolate single movement and optimise for them. Climbers rather have to constantly tune into their environment (i.e. the climbing route) to establish an agent-environment 'fit'. Although some cognitive based training activities for a single climbing movement can be argued to be useful. For example the climbing technique called a 'dyno' is a very specific dynamic movement that is often trained by practicing the movement over and over again. Figure 2.4 shows how this movement is performed within a climbing route. Although this training activity seems to follow the cognitive based approach, we would still argue that this training fits the ecological dynamics approach. A climber that practices a specific climbing technique through repetition and isolation (at that moment) aims to acquire the motor skills to transfer the climbing technique to other routes. This means that climbers rather train their perceptual motor skill to obtain an 'embodied knowing' [24] which relates to the embodied cognition theory.

Figure 2.4: Series of photographs showing a climber performing a 'dyno' to reach an otherwise unattainable hold [3].

This isolated type of training within climbing seems to fit the ideology of the constraints-led approach [25]. The constraints in climbing are embedded in the climbing route design which routesetters implement on purpose. The aim of climbing routes are often to afford for specific climbing movements to facilitate a 'lived' experience that is beneficial for the mover's motor learning. On the other hand, routesetters tend to make their intended *beta* not too easily observable with the goal to facilitate the perceptual motor learning. Climbers have to perform *route reading* on the ground (as well as on the wall) to find their 'path' and overall improving their skill in visual inspection to make couplings between their perceptions and actions.

The described motor learning strategy embedded in the situated practice of bouldering corresponds to the ecological dynamics framework. Climbers are facilitated with routes that allow a certain freedom in order to perform exploratory movements. Within the culture of bouldering, athletes appreciate the act of *route reading* and its problem solving aspect. Even during climbing competitions climbers encounter climbing routes that they have never seen or climb before. This requires them to be skilled 'route readers', meaning that they have limited time and (physical) effort to achieve success. This suggests that more experienced climbers are trained to adapt, plan *beta*s and find action possibilities in an every changing environment. Furthermore, this implies that by climbing and obtaining experiences in other climbing routes contribute to the perceptual motor skill which can be used in novel environments.

After evaluating the two theoretical lenses, the ecological dynamics perspective is identified to fit the design space. Specifically, the **embodied cognition theory** appears to be an appropriate framework to investigate the design space. The rest of the thesis adopts the ecological dynamics approach.

2.2.2 Embodied Sensemaking & Distributed Cognition

The way people make sense out of their experiences in the world is noted by psychological sciences as *'sensemaking'* [26]. The factors that relate to *sensemaking* are creativity, curiosity, comprehension, mental modeling and situation awareness. Perceptual motor skills, that are developed while acting in the world by bodily engagement and interaction, also require *sensemaking*. By interacting with the world, we continuously make connections among people, places and artifacts in relation to ourselves, culture, society and organization. Through physically interacting, humans make meaning of the context they perceive and by engaging in social situated practices a shared imagination can be achieved .

The current interests related to embodiment within the TEI (Tangbile and Embodied Interaction) community [4] can be classified in three directions: distributed representation and computation (DRC), socially situated practice (SSP), and sensorimotor coupling and enactment (SCE). All three phenomena relate to the objective of this thesis and will therefore be discussed in this section.

Distributed Representation and Computation (DRC)

The notion of *'external representation'* became known through Norman's work of 'knowledge in the world' [27]. It describes how people distribute their 'knowledge' and 'sensemaking' into their surroundings (visible in Figure 2.5). For example, by writing down items on a grocery list as a way to store the information. The *distributed cognition* also argues that people do not only store information in the world but also interact with the world for *sensemaking*. David Kirsh [28] explains this through describing that writing down notes reduces cognitive load, and with this *epistemic* action an individual is facilitated to perform computational tasks (*pragmatic* actions).

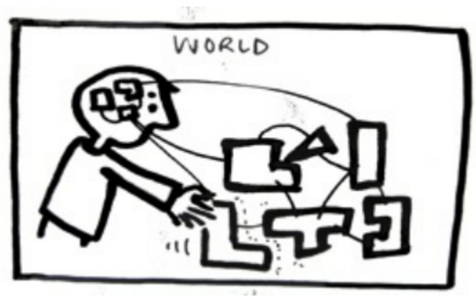

Figure 2.5: Sketch of the distributed representation and computation perspective (DRC) by Jelle van Dijk [4].

The work of van Dijk et al. (2014) [4] takes it a step further by bridging the cognitive theory with design practice. They emphasise on the importance of tangible and embodied interaction in design to promote the natural embodied sensemaking of its users.

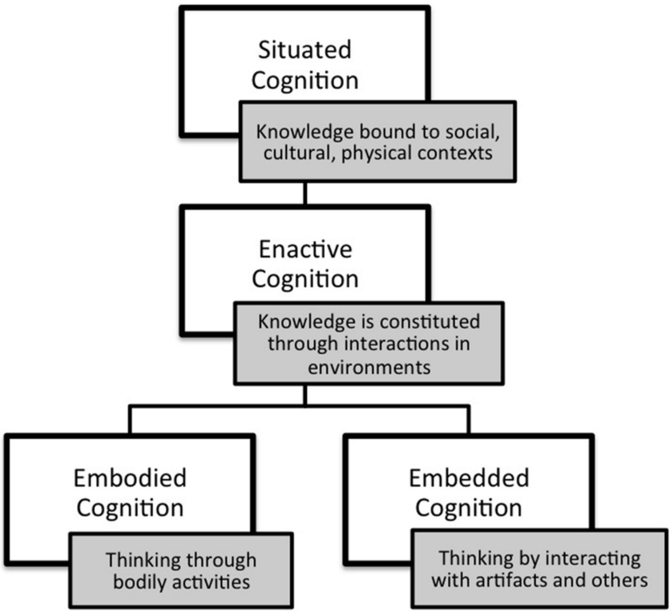

Figure 2.7: Overview of relations between *Situated Cognition*, *Enactive Cognition*, *Embodied Cognition*, *Embedded Cognition* [5]

Socially Situated Practice (SSP)

The second direction of embodied interaction stresses the social aspect of a situated practice. People act in a world where often other people are or have interacted with the world as well. In social interaction, storing knowledge 'in the world' through tangibles can facilitate communication and collaboration. They function as mediating objects (as being portrait in Figure 2.6) in the situated practice where people deal with each other.

Figure 2.6: Sketch of the socially situated practice (SSP) by Jelle van Dijk [4].

The term *Participatory Sensemaking* [29] explains the theory that sensemaking occurs in shared action spaces in which people interact with the world themselves but there is also a continuous embodied interaction between people. On top of that, even when others are not directly present, the world is still filled with norms, values, cultures, rituals and so on [30]. The work of van Dijk & Hummels (2015) addresses an example that states: "a coffee cup left on a table is immediately perceives as 'being left by someone"' [30].

The notion of *participatory sensemaking* later evolved to Suchman's theory on *situated cognition* [31]. In Figure 2.7 the relations between *Situated Cognition*, *Enactive Cognition*, *Embodied Cognition* and *Embedded Cognition* are visible in the diagram. The diagram distinguishes the "thinking through bodily activities" with "thinking by interacting with artifacts and other". However, within bouldering practice the two can almost not be separate since the bodily activities occur on the wall and therefore interactions with artifacts (i.e. climbing holds) are established.

Another specific form of embodied sensemaking within *route reading* (which is also observed in other sports) is the act of *'marking'*. It is the physical thinking technique that David Kirsch [28] refers to as a gestural language to support the sensemaking process. This bodily form of distributed cognition is often seen in the social collaboration between peer climbers [15]. Climbers use it to engage within a 'joint imagination' [32] to "figure out the *beta*".

> *"Marking and joint imagination also show that strongly embodied imagination allows for a situation whereby others can form the constraints for our imaginings." - Zuzanna Rucińska & Shaun Gallagher (2021, p. 16)* [33]

Since collaboration is in the nature of people [29], it inevitably part of our reality. Therefore, designers and researcher have to consider the social aspect when designing (digital) artifacts. Moreover, artifacts can be utilised as external representation [34] to facilitate the distribution of cognition (described in Section 2.2.2). The externalisation of knowledge in the world can be viewed by bystanders that on their turn can interact with it [28]. This perspective can be implemented within the design process in the form of co-design and other user involvement. This will be further described in Chapter 3.

Sensorimotor Coupling and Enactment (SCE)

To resume what was described in Section 2.2.1: through the embodied cognitive lens human-environment interactions can contribute to the sensorimotor development. Generally speaking, there are two types of coupling that occur during those interactions. The perception-action coupling can be established by individuals when the perception (visual or through other senses) is matched with the action possibility that they evaluate to be executable. This is not often experienced consciously by people since we have developed our perceptual motor skill to the level that those perception-action coupling happens in the background. However, when someone does not know "what to do" after identifying "what is seen", the person can consciously feel frustrated.

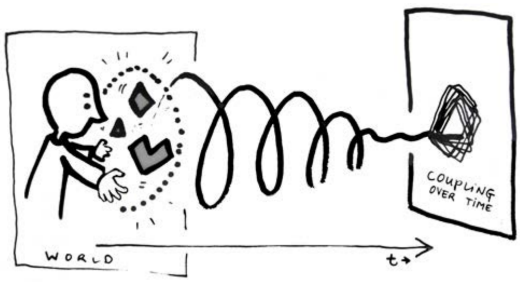

Figure 2.8: Sketch of sensorimotor coupling and enactment (SCE) by Jelle van Dijk [4].

The other type of coupling occurs when agents have to find a 'fit' their abilities and the possibilities in their environment. Within climbing you could argue that this agent-environment coupling occurs when climbers predict beforehand whether they will be able to climb a route before an attempt. As Figure 2.8 illustrates, sensorimotor coupling is achieved over the course of enactment in the world.

2.2.3 Out-of-Action Skill Acquisition

Continuing on the note of out-of-action skill acquisition, recent studies have been demonstrating that besides physical practice (PP), motor skills can be obtained through other forms of motor learning [35] [36]. Motor Imagery (MI), or *mental practice* (MP), is a multimodal cognitive process that simulates the absent sensory input that enables us to represent perceptual information in our minds ('motor representation') [37]. Nowadays, MI is widely used as a technique to enhance motor learning in sport practice [36], neurological rehabilitation in patients [38], learning to play a music instrument [39] and other related activities. The cognitive process combines visual imagery (VI) and kinaesthetic imagery (KI). Visual imagery (i.e., mental imagery) involves self-visualisation in which someone makes "pictures" in the mind and kinaesthetic imagery implies somesthetic sensations (e.g., skin sensations, body position in space and sense of gravity and balance) elicited by action.

The study from Walker et al. (2020) provides us with initial proof that expert video modelling is an effective method for skill acquisition of climbing techniques [40]. They let participants learn typical climbing techniques through watching videos of experts performing the moves which resulted in an increased performance over time. Several years before that, Boschker and Bakker (2002) showed inexperienced climbers videos of experts and novice performances [41]. Participants who watched the expert climbers learned climbing techniques and more fluent movements in comparison to the ones who watched the novice climbers. Therefore, expert modelling is a powerful tool for skill acquisition in climbing.

Motor imagery and action observation have separately proved to increase motor learning outcomes, but the combination of the two enhances motor learning even more [35]. It supports the participants' ability to generate motor images by imagining themselves in observing the actions of others. This is currently happening in bouldering practice with viewing peers and coaches climb routes or demonstrates climbing moves while the climber rests on the ground. The reasoning behind the boost in skill acquisition, when using both at once, is the stronger activation in the brain connected to a more embodied movement representation, which makes the gap between imagery and the 'real' experience smaller [35]. Moreover, the dual-action simulation hypothesis suggests that the cognitive processes involved in the external presentation of a movements (AO) and perceptual processes involved in the internal presentation of movements (MI) can occur simultaneously in the brain [42]. This evokes an enhanced generation of the motor representation, and therefore beneficial for mental practice.

As mentioned, MI (in climbing route reading on-the-ground) together with AO (viewing someone perform the sequence) creates added value to bouldering training. Nevertheless, the judgement from the viewer whether the sequence would actually work out is challenged by the lack of proprioceptive feedback. This feedback during the 'felt' experience, during the physical execution, contains information about the forces in play, muscle tension, friction on the holds and so on. The absence of proprioceptive feedback can be substituted with motor feedback augmentation. Researchers have experimented with different types of motor feedback in sport practice or other movement tasks. For example, Nojima et al. (2015) simulated a hand performing tasks where participants solely had to observe without moving themselves but placed their hands under the display so it felt like they were watching their own hands moving [43]. The study demonstrates that kinaesthetic illusion in addition to action observation leads to performance gain and elicits a higher level of illusion.

2.2.4 Affordance Perception in Bouldering

The climbing performance in climbing depends on how the individual dynamically adapts actions to the climbing surface properties [44]. Due to the complexity of the climbing wall, climbers have to constantly regulate their body position and movements in relation to the affordances perceived on the wall. Finding a feasible chain of movements to execute the route is a challenging task. Exploratory behaviour on the wall, by testing out action possibilities, supports the search for a successful attempt and 'energy efficient actions' [45]. Not only for the route at hand but the experienced actions also contribute to the acquisition of the 'route reading' skill.

The difference in skill level between climbers is often focused on the physical aspects (e.g., finger strength) [46] [47]. However, Boschker et al. (2002) [41] examined the relationship between skill level and affordance perception and found that the varying experience levels relate to the af-

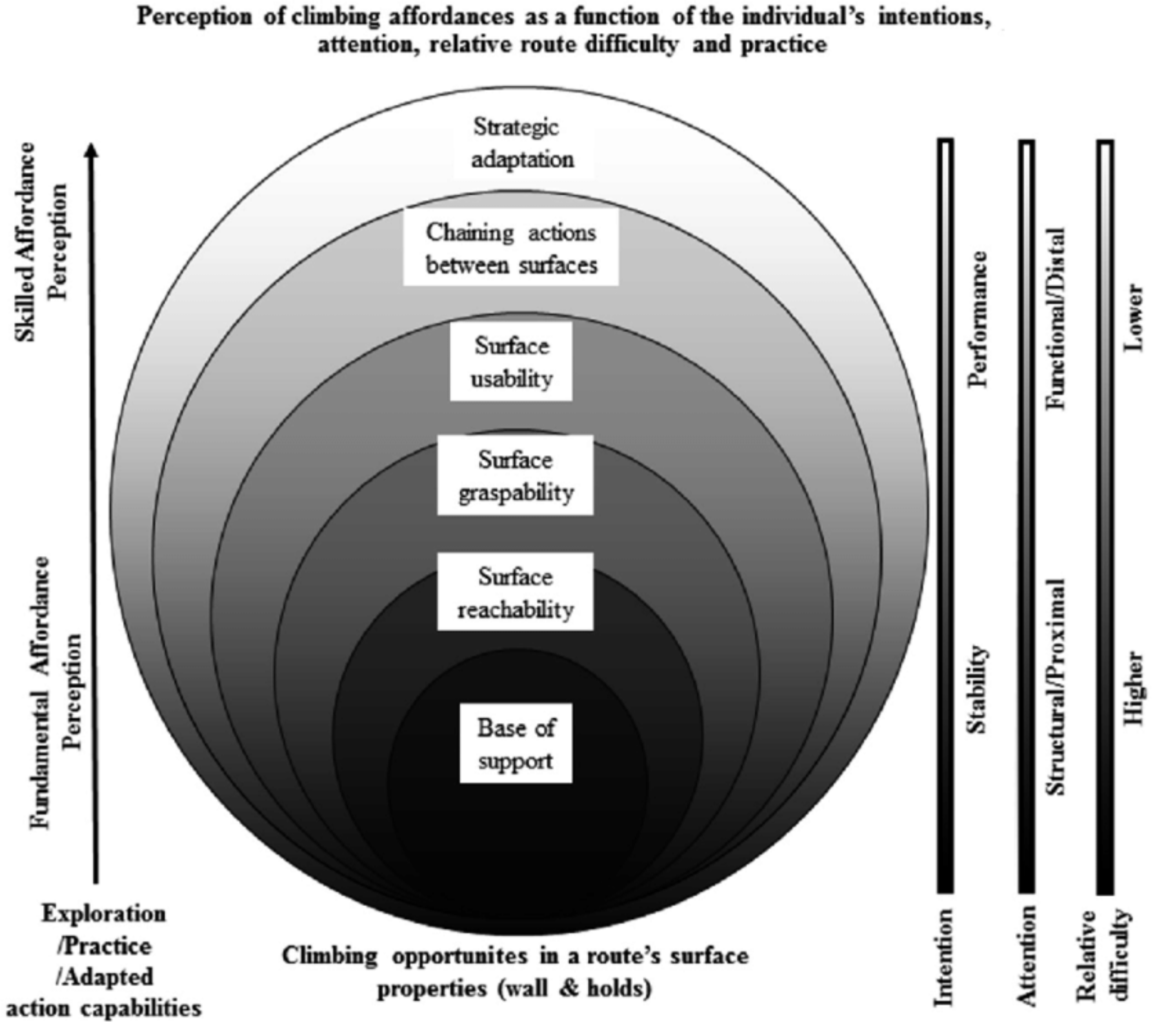

Figure 2.9: Levels of affordance perception within *route reading* [6].

fordances perceived by climbers. In their study, participants of different climbing levels were asked to visually inspect a route and plan to complete the route. A follow-up experiment required participants to speak aloud and report what they were thinking. Analysis indicate that more experienced climbers the affordance perception differ subsequently from inexperienced climbers. Participants with a higher experience level in climbing spoke more about 'functional' properties instead of 'structural' ones. Moreover, they perceived more 'nested' affordances in the form of climbing opportunities where 'clustered' information had to be picked up from the wall. That information reflect the 'functional' properties of holds, meaning their reachability, graspability, and stand on-ability, translated to specific climbing movements [41].

More researchers touch upon the different levels of affordance perception in climbing [48] [49] [6]. Figure 2.9 constructed by Orth et al. (2016) [6] represents all the affordance perception concepts that have been identified in research till 2016. The model shows that the perceptual motor skill level starts by avoiding to fall and therefore finding a "base of support". With more practice, climbers can perceive the surface reachability, graspability, usability and ultimately chaining the identified action possibilities between surfaces. The deepest level is the strategic adaptation with refers to "use of surfaces to rest or plan". An example of such use is mentioned before and visible in Figure 2.1.

These findings imply that affordance perception is a skill that is acquired from experience and that it supports effective and efficient climbing. It also indicates the importance of perceiving 'functional' features instead of solely 'structural' properties of the climbing wall. In order to develop this 'nested' affordance perception with the attention to the 'functional' properties of the climbing route, a suitable learning environment and training can support athletes. Research pinpoints the benefit of *exploratory behaviour* to support perception of new action opportunities [50] [51]. Although climbers should be aware that the trial-and-error method is bounded by fatiguing their muscular system.

2.2.5 Ecological Motor Learning Environment and Tactics

The major focus in sport training is still physical practice to improve athlete's performance. All the previous sections built up to this point where we can confirm that the mental aspects play a crucial role in (perceptual) motor learning. One could even say that physical practice cannot stand alone from the cognitive system controlling it. From the ecological perspective, the *embodied cognition* even between the mind, body and environment.

In the field of sport science, training methods are often constructed on the notion of Newell's constraints-led approach (1986) [52]. The constraints are divided into organismic, environmental, and task-related. The organismic constraints are complex since every individual possesses difference structural constraints (e.g., body composition and personality traits) and functional constraints (e.g., fatigue state and motivation) [53]. The individual, environment and tasks form a connected ensemble, where changing conditions in each elements influences the whole dynamic. By correctly manipulating the constraints within sport training, the perspective for the athlete changes. For example by getting detached from the original "game" in order to loosen up the senses to perceive new affordances [53]. Therefore, teaching approaches and (technical) interventions have to be critically designed to stimulate this shift in perception.

The positive effects of augmented feedback during skill acquisition can be the external focus of attention which is found to be beneficial for motor learning [54]. Another argument might be the reduction in cognitive load in an early stage of learning [55]. Opposed to the positive effects, Sigrist et al. (2013) also mention the loss in the performance gain during retention. This is caused by a dependency due to continuous feedback during a learning task, also known as the 'guidance effect' [56]. Research has shown that changing the frequency [57] and form of feedback [56] over time can help to reduce the guidance effect.

Providing augmented feedback throughout sport practice is one way of creating an effective learning environment for athletes. Implementing other strategies, constraints and conditions can also establish a rich learning environment. It already starts with the design of the indoor bouldering routes designed by route setters. The routes are set up by mounting of artificial holds and additional wall extensions (also called "modules") on a fixed wall. Each routesetter operates differently; one starts screwing interesting holds on the wall and tinkers with it, while others have a specific sequence of moves in mind and find holds that facilitates it. Apropos, Seifert et al. (2013) investigated the relationship between exploratory climbing behaviour and modification in technique to designed routes [50]. They placed hand holds under different angles which demands more advanced actions and reading ability. The emergence of new climbing actions, through exploration, was observed over practice. Meaning different visual search patterns, route pathways, body orientations or grasping patterns. Furthermore, Button et al. (2018) discovered that climbers perceive routes as more difficult when they are constructed by fewer holds as opposed to the same route designed with more (irrelevant) holds [58]. Both studies illustrate the importance of route design for effective perceptual-motor skill acquisition.

Another study researched the effects of errors during climbing practice on the exploratory behaviour [59]. Most of the time, errors prompt the climber to return to previously mastered movements and temporally stop exploring other movements. In order to prevent the negligence of exploration, the challenge effect can be added to the training [59]. The challenge given to the climbers in the study of Rochat et al. (2020) was to encourage the climber to execute the route repeatedly, even after finishing it, to seek for a more fluent and efficient way [59]. This led to more successful attempts and improved fluency. Similar task constrains are often used to push athletes to explore their full capabilities within the task [60]. With the use of technology, gamification can be adopted into climbing exercises. For example, by asking them to recall movement sequences, draw paths or propose alternative solutions to the same route [60]. These task and environmental constraints push climbers out of their comfort zone to expand their perceptual-motor skill abilities. The review of Holden (2005) expresses that tasks and skills can be learned in virtual environments and be directly transferred to the real world [61]. This is particularly the case for motor tasks that are considered more complex, like climbing. On top of that, virtual environments can improve the sense of immersion and placement in a task, boost overall motivation and enhance spatial interaction [62].

2.3 Related Work on Human-Computer Interaction for Climbing

This section describes the state-of-the-art of movement-based interactive technology that is related to the thesis objective. Specifically, the aim is to elaborate upon the technology that enables tracking the performance, enhances mental practice, and feedback systems to guide climbers in-action and out-of-action. It ultimately serves as an overview of what has already been done, what is possible and what are the most promising solution directions.

One of the main research directions identified is current literature is the use of technology to track movements and assess climbers' performance in-action. This is often been done by adopting wearables as activity trackers and offering either in-situ feedback or visualisation after the ascent [63]. Ladha et al. (2013) were particularly interested in investigating automatic assessment of climbing ability to generate tailored training advice [64]. They set a first step into the direction of capturing climber's power, control, stability and speed through a wrist-worn wearable. Other measures were also explored, for example the earn-worn accelerometer from Pansiot et al. (2008) analyses motion fluidity, strength, and endurance [65]. The survey of [66] portrays the current state of motion analysis in human climbing and bouldering. They conclude that motion capture is far from being solved and that there is a lack of research in the detection of typical motion errors in terms of climbing technique. Other open questions remain related to the difference between climbing styles of the novice and experts and how to provide feedback enabling effective execution and learning of climbing.

Next to performance assessment of the athlete in-action, several studies worked on automatic recognition of climbing routes and their difficulty level. Kosmalla et al. (2015) have used wrist-worn inertia measurement units to automatically recognise climbing routes [67]. Furtermore, Ebert et al. (2017) performed successful classification of difficulty levels of routes of more than 98% through tracking human motion and extract the features strength, endurance, and control required for the ascents [68]. Sensor-based qualitative analysis of in-action human motion data has also been proven to aid researchers investigating skill acquisition and motor learning efficiency [50] [69]. As mentioned in Section 2.2, Seifert et al. (2013) investigated exploratory climbing behaviour and the role of constrains in athlete-environment interactions. They captured participant's visual search, route pathways, body orientations and grasping actions to assess the climbing behaviour. Similarly, Schmidt et al. (2016) studied the evolution of exploration over practice by tracking gaze, limb and postural actions. Both studies are examples of how registrations systems can be utilised to obtain knowledge about the process of climbing skill acquisition. These insights can help further research to investigate the beneficial use of technology for effective training purposes.

In order for designers and researchers to effectively develop interactive technology, it is important to know the acceptance and perceptive levels of various hardware. Therefore, Kosmalla et al. (2016) investigated the perception, acceptance and appropriateness of wearables on different body parts and varying in visual, vibro-tactile and audible cues [70]. Participants climbed an easy and hard route while receiving (vibro-tactile, light or sound) stimuli on body parts. They reported that sound is most suitable to be received around the head (1), haptics on the arms (2), the combination of light and vibration is most suitable on the wrist (3), and visual feedback should be in line of sight (4). The fact that visual cues on wearables demands the climber to switch their sight is undesirable. The overall most relevant type of feedback through wearables turned out to be sound, followed by haptics. An important mention in this paper [70] is the influence of performing a motor task on the perception of feedback. Since climbing is a complex activity, the mental state of focus can make the climber unaware of the environment and therefore unable to properly receive feedback.

Figure 2.10: Climber sees the video stream of himself from a third-person perspective augmented with a video stream of the experienced climber in-action [7].

Since climbers have to focus on the wall, it can be more helpful to provide them with in-situ interactive technology for learning purposes. In general, augmenting feedback in-action has proven to increase the efficacy of motor learning for climbing practice and other movement-based practices [57]. Multiple studies have explored this design space due to the recent technological advancements. Presenting feedback during in-action is particularly relevant in climbing practice since watching and imitating experts' moves cannot been done simultaneously. This problem can be solved by using the climbing wall to project visual feedback. Wiehr et al. (2016) therefore proposed the betaCube, a self-calibrating camera-projection unit that tracks 3D features and displays life-size video augmented on the climbing wall [71]. Similarly, Kajastila et al. (2016) created an interface for route building as well but went further by projecting the route on the wall [72]. Moreover, their Augmented Climbing Wall contains various games to pick from that increased the diversity of challenges. Different from visual sensing, Liljendahl et al. (2005) presented a climbing wall (DigiWall) with embedded sensors, LED lights, and sound actuators enabling games, challenges and other engagement for climbing. On top of the climbing wall projection systems, Kosmalla et al. (2017a) went a step further by introducing three in-situ visualisation feedback techniques for indoor bouldering practice [7]. One of the evaluated visualisations is a projection placed next to the climber in action. The trainee sees himself from a third-person angle augmented with a video stream of the instructor, see Figure 2.10. This third-person perspective was also given through the Google Glass. Another proposed solution is a projection of a life-size in-place shadow of the instructor on the climbing wall. By viewing the visual feedback in-situ, climbers can adjust their body position on the go. By comparing the feedback given by a human instructor with all three visualisations, they conclude that life-size in-situ projection is the easiest to follow.

Next to the 2D projections on the wall, the climbing experience can also be enhanced by virtual reality (VR). Kosmalla et al. (2017b) used the physical climbing wall as a haptic feedback device in a virtual rock climbing environment [8]. Users experienced the feeling of climbing on a large mountain face by wearing a VR headset. This system could function as an indoor training device for the outdoor climbing sport, since indoor holds reveal the route right away and outdoor climbers face the difficulty of finding out the route themselves. This is illustrated in Figure 2.11. Other studies have revealed the importance of particular elements to create an immersive climbing experience. The "Venga!" system [73] built further on the VR climbing application by proposing the implementation of hand and foot tracking and Kosmalla et al. (2020) discovered the importance of including feet and hand visualisation in VR [74].

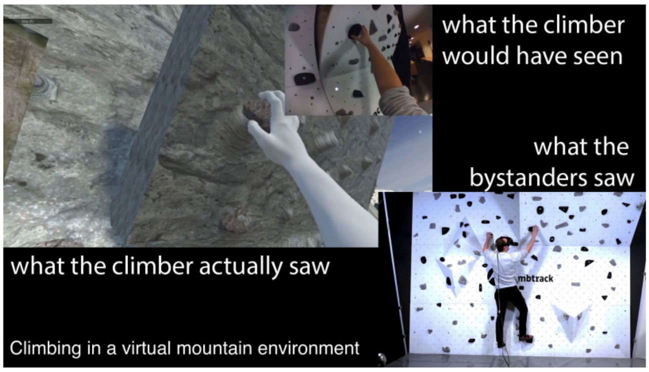

Figure 2.11: Parallel visualization of virtual reality climbing system in which users experience climbing in a virtual mountain environment [8].

Besides the design space of in-action use of interactive technology in climbing, using technology for out-of-action (i.e., situated on the ground) purposes is far less explored yet. However, the mentioned benefits of expert modelling techniques can also be used out-of-action. The study of Shiro et al. (2019) proposes a system where action videos of beginners were interpolated by the videos of expert climbers in order for them to revise their own performance [75]. This approach of expert modelling out-of-action has been exploited more often in sport interaction science, for example for gymnastics [76] and golf [77]. The videofeedback demonstrated improved performance but took some time to develop.

Although climbing is an individual sport, social interactions play a major part in bouldering training and can also be supported by technology. Social features include sharing experience and knowledge (1), collaborative training (2) and challenging friends (3) [78]. To stimulate this, Daiber et al. (2013) designed a mobile bouldering application where users can define problems and goals, manage a training diary and share selfmade routes with others. The Augmented Climbing wall by Kajastila et al. (2016) (that has been mentioned earlier) enables social collaboration by providing an augmented interface for route building and sharing [72]. Moreover, their Augmented Climbing Wall contains various games to pick from that increased the diversity of challenges.

Another interesting and difficult to grasp concept of climbing is the mechanics of movement and gravity. Kourosh Naderi researched the possibilities of synthesising complex climbing movements algorithmically [79]. His PhD thesis proposes a high-level graph-based path planner that generates sequences of plausible human-like movements. The system works together with a physics simulation model of a humanoid climber to make the animation look natural. This is a first step in the direction of a route reading and planning tool for climbers. The resulting animations seem promising but the details in hand and feet positions are still missing, which is an important part of planning and executing a climbing sequence.

Overall, most related work in sport and climbing HCI concerns the visual sense. However, augmented feedback can aid other senses to facilitate interaction in sport practice [57]. The review of

Sigrist et al. (2013) addresses different impacts of feedback strategies between visual, auditory, and haptic modalities, either in isolation or in combination. The study describes the performance enhancement by concurrent feedback in the acquisition phase. The multimodal approach is often the most fruitful one because the simulation comes closer to the real-life scenario [57]. An example is the study of Okumura Kurita (2021) in which the cross-modal effect of presenting visual and force feedback to stair-climbing was investigated [80]. This was accomplished by creating a virtual environment where visual information was synchronised with the force sensation through an artificial muscle. This led to a more immersive experience and thereby an increased illusion intensity during stair-climbing.

2.4 Design Space 0

By investigating the space of bouldering, perceptual motor learning, sports-HCI and everything in between, the direction of this research project has been outlined. However, the design space is considered to be a dynamic attribute of this Research-through-Design project. It evolves over time, and by design activities taken, it will be sharpened, reformed and reviewed throughout the design process. The design space consists of the the problem space and solution space. The aim of constructing the space at the end of this chapter is to create a starting point for the design process. By constructing the design space, we can identify what parts of the design space are still fuzzy. The fuzzy areas in the design space can on its own turn leads to choosing specific research activities that can take place in the next design iteration.

First, let us specify what is meant by the problem space and solution space. The problem space represents the current situation where the needs of the target user group lays. It includes the context, activities and other phenomena results into the existing needs. Although, most designers seem to focus on the solution space and what is technically possible, this thesis aims to enrich the problem space by applying a Research-through-Design methodology (Section 3.1).

The solution space aims to satisfy the challenges framed in the problem space. The search for feasible solutions requires brainstorming, ideation, prototyping and testing upon solutions.

2.4.1 Problem Space 0

From reading upon the bouldering practice the role of out-of-action *route reading* in it, we can conclude upon the crucial role of *route reading*, in-action as well as out-of-action, in the perceptual motor development of climbers [81] [82] [60]. The activity flow diagram (Figure 2.3) highlights that *route reading* on the wall takes place simultaneously during physical execution. A climber can almost never stay up the wall without exhausting their muscular system or the route allows for resting (shown in Figure 2.1).

The *route reading* activity is also a cycle between the situation on the wall and on the ground. Before climbers attempt the route on the wall, they will first preview the wall to perceive action possibilities, invent climbing movements, chain them together to a *beta* and evaluate them through motor imagery. Once the athlete is climbing on the wall, the exploration continues from evaluating how to position oneself to find a “base of support” to “strategic adaptation” (Figure 2.9). The cognitive and physical load of performing exploratory movements and thinking about movements on the wall fatigues the muscles [83]. However, it also provides the ‘lived’ experience with its immediate motor and proprioceptive feedback with increased kineasthetic awareness. On the other hand, the second-person perspective of imagining oneself on the wall (or watching peers) can provide a new perspective which is beneficial for perceiving new affordances. The challenges on the ground are

	On the wall	On the ground
Problems	Fatigueing of the muscles	Challenging to imagine oneself on the wall
	Cognitive load to perform physical movements	Challenging to translate the perceived affordances to feasible movements
		Less motivating to perform route reading on the ground than on the wall
Advantages	1st person perspective allows for 'lived experience' with its immediate motor feedback	3rd person perspective stimulate perceiving new affordances and tinkering on movements
	1st person perspective increases kineasthetic awareness	Body is resting, so more time and space to perform route reading

Table 2.1: Overview of the problems and advantages of route reading performed on the wall or on the ground.

the difficulty of *motor imagery*, affordance perception, translating perceived affordances to feasible movements and lastly: route reading on the ground is less attractive to climbers than physically climbing on the wall. An overview of the differences between the experience on the wall versus on the ground are listed in Table 2.1.

Both experiences (in-action and out-of-action) contribute to the climber's embodied sensemaking. From the exploratory movements, as well as performatory movements, the *embodied cognition* is developed by a cycle of 'sensing', 'acting' and 'perceiving'. In order for people to make sense of movements, they create a mental representation in their mind in which the important information is stored. This is mapped with the physical outside world and utilised during mental practice. Through tightening the identified gap between the wall and the ground experience, climbers' sensemaking process can be enhanced. We believe that climbers are most helped in their perceptual motor skill development by enriching the situation on the ground. This prevents early fatigue and "unnecessary" attempts on the wall. Therefore, the design challenge that we continue with lies in **bringing more aspects from the 'lived' experience to the *route reading* practice on the ground.**

The problem seems to be more present in beginner climbers than in expert climbers. Studies have shown that expert climbers perceive more 'functional' features instead of solely 'structural' ones from the route. More experienced climbers can translate 'structural' properties of holds and wall configurations to their functions and thus their action possibilities. This is a challenging task for inexperienced climbers and it suggests that beginner climbers could be more helped by a solution that advances their perception-action coupling.

There are still areas of the problem space that need further investigation. First, the gap between route reading on the wall and on the ground result in more questions. How is the embodied sensemaking experienced? How does the 'lived' experience differ from the 'imagined' experience? How does the mental representation of expert climbers look like? And what is reason behind the difficulty of linking 'structural' properties to one's own action possibilities? Finally, how does the 'observing peers' experience effect the sensemaking of climbers?

2.4.2 Solution Space 0

The information obtained from preliminary research helps us to construct the first solution space. The main problem retrieved from the problem space is the gap between route reading experience on the wall and on the ground. Existing literature demonstrates how similar movement-based, mental practice and climbing challenges were tackled by HCI technology. By introducing an interactive machine into a situated practice, the learning environment can be enriched. Athletes can obtain a

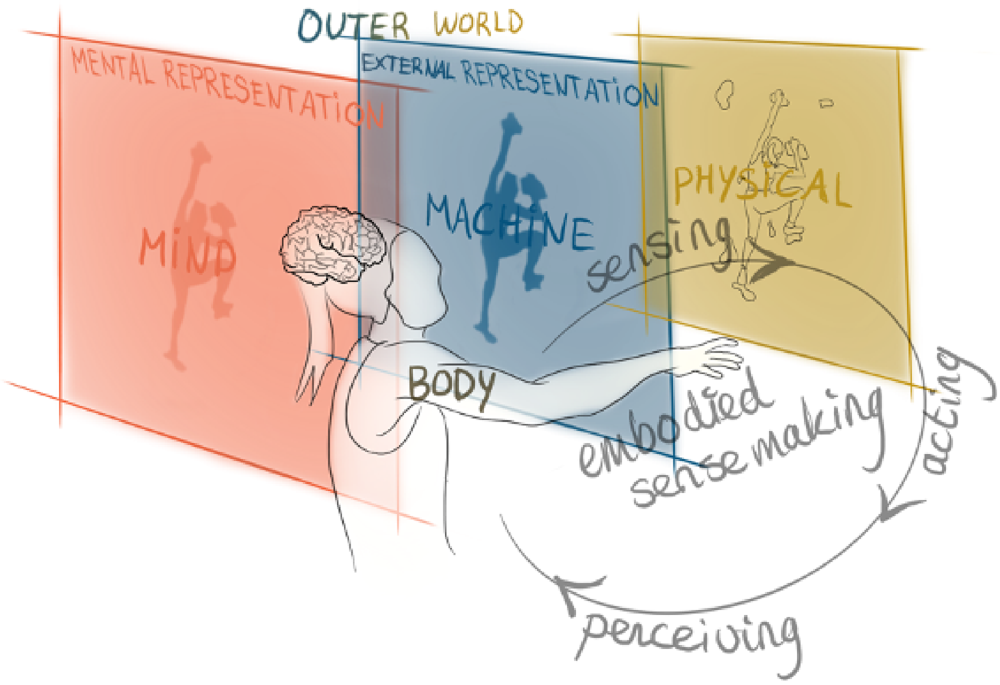

Figure 2.12: Illustration of Embodied Sensemaking through a digital distributed representation. The climber uses the 'machine' as a mediator between the outer world and the 'mind' through providing an external representation that enables the climber to perform sensemaking by 'acting' physically with the 'machine' to perceive affordances, plan to actions to finally physically re-enact on the wall. The sketch is inspired on the multiple sketches made by Jelle van Dijk.

more meaningful experience that would otherwise not been possible. However, a pitfall of including HCI in sport training is the 'guidance effect'. Therefore, we set our design intention to prevent a dependency from the athletes on the to-be-designed system, and thrive to constantly reflect upon this.

From literature we found that a distributed representation [4] can aid the sensemakers by transferring their mental representation (from the mind) into an external representation (in the outside world). Therefore we set our solution direction towards this principle through placing a machine into the sensemaking mechanism. Through the machine, climbers could 'sense', 'act' and 'perceive' affordances, which is illustration in Figure 2.12. The machine can provide the climber an extra lens that would enrich the current situated practice of route reading on the ground. Also, the solution has to allow the climber to take an active role as a learner by facilitating for exploratory behaviour. Since this would allow them to make perception-action couplings and acquire the 'route reading' skill. All in all, the solution aims to bridge the gap through a movement-based interaction design system.

Now that we know the general solution direction, the solution space still needs further exploration. For example, how can a machine represent climbing movements or a *beta* in a way that is understandable by climbers? In what manner can we distribute the mentally stored representation to the outside world? Can we transfer the motor imagery to the visual representation by a machine? And what information is crucial to perceive climbing affordances? The next design phase will focus on these questions to obtain further understanding of the solution space.

Chapter 3

Methodology

The thesis objective is to enable a climber's own 'design *of* movement' process by implementing an interactive design that allows *for* movement exploration. Other researchers have faced similar movement-based design challenges and utilised movement as a medium in the design-research activity [84]. Involving movement throughout the research process (Figure 3.1) demands for methods, tools and a framework to guide the activities. This chapter is devoted to describe the methodology of this study by referring to related work and design philosophies.

The complex design space of this thesis is based on a real practice (i.e. route reading). Therefore, a Research through Design (RtD) approach could reduce the complexity by confronting the messy reality and interactively getting a grip on the phenomenon. Secondly, 'route reading' is a form of tinkering with movements, so the to-be designed system has to facilitate movement-based interaction. In order to achieve this, the *movement-based participatory design* approach is considered to be a suitable method. This chapter explores this field by reading upon related work and reviewing frameworks. The chapter contains the following sections:

- **Section 3.1 Research through Design**
  Due to the complexity of the design challenge, and the desire to further explore the situated practice and its actors, a *Research-through-Design*(RtD) method is applied during this research.

- **Section 3.2 Design Thinking**
  By complementing the RtD method with design steps from Design Thinking, the approach is specified.

- **Section 3.3 Development of Problem, Solution and Design Space**
  Acknowledging the fuzziness of designing for a situated practice, this section describes the process of iterating upon the problem, solution and design space to obtain scientific knowledge.

- **Section 3.4 Participatory Design for Movement-based Interaction**
  Investigation on how fellow researchers have approached designing for movement-based interaction with user participation.

- **Section 3.5 Embracing All Perspectives**
  The first-person, second-person and third-person perspective can all contribute to exploring the movement-oriented design space.

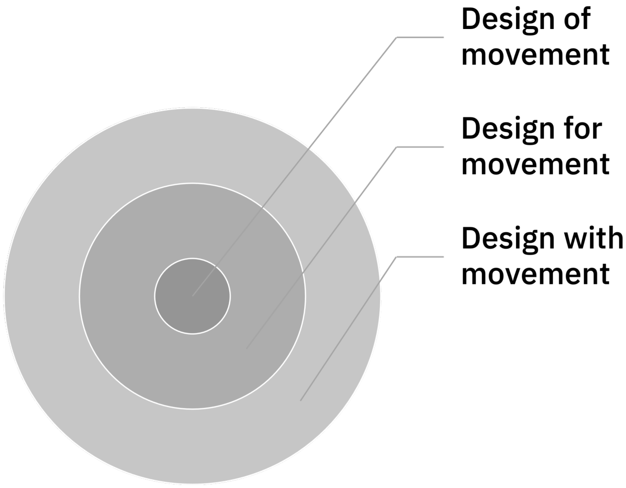

Figure 3.1: Layered representation of movements involvement in this thesis Designing *with* movement and users in the situated practice in order to design *for* a movement-based interactive system that in its turn can serve the users' need: the design *of* movement.

3.1 Research through Design

This research lays at the intersection between: climbing, perceptual-motor skill acquisition and mental practice. This relatively new domain comes with a considerable amount of ambiguities. The crystallization of a more concrete understanding of the situated practice of route reading demands for a research method that is open for serendipity. A research through design (RtD) method provides that by enabling the researcher to design artifacts in an iterative manner to further explore the design space.

Often, designers and researchers struggle with having to deal with a given challenge in a relatively unknown situation. The needs of users (and other stakeholders), accompanied by new technology as material, limited time and little to no knowledge about the underlying phenomena: they are all things designers have to deal with. Stolterman (2008) [85] refers to this as designers having to act 'designerly' to deal with these messy situations. To fully understand the situations, they have to immerse themselves in the context and develop an appropriate approach for the given design challenge [86].

Research through Design (RtD) is described as "an approach to conducting scholarly research that employs the methods, practices, and processes of design practice with the intention of generating new knowledge" [87]. It originates from the struggle of HCI researchers to connect design with research [86]. The traditional viewpoint of research being synonymous with science hinders the desire of HCI researchers to discover new ways of utilizing the practice of design for conducting research. The idea, introduced by Donald Schön [88], is that design can be a reflective practice, making design researchers argue that it helps them in their thought-process. By making and critiquing artifacts that "function as proposed solutions" [87], the problem space can be continuously reframed to address the given design challenges. The aim of RtD is not focused on the outcome of artifacts but rather generating insights through design practice.

After the initial rational of RtD, the scientific discipline has been revised and critiqued by several researchers [89] [90] [87]. They primarily raised their concern about the absence of practical tools and frameworks to bring RtD into practice. RtD should provide design-researchers ways to acquire

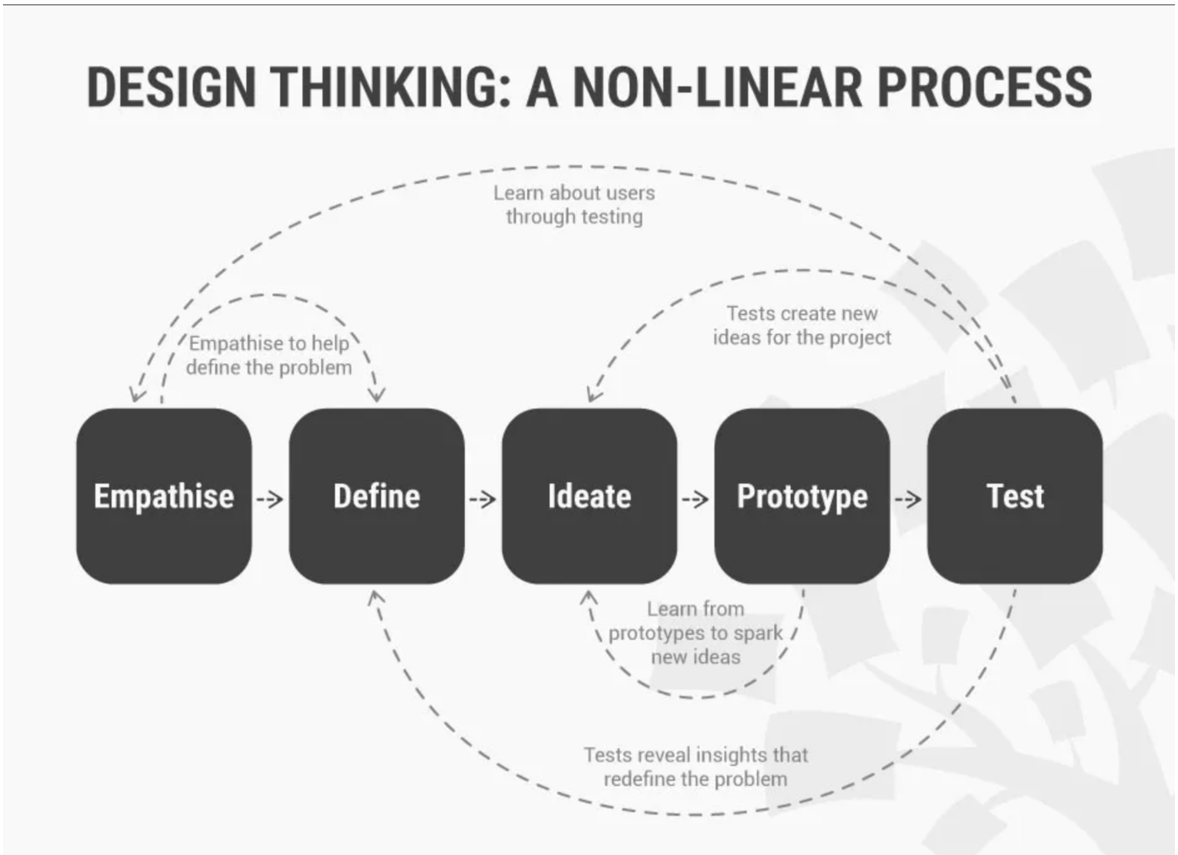

Figure 3.2: Overview of the five activities of Design Thinking [9]

profound knowledge of a certain design area. Furthermore, combining research and design should enable analysis of designs and design proposals such that future research is improved [90].

similar to adapted the reflective transformative design process (Hummels and Frens, 2011),

3.2 Design Thinking

Design thinking is known to be an innovative, iterative, human-centered and creative problem solving process [91]. In various contexts where complex human-centered problems are addressed, design thinking can be an effective strategy. The approach is focused on validating the design space through understanding user's needs, rapid prototyping and generating ideas. Traditionally, most design decisions were based on the instinct of the designer without having evidence and validation from the user context. Since this is a risky bet for business that invest in product development, an increasing number of companies and institutions have adopted this user-centred method [92].

The design thinking process is non-linear and goes through interative cycles. There are various visual representations from different disciplines but the most widely used model can be seen in Figure 3.2. Through the *empathise* stage, information and insights can be gathered to form meaningful problem statements in the *define* stage. Within the *ideate* phase ideas are generated through brainstorming, brainwriting or other visualization activities [9]. The generated ideas can be transformed into testable artifacts by quick *prototyping*. The last step is to validate the solutions which also provides feedback for the problem statement. Between each step is a feedback stream, as generating ideas, prototyping and testing brings valuable insights to the surface.

Human-computer interaction, as a discipline, addresses the human-centeredness to understand users and context in order to explore potential solutions. HCI and Design Thinking share a similar view on the importance of understanding and observing users to determine problems, ideate on solutions, prototype and test them. This prevents a mismatch between the solution and its users needs. However, going rapidly through the cycles and treating the problem and solution space as a dynamic asset, is quite new to HCI research. But it can be a beneficial addition if done well [92].

This thesis brings together the disciplines of HCI and Industrial Design, and therefore we consider Design Thinking to be a useful approach. On top of that, the goal of this thesis is to investigate the problem and solution space further with user involvement. By going through iterative design loops, we expect to receive input for the problem and solution space throughout the research process. This helps to refine and reframe the design space to match the real scenario. Figure 1.2 (from Section 1.3) illustrates the thesis process with three design iterations and all containing the steps from Design Thinking. The design space is characterized as a dynamic asset that will change over time. After each design iteration, we always come back to the design space to reframe it with new input.

3.3 Development of Problem, Solution and Design Space

The approach of iterating upon the design space, by reframing the problem statement and evaluating solution directions, fits the Design Thinking mentality. Although designers and researchers have acknowledged the fuzziness of real-world contexts and have investigated more holistic views upon a fitting design process, the focus often lies on either the problem space or solution space. The Design Thinking approach should however not only be used to seek solutions, since it can also help to investigate the problem and generate new knowledge [93].

Some people tend to develop solutions from an initial investigation into the current problems, which is characterised as a *problem-driven* approach [95]. While others neglect a deep dive into the problem space, and start directly by developing solution directions (*solution-driven* approach). These two approaches separate the problem and solution investigation into different phases. In contrast to that, a novel perspective was introduced by Mary Lou Maher (2003) [96] which argues that defining problems and developing solutions can go parallel in a process of 'co-evolution'. After Maher's model, more researchers iterated upon this concept and Hui et al. (2020) [94] incorporated the knowledge obtainment into the formula. The Triple-Helix Structured Model emphasises that knowledge, potential solutions and more understanding of the problem space can be obtained through an iterative Design Thinking process (see Figure 3.3).

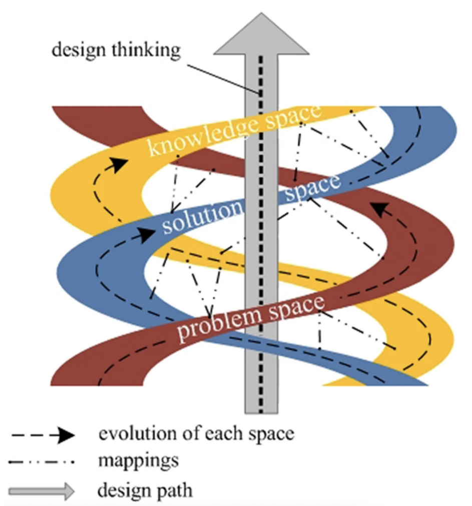

Figure 3.3: Spiraling iterative process of the evolution of the knowledge, solution and problem space. "The problem, knowledge, and solution are viewed as three integral parts of design, and can be established as three evolvable spaces. As they interact with each other, the design process is pushed forward in a spiraling manner" [94].

Hui et al. (2020) [94] emphasise that tackling design challenges at hand is both solution- and knowledge-dependent. The exploration of new solutions and entering a new design space comes inevitably with the process of problem refining. The design space investigation can be researched through a combined process of problem (re-)framing, knowledge attainment and solution creation. To streamline this process and for designers to get a better grip onto the fuzziness of an unexplored design space.

Quote on the evolution of the problem space:
"The set of design requirements and constraints helps in defining the problem goal with certain features. As the design continues, the understanding of the problem becomes increasingly clear through iterative analysis and reframing. Each time, the executed reframing can determine some implicit features of the problem. Consequently, the initial design brief may change, expand, contract, or be completely altered." [94]

Quote on the evolution of the solution space:
"According to the ambiguous problem proposition, the designer primarily generates multiple principle solutions with varying abstract solving knowledge. As the design continues, these solutions develop under the guidance of the better-defined problem and concrete knowledge, and evolve to be more detailed and appropriate, which may be specified by some sub-solutions. In the solution space, the designer explores the satisfying solutions, but not necessarily the optimum one, leaving more possibilities for innovative design." [94]

By choosing to implement a design process of co-evolving the problem space and solution space, useful information will inevitably be derived. The knowledge held in the design space bridges the design problem and solution. The constructed design space, at the end of a research or design process, will not only contribute solution ideas and a clearer vision on the problem, but it can provide knowledge that surpasses this. For example, the investigated design space can hold information about the acceptance of technology in the situated practice and/or the effectiveness of a design vision. The evolution of the design space expands the knowledge on the topic and therefore expands our current understanding of the topics (e.g. route reading) it encompasses.

This thesis settles upon the following definitions:

Problem space = A set of problems or design challenges that the initiator identifies during the seeking process. It includes some specific problems that the users face in the given context with its meanings attached to the culture, emotion, desires and other related aspects of the situated practice.

Solution space = A set of solutions (or directions) that (potentially) meet the design requirements and constraints [94].

Design space = The sum of the problem and solution space and encompasses all the knowledge within and in between the problem space and solution space.

3.4 Participatory Design for Movement-based Interaction

Users have increasingly received more attention within product design over the years. Next to technical complexity, designers are also required to user research to provide a suitable user experience.

From the increased user-centric approach evolved the term 'participatory design' describe the field. In this new paradigm, users get the role of 'experts of their experiences' [97] and designers are facilitating activities to express the users' experiences. User participation also comes with its challenges and pitfalls. Oftentimes, researchers and designers have limited resources and are therefore only involve a handful of users. This can result into a strong bias regarding user needs. Moreover, user needs are not static and differentiate over time [98]. The effectiveness of participatory practices is also influenced strongly by the environment in which it is held, the activity itself and by the facilitator's skills.

Artifacts can aid participatory design in various ways. One of the major advantages of using probes during co-design sessions is the enhancement of generating ideas and stories. Sanders & Stappers (2014) [99] have observed during their study that participants make use of artifacts to share their stories. Especially when they were involved in making the artifact within a design activity. This is also the principle behind Sleeswijk-Visser's [100] method of *context mapping* with its generative techniques that let people make designerly artefacts which enables them to tell a story about their creation.

3.4.1 Participatory Sensemaking

Participatory design methods that are based on the embodied cognitive theory became slightly more popular in scientific literature. However, the objective of this thesis is in the area of movement-based interaction design and aims to involve users throughout the process. The complex problem statement, that involves the cognitive processes during mental preparation before an ascend, is a relatively new domain. Especially in combination with the solution space of embodied interaction design. To obtain a deeper understanding of what goes through climber's minds and how technology can play a role in this, it is valuable to cultivate upon climber's experiences and embodied cognition.

The embodied sensemaking approach can also be used as a methodology by supporting physical representations of knowledge as a means of reducing internal mental representations, physical experimentation and physical prototyping of concepts in order to allow feedback in a social setting. By involving participants, researchers can make use of participatory sensemaking through collaborative design methods. This often means that the tool during the design activity are of equal access by all participants or can be directly manipulated by their hands [101]. The collaborative sensemaking is thereby supported through a distributed representation.

3.4.2 Movement-based Co-design

In order for the participatory design activities to be effective, an investigation into appropriate movement-based design methods is performed. Related work on movement-based participatory design acknowledges the crucial role of the body to articulate, translate and share the 'lived' experience of movement [102]. Various strategies can be applied to retrieve the 'lived' experience from participants. A few examples of body-centred design methods are embodied design improvisation [103], bodystorming [84], embodied sketching [104] and experience prototyping [105].

The method of 'bodystorming' by Segura et al. (2016) [84] comes from HCI research with movement. The name originates from the 'brainstorming' technique for collaboratively coming up with ideas, but instead of just thinking and talking, bodily movements and embodying artifacts are used [106]. It boosts creativity by envisioning ideas through improvised bodily expressions. The envisioned future scenario can be more vividly experienced by people through enactment with the help of probes and physical acts in comparison to solely lingual expressions [106]. The modelling effect of bodystorming can be even more amplified by situating it in the environment and with actors of the chosen design challenge [106].

3.5 Embracing All Perspectives

Through the bodily experience of climbing, with its cycles in 'sensing', 'acting' and 'perceiving' 2.4, athletes make couplings between the environment in relation to their body. As this requires their attention, to constantly attune and calibrate, they are very aware of their own body position and movement in space. The kineasthetic awareness appears almost automatically which is beneficial to the perceptual motor development. Therefore, our aim is to raise the kineasthetic awareness during the out-of-action route reading as well.

To design for kineasthetic awareness, one has to first understand the 'lived' bodily experience it is situated in. Therefore, we consider raising kineasthetic awareness during participatory design practices as a necessary medium to engage and thereby retrieve insightful information.

Numerous methods for designers have been proposed to utilise the bodily experiences during design practice. An overarching value they share is the adoption of different x-th person perspectives to cultivate kineasthetic awareness [108] [109], kineasthetic empathy [110] and overall obtain more embodied cognition.

The framework 'Moving and Making Strange' of Loke & Robertson (2013) [107] stands out by targeting specifically to movement-based HCI design. The theoretical model that is proposed in their paper is based on the concepts that all sensations, actions and perceptions contribute to the kineasthetic experience to perceive oneself. The model describes the first-person perspective as the "mover", the second-person perspective as the "observer" and the third-person perspective as the "machine". They suggest that the first-person view serves as medium to explore and evaluate qualitative and dynamic design concepts (in this case an interactive feedback system). Their toolbox-like methodology includes a series of activities, each of which is associated with a set of tools and one of the three perspectives and generated data (e.g. experiential or observational), as well as how data flows or transitions between activities. The framework with seven key activities is shown in Figure 3.4 inserted with climbing illustrations to specify the roles for our study objective.

Throughout our RtD process the participants, as well as the researcher self, will be invited to perceive bouldering, the wall and the climber from perspectives (first-, second- and third-person) that also relate to the distinction made in the 'Moving and Making Strange' methodology [107]. Based on Table II of Loke & Robertson [107, p. 12], where the seven activities are linked to a "method/tool" and "perspective/data", we have developed our own table to guide us towards the interaction design.

It should be noted that the methods and tools were created over the course of this project, but for reporting purposes the design activities held will be mentioned in the next sections and shown in one overview in Table 3.1.

3.5.1 First-Person Perspective

Integrating the first-person perspective into interaction design comes from somatic practices [111]. Somatic practice concerns the internal reflection on the 'lived' experience of one's body through self-

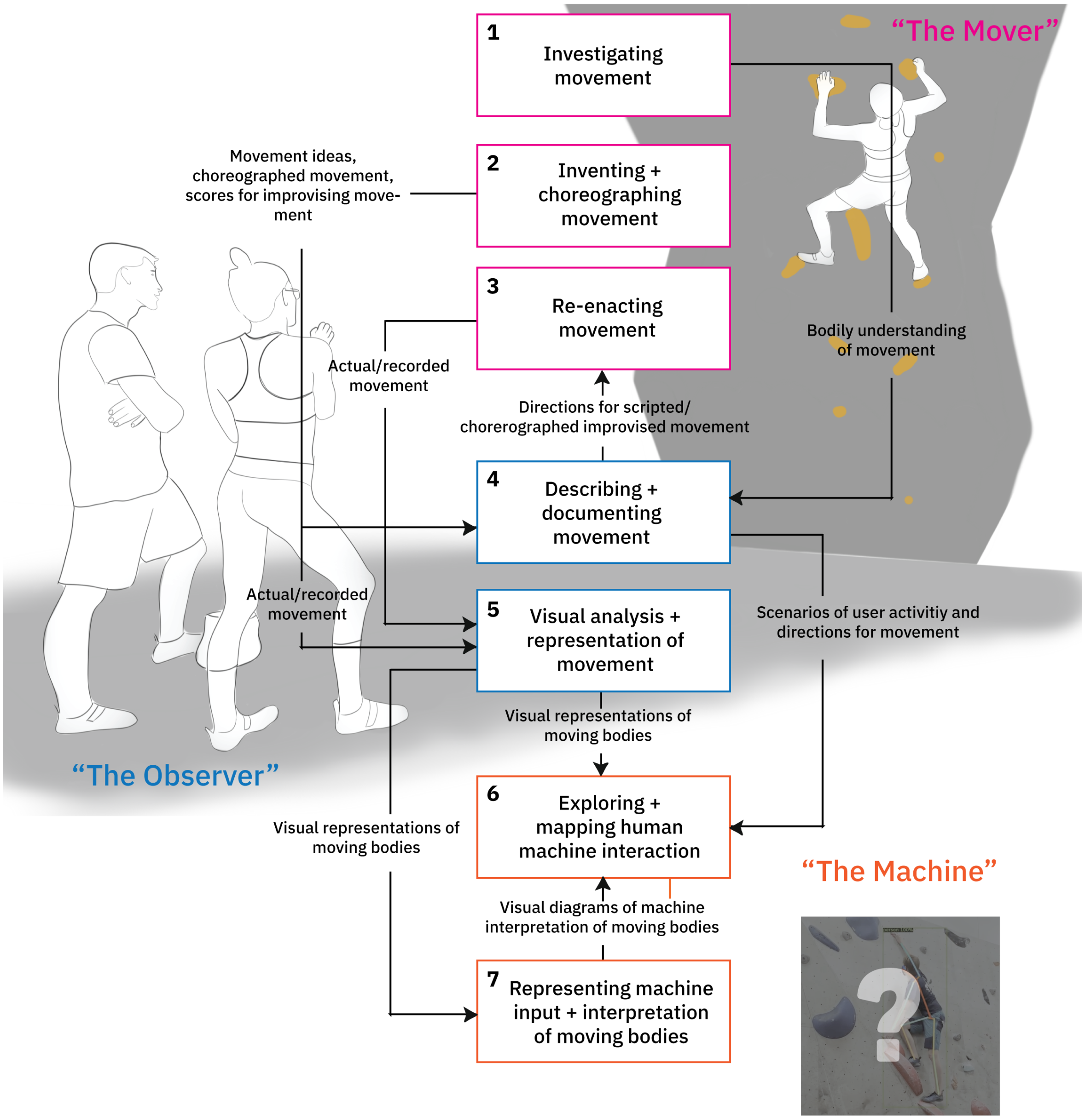

Figure 3.4: Design framework for the thesis objective
The seven key activities of Loke and Robertson's methodology [107] for design implementation adjusted to the thesis objective. The labels on the arrows indicate the data generated by an activity and the direction of the arrow indicated the flow of data from one activity to another.

	Method/Tool	Perspective/Data
#1 Investigating movement	Climbing on the wall Route reading on the ground (motor imagery)	First-person perspective - ”Mover” Experiential data on process and felt sensation of movement.
#2 Inventing and choreographing movement	Creating ”beta” that is executable	First-person perspective - ”Mover” Experiential data on movement possibilities, forms, patterns, techniques, motivations and corresponding felt sensations.
#3 Re-enacting movement	Re-enacting upon (interpreting) ”beta” manual (which includes instructions for movement)	First-person perspective - ”Mover” Experiential understandings of movement during user testing/evaluating.
#4 Describing and documenting movement	Creating “beta” manual and thereby documenting choreographed movement Translating climbing movement to visual and verbal expressions Bodystorming Manipulating puppet to represent climbing pose	Second-person perspective - ”Observer” Observational perspective documenting the movements of people and the motivations for movement.
#5 Visual analysis and representation of moving bodies	Creating “beta” manual Bodystorming Manipulating puppet to represent climbing pose	Second-person perspective - ”Observer” Visually analysing and representing human movement (mentally or externally). Social interaction on the ground to express movement ideas (collaboration).
#6 Exploring and mapping human-machine interaction	Bodystorming Lo-fi puppetry system interaction and brainstorm upon machine output/feedback	Third-person perspective - ”Machine” Mapping between human movements and machine, by abstracting the observational data into input that machines can understand.
#7 Representing machine input and interpretation of moving bodies	Bodystorming Lo-fi puppetry system interaction and brainstorm upon machine output/feedback	Third-person perspective - ”Machine” Machine perspective of the input and interpretation of moving bodies.

Table 3.1: Overview of activities, methods, tools in relation the perspective and data. Inspired on Table II of Loke & Robertson [107, p. 12]

observation and bringing the attention inwards to the felt sensations. The approach stresses that the potential of the body as a design resource to create, experience and test an interactive system. Through moving oneself, the **kineasthetic awareness** is raised and this can even be enhanced by bringing the attention inwards during the movement. This can either be done by the designer but also by participants in co-design session.

> "Conducting movement inquiries with skilled movers provides finely nuanced understandings of particular kinds and forms of movement. A structure for analyzing movement from the first-person perspective provides details of the movement process/technique, internal and external sensing and awareness, and the felt quality of the movement." [107, p. 13]

The quote implies that integrating movement into design activities enhances the understanding and verbalisation of retrieved insights. The first-person perspective (also described as "the Mover") can be split up into three activities (shown in Figure 3.4 & Table 3.1).

#1 Investigating movement

The first activity can be seen as the 'route reading' part that is on the wall. In order to investigate this experience, the designer and participants can perform bouldering but supplemented with particular exercises or prompts to vary the experience. The method of "making strange" [107] can be used to experiment upon different ways of investigating movement and positioning oneself in other first-person perspectives. For example, a designer can purposely perform movements that feel "off" or with a certain intention to put themselves into the shoes of beginner climbers.

Route reading situated on the ground is also a form of investigating movement by motor imagery. However, the felt sensations of movement are missing and it requires more effort from the practitioner to perceive it from the first-person perspective.

#2 Inventing and choreographing movement

The tinkering process of a "mover" on the wall go hand in hand with activities 1 and 3. However, the 'choreography', which is often called the '*beta*' in climbing, has been planned out on the ground and serves as a base on the wall. The climber will receive new input from activity 1 and 3 and adjust the plan, and also coming back on the ground: the route reading process will continue with input from the wall.

For obtaining an understanding of this felt experience, the designer or participants can give themselves the task to create a *beta*. Doing so requires a loop of perceiving a sequence of affordances testing the sequence on the wall and in the event of failure adjusting it on the ground. This will provide the felt experience that gives insights on certain patterns and techniques with their corresponding felt sensations. This all contributes to the exploration and shaping of the design space's part on the user's creative thinking.

#3 Re-enacting movement

The planned out *beta* on the ground has to be re-enacted on the wall to test and evaluate its viability. As a design activity, one could enact upon the created *beta* by someone else. By following someone's instructions for movement, the first-person perspective from the instructor (who created the manual) can be further explored. Furthermore, this contributes to refinement of the bodily understanding of climbers in the way they act, move, perceive and respond in interaction with the environment.

3.5.2 Second-Person Perspective

The experience from a second-person perspective, that of the "observer", can be useful to reveal deeper layers of first-person perspective. The study of Françoise et al. (2017) [109] conducted semi-structured interviews to get a better grip on the 'singular experiences' of participants. Designers often implement similar methods to observe participants in action or in interaction to gain insightful information. In order for the 'observer' to come closer to the 'real' experience, they have to view the situation through the lens of *kineasthetic empathy* [110] by imaging oneself perform the movement.

#4 Describing and documenting movement

In order to get the observational perspective, one has to document and store the perceived movements together with the imagined 'lived' experience of the 'mover'. Various design activities can touch upon the second-person experience of the 'observer' in our research context.

Since route reading on the ground is currently also aided by observing peers climb, it is a crucial activity to investigate. A corresponding design activity developed for this purpose is the creation of *beta* manuals by expert climbers. By having them document choreographed movement into visual and verbal instructions, they can truly experience the second-person perspective. More argumentation for this design activity can be read in Section 4.1.2.

Another design method adopted is *Bodystorming* [84] which is a form of brainstorming that incorporates the bodily experiences. The five main advantages stated by research are the enlargement of empathy, deep reflection, connection between the participants and researcher, situated engagement and heightened awareness.

Throughout the design phases, the idea arose for a digital puppetry system as a way of manipulating, documenting and analysing movements. The interactions with the prototypes that followed also contributed to the investigation into the activity of "describing and documenting movement".

#5 Visual analysis and representation of moving bodies

The design activities of the fourth activity can also give enlightenment about athlete's visual analysis and representation of moving bodies. This point of view was later enhanced by the visual representation from the machine. By evaluating the visual feedback during the final test (Section 6.4), not only input for the 'machine' perspective was generated, but also further understanding of the user's cognitive activity of analysing was obtained.

3.5.3 Third-Person Perspective

The last perspective, that of the 'machine', requires the designer to translate the 'lived' experiences to an objective form.

#6 Exploring and mapping human machine interaction

By mapping the human movements and the sensing of these movements by the machine, a movement-based interaction can arranged. The 'machine' demands for an abstraction of the movement. Therefore we have to explore the parts of the movement that is necessary to display to the user for sense-making of that movement. On top of that, the 'machine' has to 'make sense' out of the input given to the system.

#7 Representing machine input and interpretation of moving bodies

The sensemaking of the machine means it has to interpret the moving bodies. This can be done in numerous ways and this will be explored after the decision is made on what the human-computer interaction should be. This will be further elaborated in Chapters 5&6.

Chapter

04

Design Phase 1

Towards a Visual Representation of Climbing Movements

Design space 1

Empathise

Define

Ideate

Prototype

Test

Co-design: Sketch It Out!

Design Sketching

Self-observation

Chapter 4

Design phase 1: Towards a Visual Representation of Climbing Movements

The current design phase is already filled with valuable information retrieved from preliminary research. The exact cognitive process of expert climbers during out-of-action *route reading* is relatively understated. It is known what experienced climbers perceive affordances on a deeper level as more *'nested'* and *'functional'* compared to beginner climbers. However, much is unknown still about climbers' *embodied cognition*, their *lived* experiences, their created *mental representations* to plan out actions.

To get a better understanding about these topics, the first design phase focuses on finding a visual documentation of climbing movements that can serve as a digital *distributed representation*. Climbers create a mental representation to invent, plan and evaluate climbing movements. The aim of this thesis is to design a system that provides climbers with a distributed representation aiding the sensemaking process, by transforming climbers representation of movements from a mental to a external representation. The goal of this chapter is to find design directions for this external representation that fit the climbing context. This will ultimately lead to a richer understanding of the design space. The research question that is constructed for this chapter is as follows:

> *What visual representation of bouldering movements can accommodate route reading on the ground?*

This chapter reports on the first cycle of a design iteration, following the steps of design thinking. The sections of this chapter, together with their design step, occur with the following structure:

- **Section 4.1 Co-design 1: Sketch It Out! | *Empathise & Define***
  With climbers' participation, activities were held to define suitable visual translations of climbing movements.

- **Section 4.2 Ideation: Exploration of External Representation of a *beta* for Skill Acquisition | *Ideate***
  Further conceptualisation of an external representation was done by iterating upon the outcome of co-design 1.

- **Section 4.3 Self-Observation: Moving between 1st-person and 2nd-person Perspective | *Prototype & Test***

The concept that showed most potential was tested by the design-researcher through switching between the 'mover' and 'observer' experience.

- **Section 4.4 Design Space 1**
  Reframing the problem and solution space with the acquired information from this design phase.

Empathise & Define

4.1 Co-design 1: Sketch It Out!

The following section reports on the conduction of co-design session. Participants were asked to perform tasks in a bouldering context, followed by a discussion together with the design-researcher. The co-design was called "Sketch It Out!", since the main materials used were pen and paper. The reasoning behind this is simple: the materials are known by everyone and are often used to easily and quickly visualise ideas, concepts and images.

4.1.1 Aim of the Session

This participatory activity aims to obtain insights about the *route reading* process of climbers with its part on the wall, as well as on the ground and the gap in between. With more understanding about the mental representation and the sensemaking process, we will gain input for the problem space. On top of that, the way climbers document their *beta* in their minds can serve as inspiration for the design of an external representation. In the end, the to-be-designed system does not aim to exactly replace the athlete's visual representation. Rather, it will be an abstraction of the 'lived' experience of the wall to facilitate climbers' sensemaking. This could enhance perception action coupling throughout the experience which ultimately results in perceptual motor skill acquisition.

In preparation to the session, the following research question was formulated to help pick the method, material and setting for the session: **How can climbing movements be externally represented in a comprehensible visual manner?** The question can be split up into sub-questions to target specific subjects:

- **Perspective of the 'mover':** How is route reading experienced by expert climbers on the wall and on the ground? How do they (mentally) represent, analyse, plan and recall climbing movements during their bouldering training?
- **Perspective of the 'observer':** How would experienced climbers intuitively visually communicate their plan of execution or *beta* to a peer? And how would a peer interpret this communication and re-enact upon it?
- **Perspective of the 'machine':** How can climbing movements be modelled through a two-dimensional external representation? What information from the climbing movement and environment is important for route reading?

4.1.2 Method

For this co-design session a movement-based participatory design method that suits the design stage of exploration is 'bodystorming'. As mentioned in Section 3.4.2, bodystorming is an embodied ideation method for design with physical movement. By enacting the situated practice and provoking the connected embodied cognition, it helps participants to attain awareness of their cognitive processes. This is required in order to express it into words or other forms of output. To facilitate the visual expression, participants used paper and pen to sketch an external visual representation. After the session, we evaluate whether this method enhanced the conversion from the unconscious embodied cognition to a visible representation.

Participants

In total six male participants volunteered to take part in the co-design session. All of them are experienced climbers and are often found in the local bouldergym. Their climbing level is between intermediate and advanced and therefore they are able to execute the climbing routes that were selected for this study. Prior to the study, all participants were informed about the procedure and gave written consent on the day of the session. All participants were acquaintances of the design-researcher and most of them also knew each other beforehand. To thank the participants for their participation, they were given a drink of choice during the discussion.

Setting & Material

The co-design session was held in the local bouldergym. In the middle of the hall is a section of climbing wall that is relatively straight, quite separate from the rest, and with benches in front. This sections was reserved for the session. The co-design session was held on a Sunday afternoon during open hours and therefore other visitors were also indirectly present during the session. They were not climbing on the reserved section but they were sometimes interacting with the participants out of curiosity.

The section wall chosen in the bouldergym is a relatively straight wall and therefore easier to have an overview in 2D compared to a wall with either a positive or negative incline, which results in more depth variety. It is also wide enough so that 3 people can climb at the same time next to each other. Lastly, the section is a separate wall from the rest of the bouldergym and therefore easy to close off from it so that other visitors are not disturbed.

Before the session, climbing routes that were already built on the section were reviewed to determine which would be suitable for the session to use. Together with the owner of the bouldergym, who is also an experienced route builder, the boulder routes were discussed. The three chosen routes, like most climbing routes, allows for various methods or *beta*'s to be used to ascent the route. However, some routes allow for more variety of methods while others allow for a smaller amount of options. The chosen routes can be climbed in various ways and are therefore fitting the assignments in the co-design session. The three routes can be seen in Figure 4.1.

Next to actual bouldering and the discussion of bouldering topics, the translation into the visual expression of climbing movements had to be facilitated. This was done by paper sketching exercises since pen and paper are familiar tools to everyone. Although some felt more comfortable in their drawing ability than others, everyone at some point grabbed pen and paper when something could not be explained in words.

The 2D visualization method by creating an external representation on paper is open for participant's own creative directions. Also, one has to come up with creative solutions to explain an experience in a 3D environment (the real world) on a flat sheet. Because the aim of the co-design was to work with the creativity of the participants, directing them into a specific way of thinking had to be avoided. However, from the design-researcher's own experience in climbing, there was an expectation that climbers would like to draw ideas on top of a 2D overview of the climbing route

Black route: intermediate level route, requires good climbing techniques.

Blue route: intermediate level route, requires good climbing techniques.

Red route: beginner level route, good hand and foot holds and an interesting move to reach the end hold with two hands.

Figure 4.1: Setting of co-design 1: The selected three bouldering routes for participants to perform the assignments with.

from the viewpoint from the ground. This is the perspective where climber perceive the wall from in between attempts and the setting in which they process climbing movements. This was the reason that for every climbing route a template paper was made. This could them be introduced to participants in their sketching exercise when they already showed signs that they took this approach of communicating a *beta*. The templates are shown in Appendix **??**.

Activities

At the start of the co-design, the participants were briefed about the objectives of the session and what they could expect from it. They received an information brochure before the session so they already knew that they had to climb and brought their own climbing gear. After the briefing, all six of them signed the consent form so we could start recording. Throughout the activities, either video recordings or audio tapes were made as documentation and reference for analysis afterwards.

The first assignment, with the purpose of warming up, was to sketch several illustrations to get the participants become somewhat familiar with the material (physical as well as conceptual). The illustrations that they were asked to draw were:

- Sketch a map of the bouldergym
- Sketch a person
- Sketch a person that jumps
- Sketch someone doing a *dropknee*

The items were given in order of sketching difficulty as well as more directed towards the purpose of the study.

After the warm-up assignment, we changed locations from the table to the reserved section of the climbing wall. There the main assignments were given based on bodystorming, an embodied ideation method. Participants were grouped in pairs and each group got assigned to one of the three climbing routes. For that climbing route, they were asked to figure out a interesting *beta* to reach the end hold. The *beta* that they come up with had to then be translated to a manual to communicate it to peers. After this first stage, the created manuals were given to one another to see how peers perceived it and how they acted upon them. This rotation could be done twice so that every pair tested the two manuals of the other groups. At the end, we gathered again at the table to have a discussion about the assignment followed by their experience in route reading in general.

During the session, notes were taken on: the interaction within and between groups, overall actions and behaviour of participants and verbal communication.

4.1.3 Results & Discussion

The most interesting notes that are worth mentioning and help answer the research question of this session will be stated in this section. The results from the analysis of the session include more in depth information about the problem space as well as potential directions for the solution space. Finally, overlying results about the co-design process will be discussed.

During the session, it became more and more evident that there is no such thing as ‘a *beta* for everyone’. Due to the physical differences between climbers, one has to find their own way of reaching the top. The most obvious factor is the athlete’s body measurements. While some climbers can reach a hold relatively easily, others have to jump to reach it. Additionally, some prefer to climb more ‘dynamically’ and others more ‘statically’. Among climbers, ‘dynamically’ translates into using momentum of the body when moving from one hold to the other hold. In contrast, a ‘static’ move can be stopped anywhere during its execution.

Considering the requirement for climbers to figure out ‘their’ way of moving on a particular route, it is important that it is taken into account that climbers benefit from tinkering with their own preferences. Also, the to-be-designed system should not instruct or push climbers into a certain approach since this will not help their perceptual motor skill development. Each climber should be able to develop ‘their’ own perceptual motor skill in order to perceive nested affordances. Additionally, climbers repeatedly mentioned that‘solving a route’ in their own way is what makes the sport fun. It would take away that joy of climbing, if someone or a machine would tell them exactly how to climb a route.

The manuals made by the participants, which can be viewed in Figures 4.2-4.4, show that they tend to visually communicate climbing movements by drawing poses on a configuration of the route. Although this was also the hypothesis, described in Section 4.1.2, participants were not forced into this approach. However, they showed signs of drawing the configuration of holds on the blank paper before sketching climbing poses on top of that. This indicates that the configuration of holds together with climbing poses can be a form of documenting a *beta*. It seems to be a form that resonates with climbers’ cognition, as during the discussion this framework was often mentioned. Together, we evaluated the exercises, the developed manuals and the indented *beta*’s. Participants described the *beta* from a second-person perspective and chained climbing poses together from start to the end hold. Additionally, they used hand gestures to clarify arm positions. Sometimes they started to use their whole body to explain a pose or movement.

The static documentation that participants used in their manuals is not entirely covering the *beta* since a significant part of climbing is dynamic. Participants highlighted that intermediate and expert climbers are more challenged to find manoeuvred to move from hold to hold. This dynamic part, was difficult for climbers to describe in words. They mentioned that it has to be felt and to become more skilled in planning for it, one has to built up enough experiences to know how to use their body’s

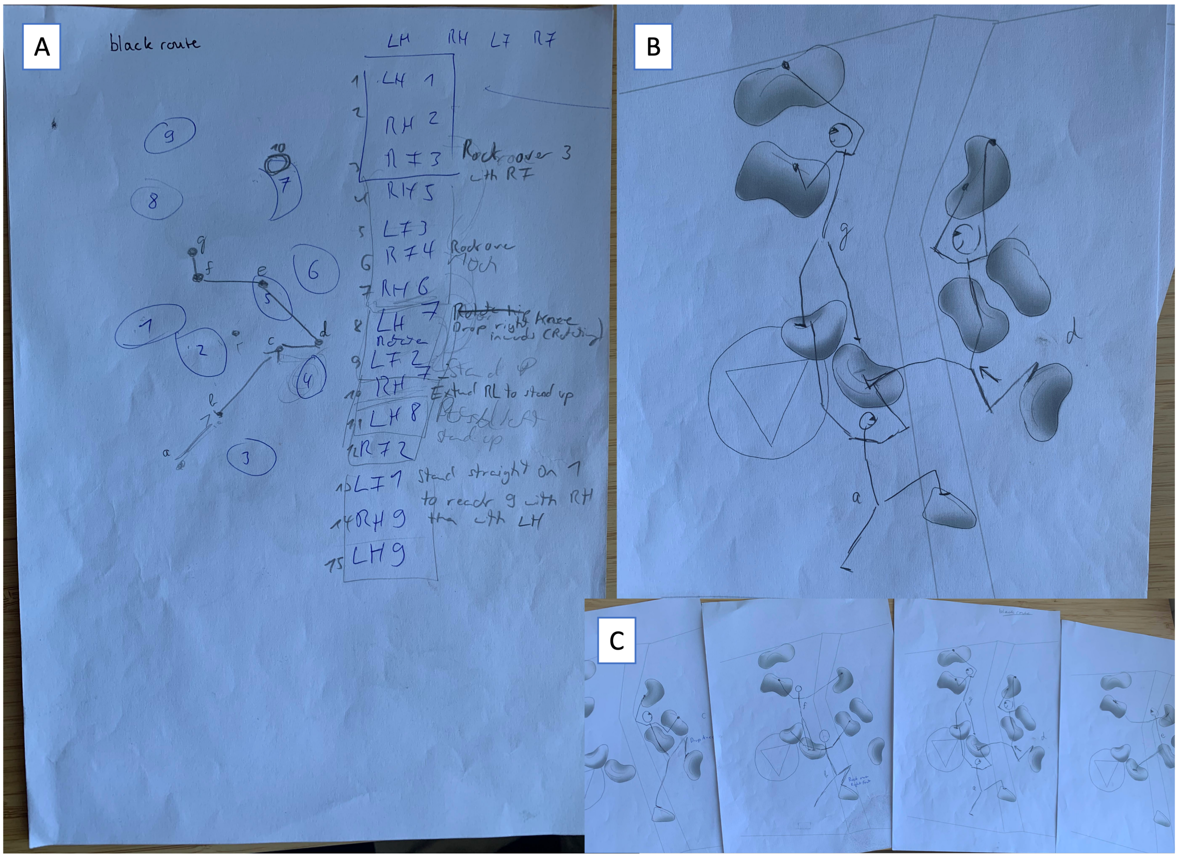

Figure 4.2: *beta* manual for the black route created by group 1.

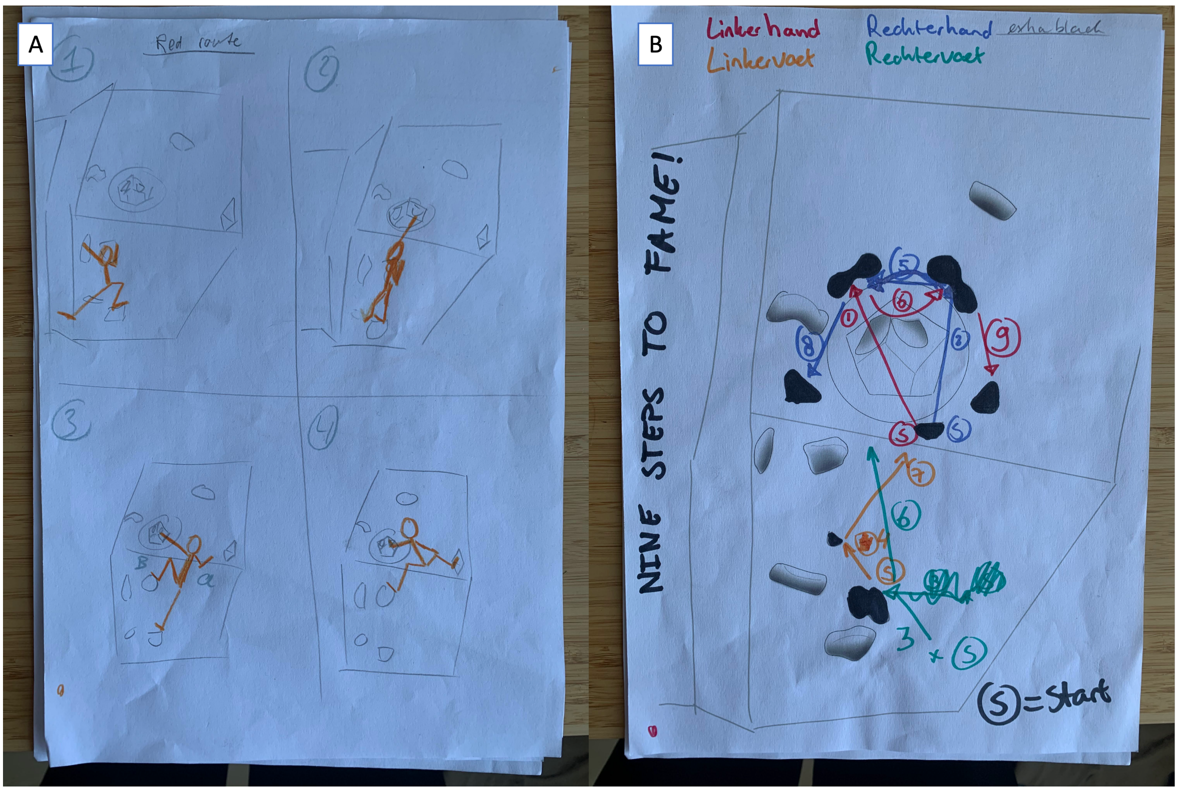

Figure 4.3: *beta* manual for the red route and black route 2 created by group 2.

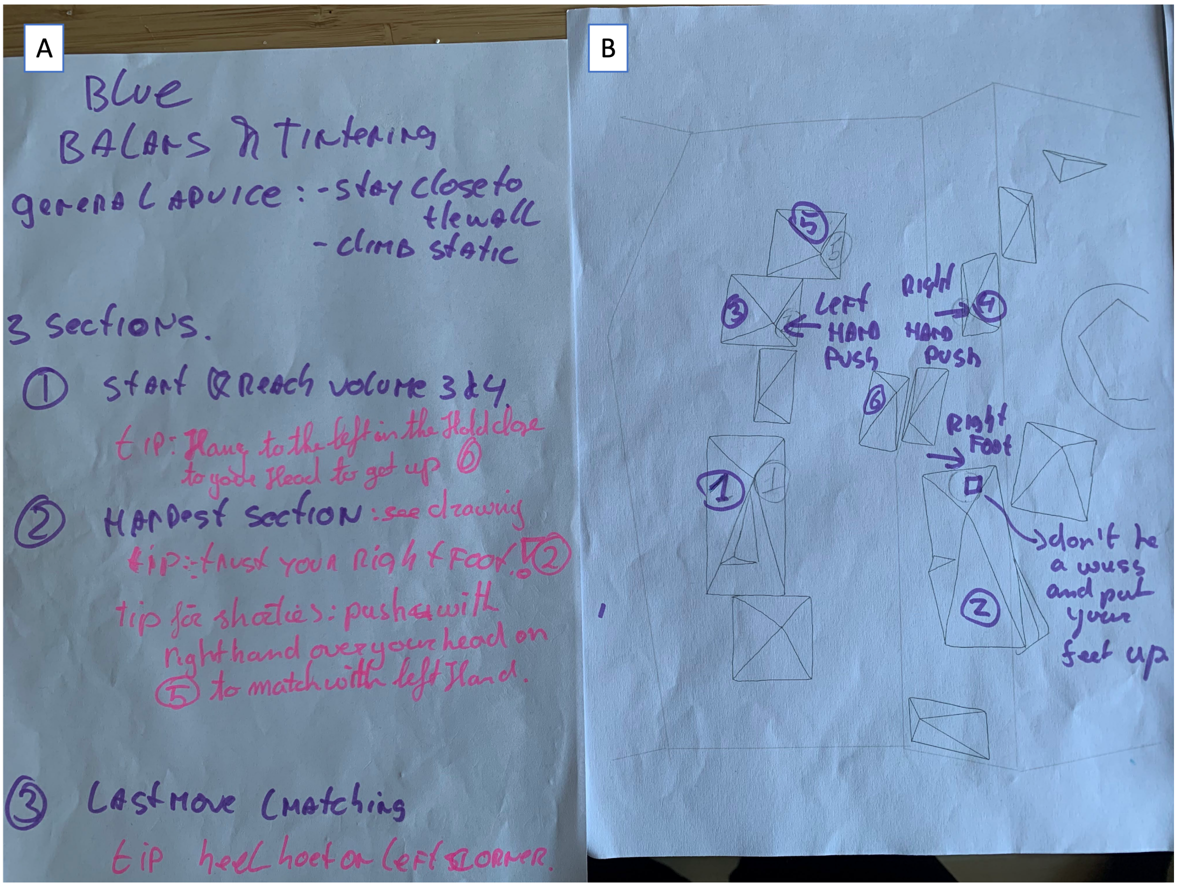

Figure 4.4: *beta* manual for the blue route created by group 3.

momentum in the right way.

In the manuals, it is visible that there are some additions to the static poses that hint to the dynamic part. For example, one group made a coding language to indicate how to move from pose to pose. For every foot and hand was abbreviated and for every hold numbered (e.g., left hand on first hold = LH1). Next to that, they put on top of a hold configuration a flow of the centre of gravity point per pose, see Figure 4.2. This group described during the discussion that the particular route needed extra guidance since it was more a ”dynamic route”.

Another group made color coded each hand and foot and used these colors for drawing arrows to indicate the movement direction, see Figure 4.3. The third group took the movement communication away from the visual side by articulating ”general advice” and ”hints”, see Figure 4.4. What stood out was the start of the manual where they literally stated “Balans & Tinkering”, followed by “Stay close to the wall” and “Climb static”. This group explained during the discussion that they made a conscious choice to explain the most difficult part of the route, the ‘crux’. They believed that it would help climbers the most and that they felt that the hardest part was to “trust their feet”. This made them put the hint: “Don’t be a wuss and put your feet up”.

The slightly different approaches, together with the explained choices for them, demonstrates that each route requires a different approach. Some routes are more dynamic, while other more static. The dynamic routes require more problem solving in terms of movement. The static routes can be better explained by poses, hints and are more focused on a specific ‘crux’. It was expressed in the general discussion of out-of-action *route reading* that climbers often focus on “solving the crux”. In most routes, there is a specific part or move that requires creative problem solving. Routes are often built this way on purpose by route builders. Solving the crux is what climbers derive most of their joy in climbing from.

The way climbers construct a mental representation of a climb in their head differs per person. Some think in actions (e.g. “twist my hips to the right side, than a heel hook”) while others imagine themselves in body configurations and where to put their hands and feet. Participants mention that it differs per person and per skill level. It became apparent that the *route reading* skill varies per climber due to the climbing experience and individual’s motivation to develop the skill. Participants also mentioned that it is “a matter of talent”. “Some just have a better spatial understanding and can imagine themselves better on the wall”, stated a participant.

Participatory Ideation

The last part of the discussion was dedicated to a brainstorm about potential solutions for a ”route reading system”. Participants were asked to thing about ideas for how technology could help climbers to become better ”route readers”.

Participants pointed out that transferring learned climbing movements to other routes can be challenging. What they noticed when observing beginners in the bouldergym was that they could feel and learn a certain move, but that they could not immediately apply it in another situation. For example, a beginner could feel at a certain point that bringing your hips closer to the wall reduces the muscle tightening. However, it is easy to forget about it in the next route or training session. For this scenario, an idea came up to make a tool where climbers could record these kind of movements/experiences/techniques, and to be able to retrieve them in another route.

From the notion of ”having to experience it first”, climbers argued that certain techniques (e.g., a *‘dropknee’*) needs to first be experienced on the wall so that an athlete receives a bodily understanding of the advantage. For this issue, the climbers in the session thought about tactics to make a technological solution that stimulate to experience these to increase the bodily understanding of climbing techniques. The most obvious idea is to show video’s of an expert performing the movements. They thought that mirroring the expert would help beginners to obtain the correct experience of certain movements. This method is also utilized during bouldering training: the trainer explains techniques and the students will follow the instruction on the wall.

The brainstorm also led to meaningful insights about common issues that beginner climbers face. First problem is that they position their hand and feet wrong. A solution from a participant is to guide the novice by displaying ”heat maps” on top of holds so it is visible where the hold can best be hold. The second obstacle is the mental imagery. It is difficult when someone comes off the wall, to first remember what he or she just did on the wall, and secondly how their bodily proportions relate to those of the environment. Climbers get a grip of this over time. It can also help to record themselves to watch themselves back or have a peer explain what he or she saw. All participants agreed on the fact that for climbers of every level it remains challenging to answer: ”Do I fit there?”. Therefore, it would be helpful to be able to position an ”artificial self” on the wall to be able to answer that.

Another thing that stood out during the conversation about beginners was the struggle with creativity. Novice climbers often struggle to believe or see that certain movements are possible. Someone mentioned that ”they are afraid to use the wall”, which means that they hold on to the screwed-on holds where often using the rest of the wall helps them further.

Additionally to the practical challenging, out-of-action *route reading* is often skipped by climbers because it is hard to motivate themselves to do so. ”It is just more fun to climb”, said a participant. Although climbers know that reflecting on their performance and planning ahead is helpful, doing it in your head alone is not motivating. Therefore, the social aspect helps climbers to perform mental practice by doing it together.

4.1.4 Conclusion

First of all, we can state that every climber has a different embodied understanding, motives and experiences with route reading. It became apparent in the discussion that some invest more time and effort in route reading on the ground, or seem to be more conscious about it, than others. Still everyone performs route reading on the ground in some form, either by chaining poses to one another or by focusing on the ‘crux’ to explore new action opportunities. The participants could see more potential in a system that would focus on “solving the crux”. Additionally, it became apparent that novice climbers often skip the practice on the ground, although they could benefit a lot from it to become “better climbers”.

Visual representations of climbing movements developed by participants imply that it is possible to represent a climbing pose in a two-dimensional space. The ‘dynamic’ part of climbing movements are more challenging to represent in a visual abstraction than the ‘static’ part. The ‘static’ part can be documented through a series of climbing poses. For a climbing pose, a representation in the two-dimensional environment seems to be understood by climbers. This suggests that it can be a suitable approach for an external representation. An important aspect is the ratio of the body in relation to the environment. Also, climbers are helped by something that supports their exploratory behaviour, their own tinkering, discovery and reflection. Those elements not only stimulate the perceptual motor learning but it is also the thing that the sport fun. Therefore, solutions targeted to instruct climbers a particular way are eliminated.

Ideate

4.2 Ideation: Exploration of External Representation of a *beta* for Skill Acquisition

The results from co-design 1 indicate that a proper visualisation of a *beta* for exploring action possibilities need a proper representation of the environment and of the body's poses. The affordance perception in climbing consists of layers, described in Section 2.2 and shown in Figure 2.9, and the co-design outcome also implies this is experienced by climbers. With that notion, we determine that *route reading* is most challenging for beginner climbers and therefore it suggests that designing a solution for this group will be most effective. In the reframing of the Design Space we will elaborate more on this consideration. For now, it is sufficient to know that this ideation is based on the following design decisions:

- Target group are beginner climbers
- Second-person perspective for the external representation
- Visual representation that can be displayed on a screen/projector
- Focus on climbing poses and eliminating the dynamic aspect in the representation
- Most important features in the representation is the body-environment configuration

4.2.1 Visual Representation of Climbing Poses

This design exploration starts with design sketching various visualisations of climbing poses that deviate from the second-person view that someone receives when observing a peer climb on the wall, see Figure 4.5a. The rest of the images (4.5bcd) are methods of portraying the pose on top of the actual pose. The general idea for the visualised pose is that the figure represents the user during their out-of-action *route reading* on the ground. The virtual figure would demonstrate the climbing poses coming from the ideas of the user. In order for the figure to enhance the enactive planning, users have to identify themselves with the virtual figure.

This leads us to evaluating the three concepts. Starting off with the stickfigure concept (Figure 4.5b) which focuses on the position of certain body parts and connecting them through simple lines. Although generally people are familiar with the stickfigure representation, there are many flaws for utilising them in the case of route planning. The main disadvantage is the loss in valuable information such as the direction of the head and the turning of the hips. Thereby, comes the pitfall of the user's recognition in the figure. We predict that the stickfigure would not be recognisable as a 'human figure' by everyone which takes away the immersion.

The shadow concept (Figure 4.5c) would probably be more recognisable as a 'human figure'. However, still spatial information is lacking when the fill in color is flat. The last concept for representing a human figure in a climbing pose, is the simplified character shown (Figure 4.5d). Here the figure wears clothes and the fill in color got a gradient to give it definition. This makes it easier to perceive the spatial orientation of the figure in space. Since spatial orientation is an essential piece of information, it would be more preferable to have a pose representation that comes closer to the concept of the simplified character than the other directions.

4.2.2 Visual Representation of The Route Environment

Displaying the climbing pose on its own would not provide enough information to the user to perceive affordances and assist the *route reading* process. It is necessary to position the figure in a visual

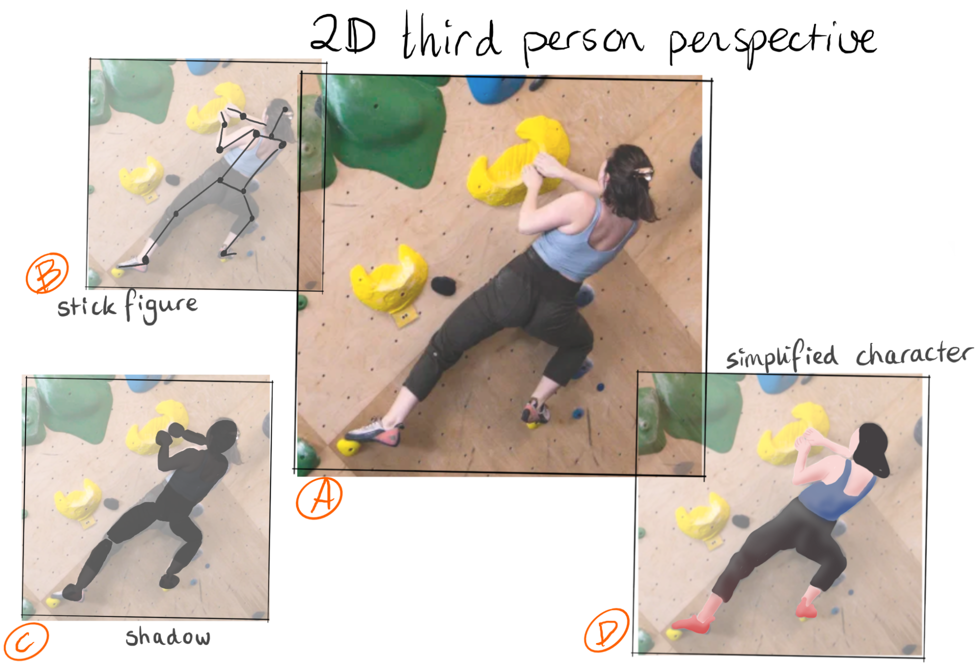

Figure 4.5: Pose representation ideation. a) Second-person perspective of climbing pose during peer observation b) Stickfigure concept c) Shadow concept d) Character concept

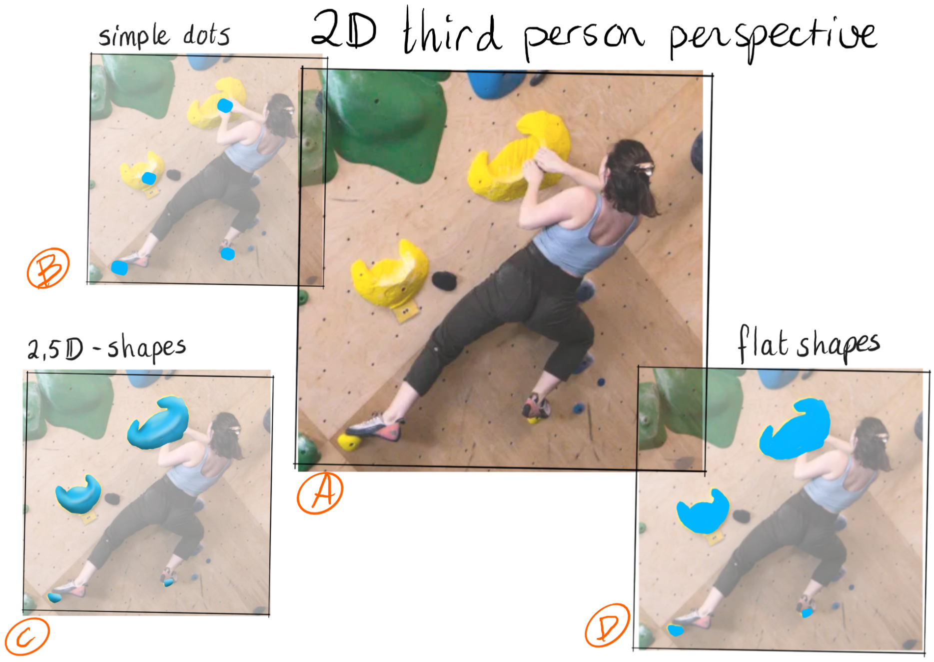

Figure 4.6: Route representation ideation. a) Front view perspective of climbing route during peer observation b) Dots concept c) 2.5D-shapes concept d) Flat-shapes concept

representation of the route environment. In order to explore the various solution directions, the starting point was the view on the wall from the ground. What an observer would see is shown in Figure 4.6a. With the image as a template, design sketching was performed. The three main directions are shown in the same figure.

The simple dots concept (Figure 4.6b) is the most abstracted visual form of a climbing route. When critically observing the simple dots concept, one can detect that much of the spatial information of the hold is missing. This information relates to graspability and usability which are both crucial in climbing affordance perception. The same critical observation is also transferable to the concept of flat shapes (Figure 4.6d) where the form is already more defined but it lacks the 'structural' properties and therefore no translation can be made to 'functional' properties. From the three main concepts, the *2.5D*-shapes concept is predicted to provide the most meaningful representation of a route. As was also described in selection of the climbing pose figure, with more definition on the shape (2D to 2.5D), more spatial information can be given to the user.

Prototype & Test

4.3 Self-Observation: Moving between First-Person and Second-Person Perspective

The outcome of the previous design activities led to the *2.5D* representation of climbing poses and environment. This is potentially a suitable external representation to facilitate climbers' *route reading*. Going forward with this design direction requires more validation on the concept. Although this visual representation was retrieved from observations of the co-design, it is still difficult to evaluate the usefulness of utilising the distributed representation within the sensemaking process (Figure 2.12).

4.3.1 Aim of the Session

This first-person perspective design activity aims to enable the design-researcher to obtain a deeper *bodily knowing* of the in-action experience and the out-of-action experience of route reading facilitated by an external *2.5D*-representation of her own climbing poses. By exposing the design-researcher to a imagined future scenario of route reading with a distributed representation, the prospect is that the somaesthetic reflection can result into a deeper understanding of the experiences.

In this session, the goal is to find differences and similarities between the 'lived' experience and the experience of re-watching a recording of oneself during the 'lived' experience. Furthermore, we would like to know in what way affordance perception differs between the in-action experience and the experience of viewing an external representation of a climbing pose on the ground. Lastly, by emerging into the experiences of route reading, the added valued of introducing an external representation can be evaluated.

4.3.2 Rapid Prototyping & Self-Observation

The methodology of the overall study strives to include all perspectives into design activities throughout the process. The first-person design research method of self-observation comes from the acknowledgement of the body as a source of meaning-making. This originates from existing literature on interaction design methods based with the appreciation for somatic practices (Section 3.5).

This self-observation session took place in the local bouldergym. The design-researcher came on a moment when little visitors were present, so she would be less distracted from tasks. The order of the tasks during the self-observation activity is listed as follows:

Step 1: Select a route that is not too easy and not too difficult, so multiple attempts are necessary but there is a finish.

Step 2: Route reading on the ground before first attempt.

Step 3: Place camera on a spot before the chosen route, so that every hold and expected movement of the climb will be visible on the recording.

Step 4: Press 'record' and climb the route.

Step 5: Come back on the ground and watch the recording by sliding through the frames.

Step 6: When a new plan of execution is made, go back on the wall. Repeat steps 3 to 5 until the route is successfully ascended.

The video recordings are seen as forms of 'rapid prototyping' and an easy method to facilitate the observational experience through the external representation envisioned.

After the tasks were performed on several climbing routes in the bouldergym, notes were taken on the 'lived' experiences. This was not done during the tasks on purpose, since it could distract the kineasthetic awareness and somatic focus. However, we assumed that writing down the experiences and thoughts right after the session would help to connect with them easier. This was based on the note quoted here:

> "Although the body is not moving or performing during introspection, it still extends the field of attention and connects with past lived experiences and with our muscle memory." [112]

4.3.3 Results of Self-Reporting

Right after the self-observation session, notes were taken about things that were remarkable about the experiences. They are listed in Table 4.1. Generally, filming oneself led to being more conscious about the climbing experience and aided in the decision making process. This suggests that video taping oneself led to an increased kineasthetic awareness and somatic focus. Furthermore, reviewing the video back by looking at static frames enables climbers to take the time to reflect upon static poses. This was experienced to be insightful, since looking at a static pose for a longer period was a new experience. Usually, one observes peers climb in their dynamic movements and the 'static' poses can not be reviewed for longer than a split-second.

The differences and similarities between the 'mover' experience and the 'observer' (through distributed representation) became also apparent. First of all, the 'observer' perspective facilitates an overview of the whole route whereas the 'mover's' perspective is limited to the position of their head/eyes on the wall. This statement is quite obvious but before this exercise, we were not conscious about its effect on the *route reading* process (and therefore our design space). Furthermore, the 'observer' perspective provides an overview of the whole body pose in relation to the wall. On the wall, most of the time, the body is close to the wall and the climber cannot see their toes although the position in space is felt (kineasthetic awareness). Observing the video tape of the climbing performance brought out the 'lived' experience by the observer. It brought back the sensations and emotions felt during the execution on the wall. Although the 'lived' experience and the 're-lived'

Figure 4.7: Screenshot of video recording watched to 're-live' the experience

Figure 4.8: Screenshot of video recording in which the invented pose is re-enacted

Design-Researcher's Narrative
"Filming myself made me more conscious about my actions on the wall."
"When I was on the wall, my body had to stay close to the wall in order for me to stay up there. My head was then turned away from the module where my knee could rest on. From the ground I could perceive this action possibility." (Referring to climbing pose in Figure 4.8)
"Viewing myself from this perspective, I have a better overview of the wall."
"It is hard to see the shape of the holds from solely looking at the video, I also need to see the hold in real life to know if I can grasp it under that angle."
"Looking back at my movements on the video, I had a different perception on the wall. I thought I was closer to the wall."
"It looks easier on the video than it actually was."
"From the video it looks like I can reach that hold but in position on the wall the hold looked further away."

Table 4.1: List of experiences

(out-of-action) experience gave a similar kineasthetic feeling, there was still a difference between the two. One of the major dissimilarity, related to *route reading*, was the perception or the estimated amount of strength required to execute a climbing movement. On the ground it was perceived to be 'easier' than on the wall. Furthermore, the distances between the holds and also in comparison to the body position were different from the two perspective. On the wall, holds seemed further away and harder to reach, whereas on the ground it was perceived to be closer.

The mismatch in perception on the wall and on the ground (while observing oneself on the wall) could have a significant impact on the affordance perception of climbers. Again, on the wall they are limited to the position of their eyes to look for new affordances. An explicit example of how watching oneself on the wall led to perceiving new affordances relates to the screenshot in Figure 4.8. The climbing pose that is visible on the screenshot is known to be a 'knee bar'. Although the design-researcher (here the climber) is familiar with the technique, on the wall this action possibility was not perceived because the head was turned to the other side. While reviewing the video tape of a failed attempt, the action possibility was perceived. It should be noted that the action possibility was perceived during the video observation but verified by having a glance on the 'real' climbing wall/route.

4.3.4 Conclusion

It can be concluded that the activity of self-observation gave new input for the design space. Through experiencing route reading on the wall versus route reading on the ground aided with a distributed representation, our findings suggests that: **the second-person perspective to observe one's own climbing pose positioned in the route contributes to route reading**.

This study was limited by the rapid prototyping decision to focus on the 'observing' act and exclude the 'interactive' part where a user could invent movements. However, we could still effectively accomplish the goals set (Section 4.3.1) with this efficient method.

Reframing Design Space

4.4 Design Space 1

The design space is cultivated with new information obtained from design phase 1. This section aims to emphasise what new inputs are taken from the design activities and what its effects are on the continuation of this research. The outcome of this design space serves as input for the new design phase.

4.4.1 Problem Space 1

Existing literature provided us with fundamental information about route reading, the sensemaking process and the current challenges of perceptual motor learning in mental practice. This caused the identification of a gap between the 'lived' experience on the wall versus the 'imagined' experience on the ground. The experiences and know-how from expert climbers supplemented the problem space by validating ideas and bringing in new ones.

The major concept that was evident in literature as well as in practice was the crucial role of *route reading* within bouldering practice. Expert climbers also agreed that the skill required for route reading differs per person and can be developed over time. Nevertheless, they mentioned that some people "have more talent" and "just see it". Additionally, the different levels of affordance perception found in literature (Figure 2.9) came back in the stories of the expert climbers. Beginner climbers struggle to translate what they feel and see into meaningful information such as the affordances 'surface graspability' and 'surface usability'. A step prior to 'surface graspability' and 'surface usability' is 'surface reachabilit', which is something even experience climbers struggle with. Before an attempt on the wall, climbers find it difficult to perceive whether they "fit in there", or if they can reach the next hold in a certain position.

Due to the physical strengths, weaknesses and body measurements, every climber has to find their own unique *beta*. Thus, climbers have to develop their own perceptual motor skill in order to perceive affordances that fit their capabilities. The outcome from the co-design as well as the self-observation delivered the understanding that it helps to take the role as an 'observer' from the ground. From the results, we can say that watching peers contributes to the skill acquisition.

The outcome of design activities in the bouldergym provided a deeper understanding of the *route reading* skill. We classified five sub-skills that hang under the *route reading* skill that are displayed in Figure 4.9. The similarities of the identified skill division (from experience) and the 'sensemaking' activities from Loke & Robertson's framework (Figure 3.4) are striking. However, the framework is based on movements performed on a flat ground. Within climbing the environment plays an important role in the kind of action possibilities that can be performed. Therefore, the focus in *route reading* reaches further than the climbing pose but lies in the interaction between the body and environment. This means that the lack of motor feedback is an important aspect in the gap between the wall and the ground experience.

More understanding was also obtained about the mental representation of climbers when they were route reading on the ground. From the discussion it seemed that some thought more in 'structural' properties but most expert climbers planned in terms of 'action' linked to 'functional' properties perceived (which corresponds to literature findings, Section **??**). The findings from analysing the *beta* manuals revealed that a common visual representation for *beta* is: a set of *2.5-dimensional* (2.5D) second-person perspective representation of static climbing poses where the climbing pose

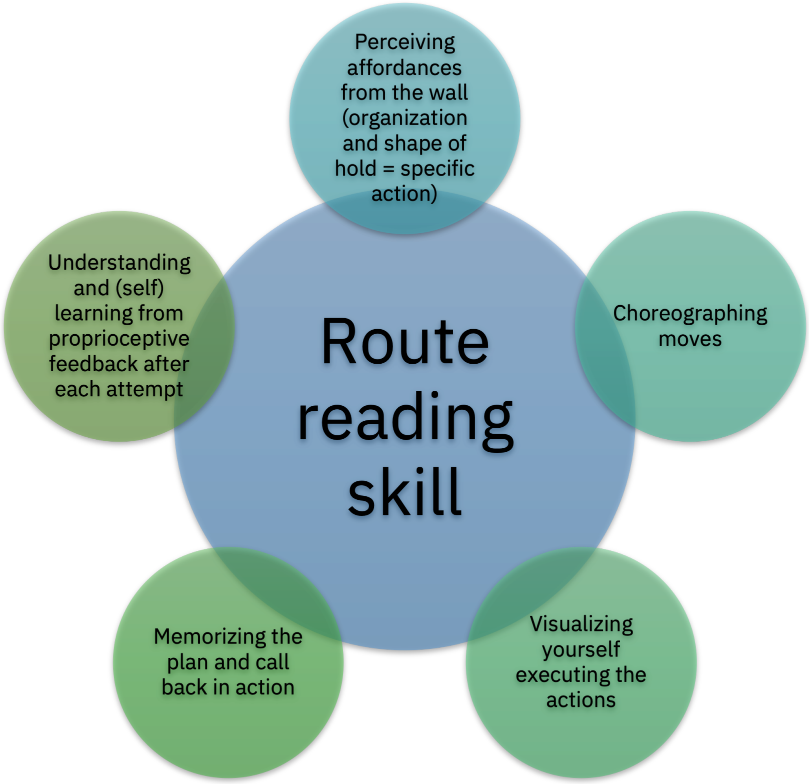

Figure 4.9: Definition of route reading skill divided by 5 parts.

is displayed on the hold configuration. Additionally, the pose as well as the route should be displayed in *2.5D* since this will include information about graspability that translates to affordance perception. Furthermore, participants in co-design 1 focused on portraying the 'static' part of the climbing movements on purpose. They mentioned that this is the base and most important for solving the 'crux' (= most challenging part of route).

Additionally, from self-observation it became apparent that inspecting the environment while being on the wall is restricted by the head's position. Therefore, an overview of the route that is present on the ground helps to to perceive new affordances. Another finding from the self-observation was the that the gap between the 'lived' and the 'observed' experience also consists of the misjudgment of required effort, strength and distances to overcome.

Questions that remain unanswered and need further investigation are: How is a climbing pose perceived by climbers when they have not performed/experienced it yet? How does the spatial cognition and kineasthetic awareness contribute besides the visual inspection to *route reading*? And how can the exploratory behaviour be distributed over the *route reading* activity on the wall and on the ground?

4.4.2 Solution Space 1

The solution direction of developing an external representation tool inspired from the mental presentation was a starting point for this design phase. With the bodily and verbal expressions from expert climbers about their sense making process and how mental representations manifest during motor imagery, insightful discoveries were made that contribute to the refinement of the solution space.

From the co-design, followed by the ideation, and a visual representation of climbing movements was developed. The focus on the representation was on the 'static' part of the movements and therefore "a climbing pose presented on top of the route environment" was identified to be a potential distributed representational aid for *route reading*. It is inspired on the situated practice of "watching peers climb" but in the new solution concept the climber would observe oneself on the wall.

Route reading consists of many elements (Figure 4.9) and for "solving the crux" the most critical activities are the affordance perception, choreographing movements and visualising oneself to evaluate the invented plan. Therefore, the solution direction will be aiming to enhance those activities and leave the other ones out of scope.

The visual representation of climbing poses as well as climbing routes need to be in the *2.5D* environment. Too much of an abstraction would probably lack important information such as hip orientation and hold graspabillity. These kind of elements can be observed in the *2.5D* environment, however, situating the solution in front of the actual route is important. From the self-observation it was found that when an action possibility (in that case the 'knee bar') was perceived, a verification by having a glance on the real wall was necessary before testing it out in-action.

The desired solution was found to facilitate a *2.5D* second-person perspective visual representation of a climbing pose on the route. Since, the aim of the solution is to enhance the perception-action coupling and thereby contribute to the skill acquisition, the to-be-designed system should let the climbers have the freedom to tinker and invent their own climbing poses. This results in more questions that require further exploration in the next design phase: How can the current visual representation of a climbing pose be manipulated by the user? How can we design an user interface that invites for exploratory behaviour?

Chapter

05

Design Phase 2

Tangible UI for Pose Manipulation on Distributed Representation

Design space 2

Empathise	Literature Review
Define	Literature Review
Ideate	Design Sketching
Prototype	Lo-fi Prototype
Test	Co-design 2: Play It Out!

Chapter 5

Design phase 2: Tangible UI for Pose Manipulation on Distributed Representation

Extending the bouldering practice by adding a technological artifact seems to contradict the embodied cognition theory. The idea is for climbers to obtain an embodied cognition of the sport through *lived experiences* and physical interaction with the environment, not by stepping out of this context and placing oneself behind a computer. However, situated on the ground, the route reading process already lacks the in-action interaction with the environment. The main problem is that it is challenging for climbers to perform embodied sensemaking out-of-action with the lack of direct embodiment. Interactive technology can bridge this gap between the wall and the ground.

With technology comes the risk of adding an extra dimension that can hinder the embodied experience of motor imagery. In the worst case, users will have to dedicate all their attention to making sense of the technological device instead of helping them to bring their attention to the route-solving task. Situating the interaction in context partially tackles this obstacle, as discussed in Section 4.4. Therefore, this thesis aims to situate the interaction in the bouldergym in front of the wall. Additionally, as discussed in Chapter 4, it was decided that the external representation should display spatial information of a climbing pose on the route environment that mimics to the scenario on the wall. This provides enough information for the user to tinker and prepare for the climbing route.

On top of that, the interaction with technology can be designed more embodied compared to the traditional Graphical User Interface (GUI). Therefore, this thesis studies how tangible and embodied interaction (TEI) can support the movement-based interaction. Hypothetically, following the direction of embodied interaction design will enhance the route reading process instead of hindering it.

From the initial literature review we obtained the understanding of embodied cognition and how making interaction more embodied is valuable for the objective of this thesis. Therefore, this design phase is determined towards finding a TEI that relates to the design space that insofar has been investigated. This leads to the following research question that will serve as the guide through this design phase:

> *What tangible and embodied user interaction can enable 2.5D pose manipulation to enhance climbers' route reading on the ground?*

This chapter reports on the second design iteration, following the steps of design thinking. The sections of this chapter, together with their design step, occur with the following structure:

- **Section 5.1 Design of Tangible and Embodied Interaction | *Empathise & Define***
  Investigating literature and related work on TEI to seek forms that fit the out-of-action sensemaking of spatial information.
- **Section 5.2 Ideation: Exploration TUI for Embodied Learning | *Ideate***
  Iterating further upon design opportunities derived from literature.
- **Section 5.3 Design Concept of 'Trial–Mirror' | *Prototype***
  Introducing the concept of the digital puppetry system, including the development of the lo-fi prototype.
- **Section 5.4 Co-design 2: Play It Out! | *Test***
  Gathering insights on the user interaction with the lo-fi prototype of 'Trial-and-Mirror', along with participatory brainstorm about the visual translation of motor feedback.
- **Section 5.5 Design Space 2**
  Reframing the problem and solution space with the acquired knowledge from this phase.

Empathise & Define

5.1 Design of Tangible User Interfaces

Tangible user interaction is a rapidly growing topic within HCI and EI with the potential to enhance human capacities in the digital world [113]. Tangible and embodied interfaces (TEIs) seek to go beyond the traditional graphical user interface (GUI) by integrating it in a physical environment. By incorporating more physical aspects as input for device and/or giving tangible/haptic feedback as output, TEIs can improve bodily and spatial awareness [10].

Whilst the interaction design tends to focus on the visual experience of the system, more and more researchers recognize the value of TEIs. TEIs engage the users' motor systems which plays a crucial part in the perception-action coupling, mentioned in Section 2.2. Thus, TEIs are favoured over GUIs when considering the natural interplay between body, action and environment. From this, we indicate that TEIs can be effective in this thesis' objective of movement-based interaction. By increasing the engagement of the body in the interaction, we foresee that climber's out-of-action sensemaking can be enhanced and ultimately their perceptual motor skill can be developed.

Tangbile user interfaces (Tangible User Interface (TUI)s) have shown to invite users to grasp, manipulate and interact with the physical artifacts that represent recognisable data (so when affordances are perceived) [114]. This active engagement converts into an enhancement of users' perceptual motor skill acquisition and creative thinking [115]. Research also suggest that TUIs can reduce cognitive load during problem-solving tasks [116]. All these promising results gave us the motivation to investigate how TUI can be integrated in our solution space. To empathise further on the topic, more literature has been examined to obtain more understanding as well as inspiration to ideate upon a suitable TUI for our solution space.

5.1.1 TEI for Spatial Cognition

Route reading is a sensemaking process that involves perceiving spatial features from the environment in relation to the human position. TEI for spatial related tasks have already been studied. Several studies compared the traditional GUI with its embodied counterpart (TUI) and they have shown the benefits of the embodied capacitities to enhance spatial cognition [117] [113] [118] [10].

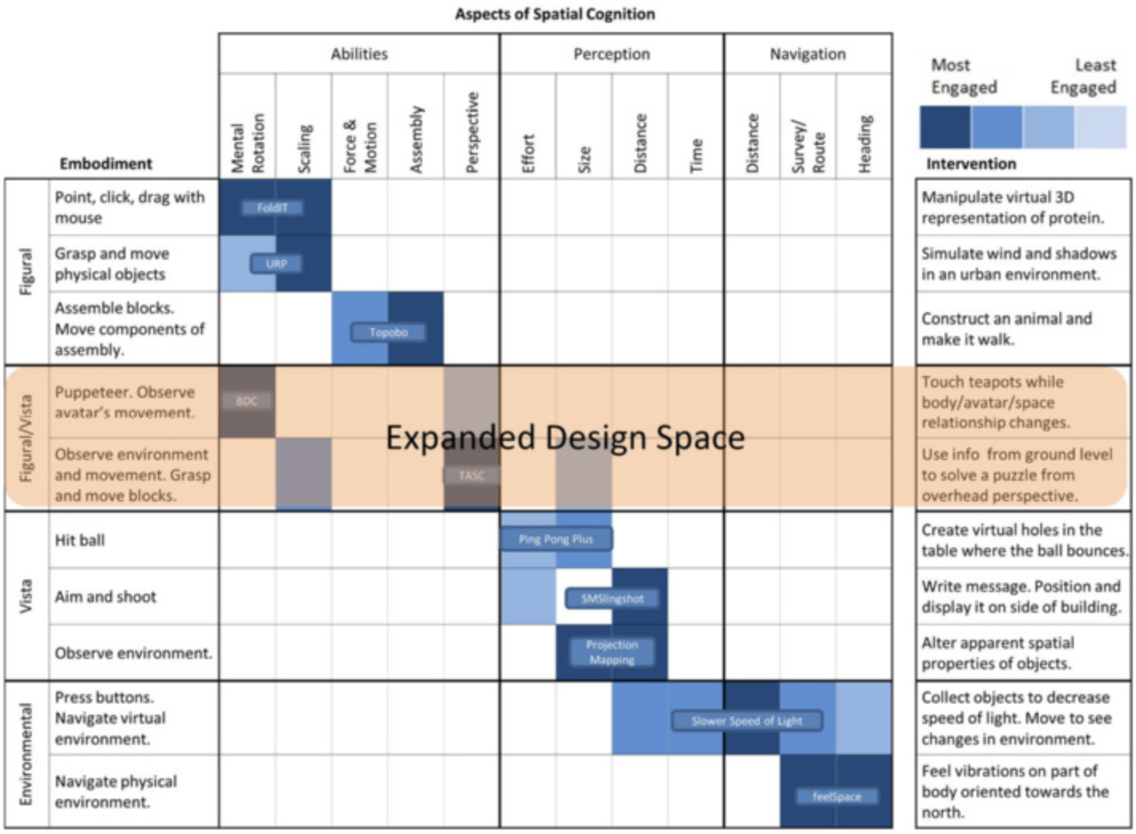

Figure 5.1: The expanded design space diagram for embodied design for engaging in spatial cognition [10].
The paper identified that the combination of figural and vista embodiment can lead to an expansion on the previous investigated design space.

In the groundbreaking study of Kim and Maher (2008) [118] they performed an user study influenced the popularity of TUI in a positive way. In the user study, participants are asked to perform a spatial task through a GUI and a TUI. It was found that the spatial task took longer to perfom with the GUI compared to the TUI. Moreover, it increased the perception of new and existing "visuo-spatial features".

The knowledge found in existing literature suggests that TEI is a suitable method for the spatial skill enhancement of route reading. This statement was also acknowledged by work of Clifton et al. (2016) [10] when they studied related work of embodied design for engaging in spatial cognition. They created a design space with on the horizontal axis the "aspects of spatial cognition" and on the vertical axis the parameters of embodiment, defined as 'figural', 'vista' and 'environmental' (Figure 5.1). The researcher expanded the design space by finding the possibility of combining 'figural' with 'vista'.

5.1.2 TEI for Embodied Learning

Various studies have demonstrated the benefits of interacting with physical artifacts during learning or sensemaking tasks [119] [120]. The physical artifacts are often referred to as 'thinking props' and 'memory support'. They are especially recommended for embodied learning because they contain spatial information that help the investigation of epistemic actions. From that notion, TEI re-

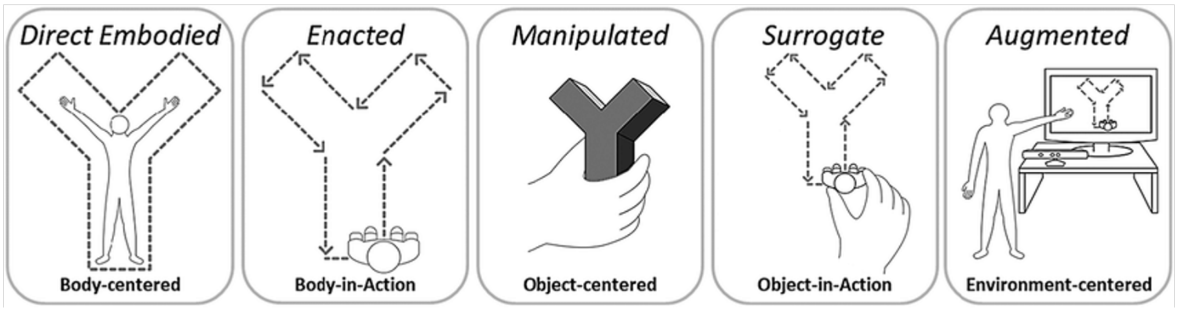

Figure 5.2: The five distinct values for the physicality dimension of the "Learning with the Body" design framework. [11]

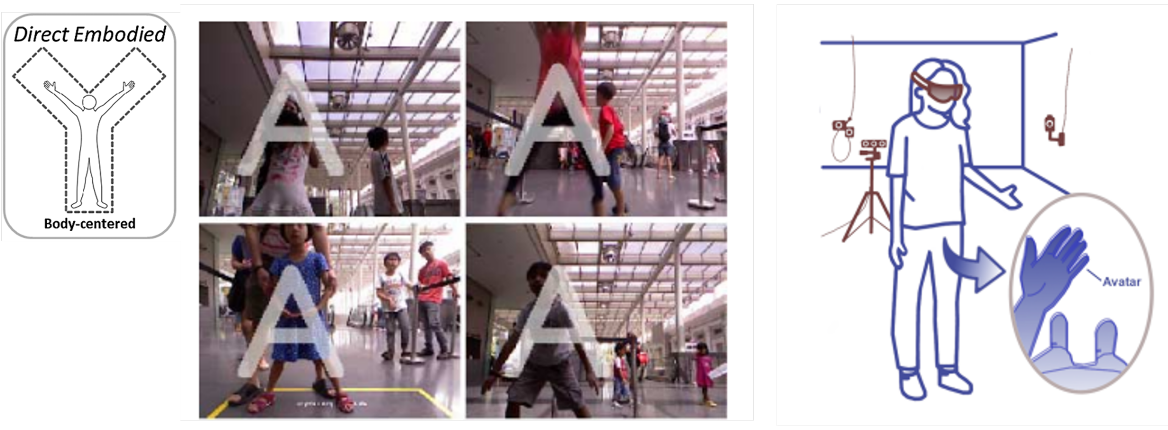

Figure 5.3: Related work of *Direct Embodied* interaction as inspiration for ideation phase. On the left: a full body interactive game Word Out [123]. On the right: First-person perspective through providing user an AR HMD. When she looks down, she sees her fully avatarised body. [124].

searchers have studied the benefits of physicality in the digital world.

A beneficial trait of TEI for embodied learning is the enhancement of immersion into the digital or mixed environment. Research has shown that giving users the ability to manipulate spatial temporal characteristics of their self-representation affects the users experience and stimulates self-perception [121]. The bodily engagement and task integration stimulates the embodied learning [122].

Due to the novelty of TEI and the specialty of the *route reading* process, a further investigation is performed on a suitable framework that serves the next ideation step. The work of Melcer & Isbisterr (2021) [11] equipped our investigation for a suitable TUI with their design framework for embodied learning. In Figure 3.4 presents the five distinct values for the physicality dimension that can be utilised for TUI design.

Direct Embodiment: Body-centered

The first value defined by the design framework [11] is 'direct embodied'. Designing an interaction with 'direct embodied' values the gestural congruency and how the body can physically represent learning concepts (e.g., Word Out [123]). The 'direct embodied' concept can be seen as the HCI where users are most bodily emerged. It can be well applied in digital spaces such as Virtual Reality when a full-body interaction is applied. Another feature of 'direct embodied' is the first-person per-

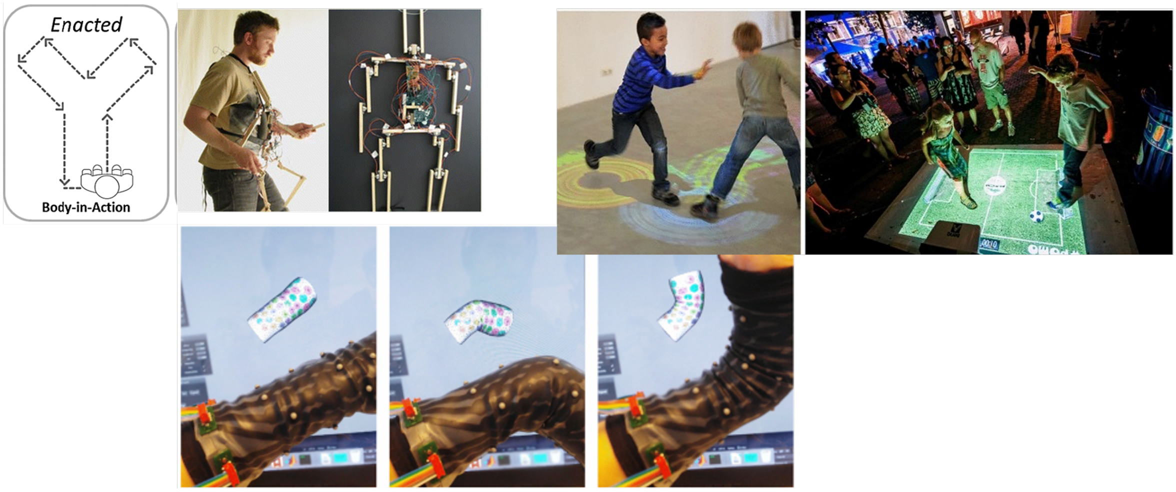

Figure 5.4: Related work of *Enacted* interaction as inspiration for ideation phase. Top-left: the emBodied Digital Creativity puppetry interface [125]. Top-right: Interactive Playground with AR floor projection [126]. Bottom: Deformation capture via stretchable sensor arrays [127].

spective that is provided. This is visible in the example on the right of Figure 5.3 where the user looks at performs the movement to look at her hand and sees her fully avatarised body in first-person.

Enacted: Body-in-Action

The 'enacted' value is closely related to the 'direct embodied' value because both are full-body interactions. The 'enacted' embodiment differs in the fact that the the body-in-action is (en)acting out a certain physical action, knowledge or phenomena. For example, following a projection on the ground that represents the the trajectory of planets. Another example shown in Figure 5.4 is the enacted puppetry interface where the user is attached to a puppet that can be manipulated through the users' movements.

Manipulated: Object-centered

The 'manipulated' embodiment is centered around interaction with a physical object. In Figure 5.5 presents various examples where users can learn concepts through manipulating objects.

Surrogate: Object-in-Action

The 'surrogate' embodiment allows users to manipulate a physical figure or form that represents themselves to enact learning concepts. This tangible interaction facilitates real-time virtual simulation and user immersion. For the modelling of human movements or poses, a puppet that represents a 'human-like' figure can be an useful form of 'surrogation' (see Figure 5.6).

Augmented: Environment-centered

The fifth value of embodiment is 'augmented' which combines the use of an external representational system (display) with a full-body user input of the user that is mapped to the avatar on the display. The two examples in Figure 5.7 show how the avatar on the users GUI is mapped with the users' movements through a camera system.

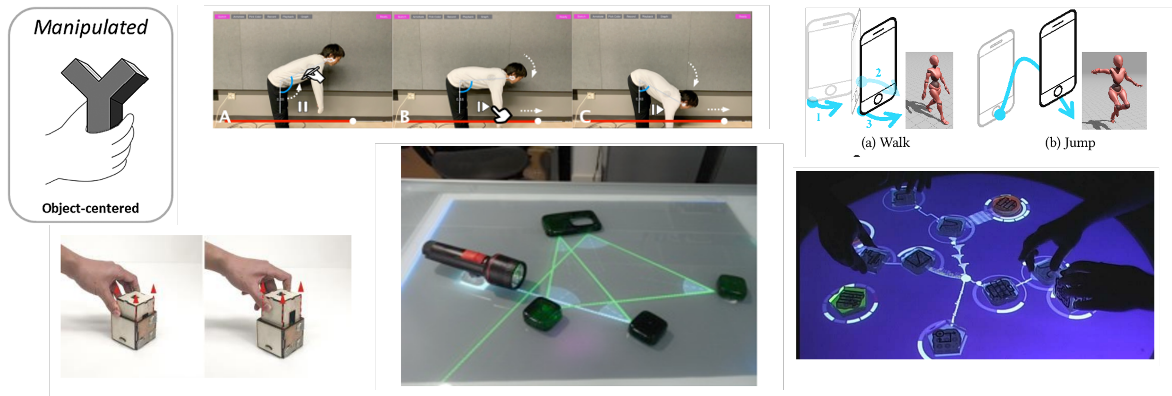

Figure 5.5: Related work of *Manipulated* interaction as inspiration for ideation phase. Top-left: RealitySketch: AR user interface to measure an angle of body joints to check a body pose [128]. Top-right: ARAnimator allows users to move their mobile device to control a virtual character [129]. Bottom-left: CodeRhythm: Tangbile Programming Blocks. Here the user can directly control the paramter value by pulling and pushing the cube [130]. Bottom-center: Interactive tabletop environment running an application on the physics of light [131]. Bottom-right: the reacTable for co-playing a musical instrument [132].

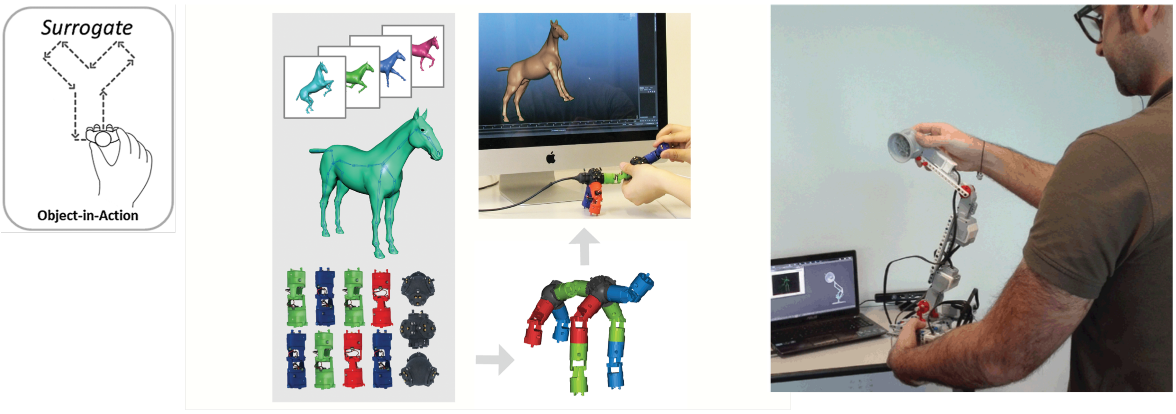

Figure 5.6: Related work of *Surrogate* interaction as inspiration for ideation phase. Left: Tangible and modular user interface for rig animation [133]. Right: Controlling a lamp armature that is mapped with body joints for virtual character manipulation [134].

Figure 5.7: Related work of *Augmented* interaction as inspiration for ideation phase. Left: Video game where users have to mimic the dance moves of the virtual character on the screen [135]. Right: The action-affordance gestures from the user are situated in an embodied space shared by both the virtual agent and the human [136].

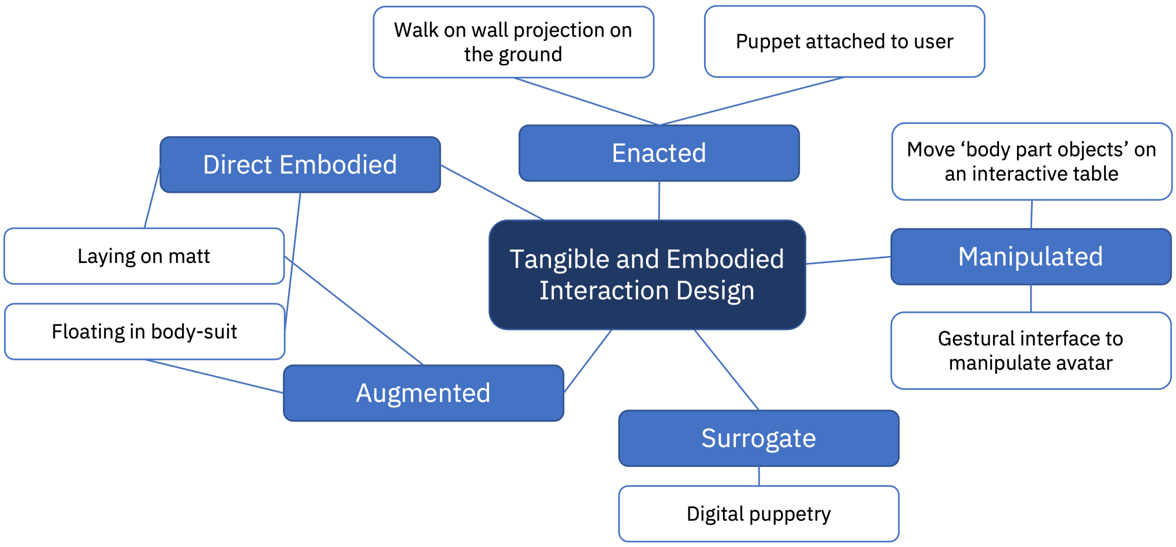

Figure 5.8: Spider diagram of TEI design concepts based on the five key values of embodiment

Ideate

5.2 Ideation: Exploration TUI for Embodied Learning

The ideation process started from the five key values of physicality in embodied interaction (defined by Melcer Isbister (2021) [11]). In Figure 5.8 is the spider diagram visible where the five types of embodiment are connected to the solution space of TEI that is aimed for. A brainstorm session led to various *route reading* concepts connected to a type of embodiment.

The 'direct embodied' interaction in the context of *route reading* on the ground would have to allow users to perform climbing poses and movements. However, climbing poses are connected to the composition of the wall. So a pose where someone hangs onto climbing holds is difficult to reconstruct on the ground. It would only by possible if users are **laying on a mat** or **floating in body-suit** in a harness. The same two concepts are connected to the 'augmented' embodiment. The difference is the appearance of users is demonstrated to them. For 'direct embodied', users would perceive themselves from the first-person perspective, as if they were actually climbing on the wall. This could for example be done through virtual reality goggles (see Figure 5.9) where climbing would lay on the mat and be able to 'climb' in a virtual simulated environment. The same concept of the mat is also sketched out in Figure 5.9 for the 'augmented' embodiment. There, the climbing would perform the same physical movements but the movements are visible on a projection on the wall, so from the second-person perspective. For the concept of the harness to float into air, users could even hang in front of the wall (hanging in the air) and perform climbing poses for *route reading*. That would be labelled as 'direct embodied', whereas the 'augmented' variant would visualise a character on the wall which users manipulate through their movements.

One of the concepts, where *route reading* out-of-action can be supported through an 'enacted' interaction, relates to the work "emBodied Digital Creativity" puppet system of Clifton (2014) [125]. In Figure 5.4 on the top-left, an interaction through a construction of beams that represent a **puppet is attached to the user's body**. The same idea can be put into use for a *route reading* system on the ground. Another idea that was derived from the brainstorm session, with the 'enacted' interaction, would enable users to **walk on a projection on the ground** that represents the climbing wall. The

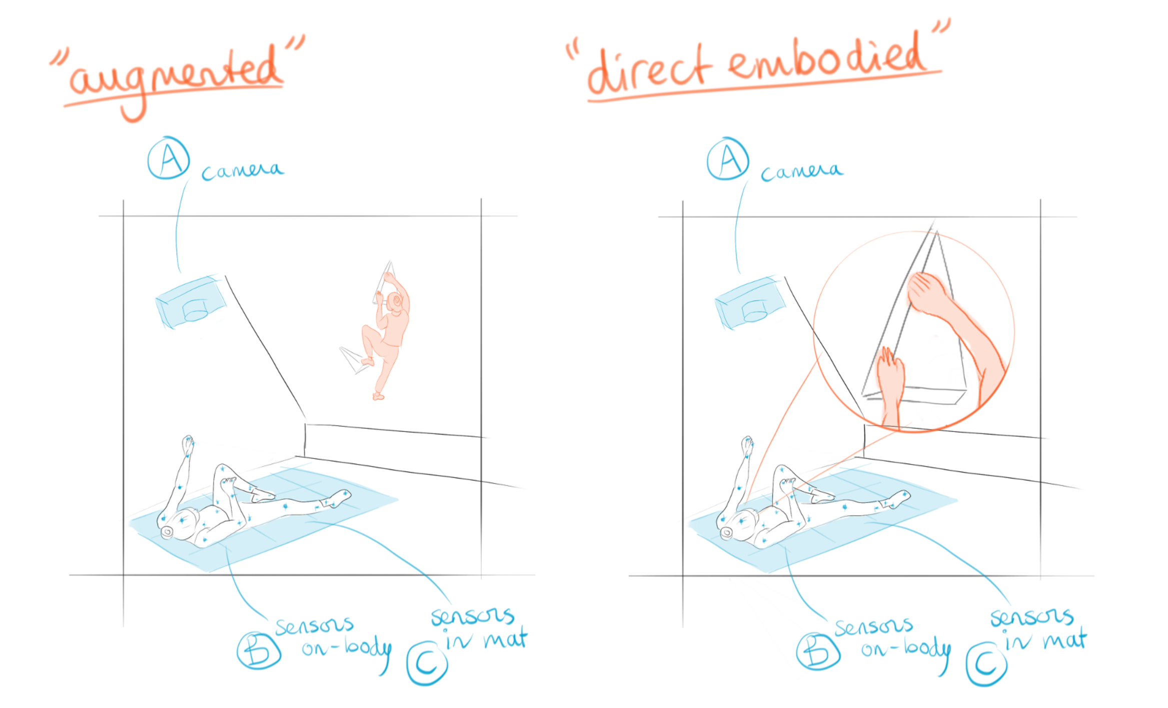

Figure 5.9: Design sketches of *augmented* interaction vs. *direct embodied* interaction for route reading system.

steps would be detected and mapped with the virtual figure that is also projected on the ground. Thereby, users can manipulate the figure from a second-person perspective with their feet.

Since climbing, with its *route reading*, is focused on making sense out of movements and body poses, it was quite challenging to think of 'manipulated' interactions. Despite the fact that an embodied interaction in that case would be logically mapped through a 'human figure', still two concepts derived where objects are used to support the climbing pose sensemaking. The first one is an interactive table where users can **move objects that represent body parts** (e.g., the right upper arm). This would allow users to focus on fragments of the climbing pose that require attention instead of having to position a whole body pose. The interactive table would represent the climbing route. The second 'manipulated' interaction relates to the concept of 'augmented' on the mat (Figure 5.9 on the left). Transforming this interaction to 'manipulated' would mean that users hold a stick or alike that serves as a remote control and user **gestural arms movements to put the virtual character in a climbing pose**.

The last variant of embodiment facilitate users to manipulate their 'surrogate'. For our design space it could mean that a posable puppet can be put into climbing poses that users would like to test out. This concept of **digital puppetry** would allow users to 'freeze' a climbing pose and to have the time to observe, think and evaluate upon the pose.

5.2.1 Towards a Digital Puppetry System

From the concepts created during the brainstorm session, it became clear that the 'surrogate' concept of digital puppetry would be a suitable option as an embodied interaction. The expanded design space that [10] is created with the example of digital puppetry, as a way to bring 'vista' and 'figural' into one space, made us go forward with the digital puppetry system.

Group	Dimension	Values				
Physical Interaction	Physicality	Direct Embodied	Enacted	Manipulated	Surrogate	Augmented
	Transforms	PPt	PDt		DPt	
	Mapping	Discrete	Co-located		Embedded	
	Correspondence	Symbolic	Indexical		Literal	
Social Interaction	Mode of Play	Individual	Collaborative		Competitive	
	Coordination	Other Player(s)	NPC(s)		None	
World	Environment	Physical	Mixed		Virtual	

Figure 5.10: Initial 'surrogate' concept: An overview of the design decisions made upon the various dimensions of embodied interaction.
The table is based on Figure 7.1 of the design framework for embodied learning of Melcer & Isbister (2021) [11]. The framework is explained in Section 5.1 and the yellow filled cells indicate the design choice made for that dimension.

With the design framework of Melcer Isbister (2021) [11] came a table that facilitated the decision making for the concept (see Figure 5.10).

Prototype

5.3 Design Concept of 'Trial-and-Mirror'

The discovery of the digital puppetry system found in the ideation phase led to the design concept of 'Trial-and-Mirror' (T-&-M). A concept board was sketched out to illustrate all the facets of the interactive *route reading* system (Figure 5.11).

The user interaction is situated on the ground in front of the climbing wall where the (chosen) climbing route is situated. A miniature version of the wall is standing on a table so the user can easily reach and interact within the miniature environment. In the miniature environment is a 'surrogate' of themselves represented through a posable puppet. On the hands and feet of the puppet are magnets attached and the miniature wall is made of metal. This allows the puppet to be placed on the wall in a climbing pose without it falling off. It replaced the physical effort (or strength) of climbers on the wall since that causes them to stay on the wall. The miniature wall resembles the actual climbing wall with its 3D composition of wall elements. In order to facilitate for multiple climbing routes, they can be stuck onto the wall by miniature holds with magnets in them. Additionally, the hold configuration could be displayed on the miniature wall through the mini projector in front of it. A tripod that is placed in front of the miniature environment hold the mini projector with a camera. The idea is that the camera footage is received by a computer that can sense the climbing pose and push out visual feedback that would be augmented on the puppet and environment. The exact design of the visual feedback will be further explored in the next design phase (Chapter 6).

The *route reading* on the ground through the T-&-M would allow users to investigate climbing poses, perceive affordances, invent new climbing poses and enact them out in the simulated scenario. The puppet supports by describing and documenting climbing poses in a 3D-representation that enables users to observe the climbing pose from various angles. After climbers would feel prepared for their next physical attempt, they could re-enact the climbing poses on the 'real' wall in

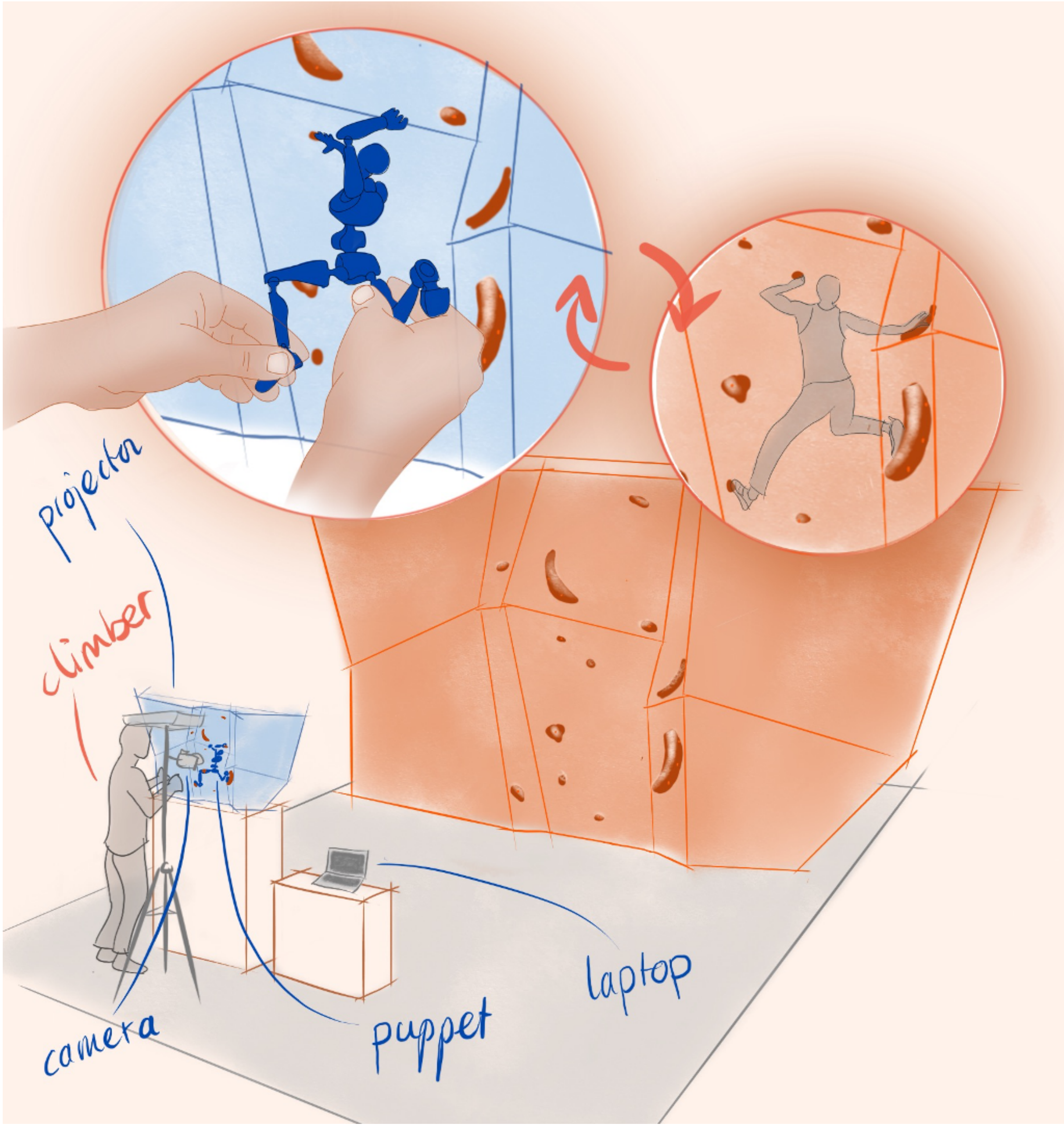

Figure 5.11: Conceptboard with imagined scenario of climber's interaction with the Trial-and-Mirror system.

Figure 5.12: Schematic overview of lo-fi prototype set-up in bouldergym.

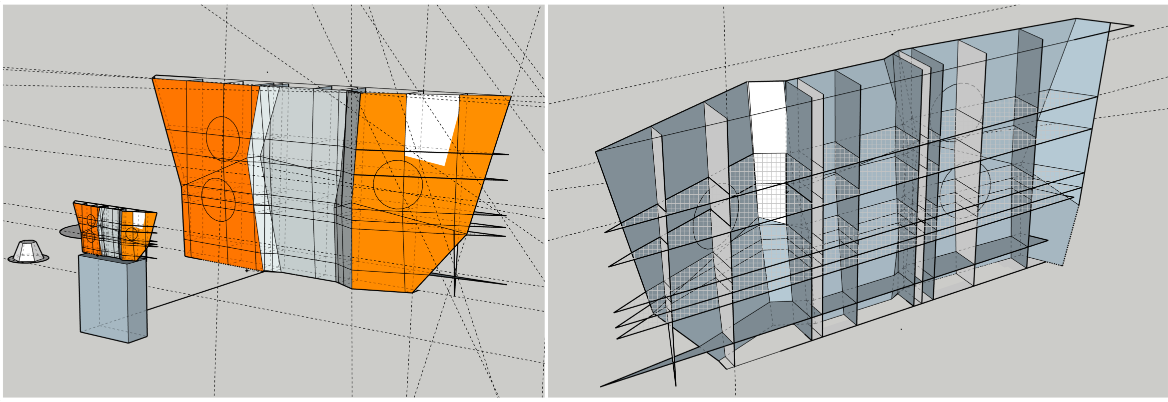

Figure 5.13: SketchUp screenshots of 3D model renderings as part of the lo-fi prototyping process

front of them. The top part of the concept board highlights the iterative process of *route reading* on the wall (through their the ‘lived’ experience) and on the ground (through the ‘surrogate’ experience).

5.3.1 Lo-fi Prototype

The concept of ‘Trial-and-Mirror’ is transformed into a lo-fi prototype which can be used to test the puppet interaction and develop it further. The construction of the lo-fi prototype started off by selecting a climbing wall in the local bouldergym. The section of the wall needed to be suitable to build into a miniature version of it. The design-researcher discussed with one of the route builders of the local bouldergym to come to a decision on which section of the wall to copy. It turned out that the same section as was used as the environment for Co-design 1 (Section 4.1) was suitable.

The structure of the selected wall has peculiar dimensions, with panels attached to each other at small angles. As is described in solution space 5.5.2, every detail of the climbing environment counts in order for climbers to perceive the correct affordances. Therefore, the construction of the selected wall was measure precisely and transferred to a digital twin in SketchUp (3D design software). In SketchUp the dimensions were changed on a scale from 10:1. This scale makes the miniature wall as well as the puppet a size that can be physically handled by users. In order for the miniature wall to stand upright, a beam structure was prepared in SketchUp, see Figure 5.13 on the right. Another function of the beam structure is to help attach the panels on the front side at a particular angle. The structure of the miniature wall is made from wood and metal plates (Figure 5.14 on the right).

Alongside the major structure of the miniature wall, the holds of the climbing routes also needed to be represented. A lo-fi method used for it was to mold the holds out of clay with a magnet placed in them. The holds were created a day before the co-design (Section 5.4) because the climbing routes are often changed in the local bouldergym. This circumstance was also the reason to use exchangeable magnetic holds in the first place. The expectation was that the lo-fi prototype parts could be re-used in the High fidelity (hi-fi) prototype as well. When the climbing holds would be fixed on the wall, the miniature wall could not be updated to the real wall that would contain new routes.

For the puppet of the lo-fi prototype, there was already an order placed on the website of Stickybones (described in Section 6.3). Due to delivery problems, another lo-fi solution was needed. On the website Printables.com a 3D model of a configurable puppet was found [137]. The 3D printable puppet was printed in separate parts on 150% which gave the puppet a height of 1800 mm. This

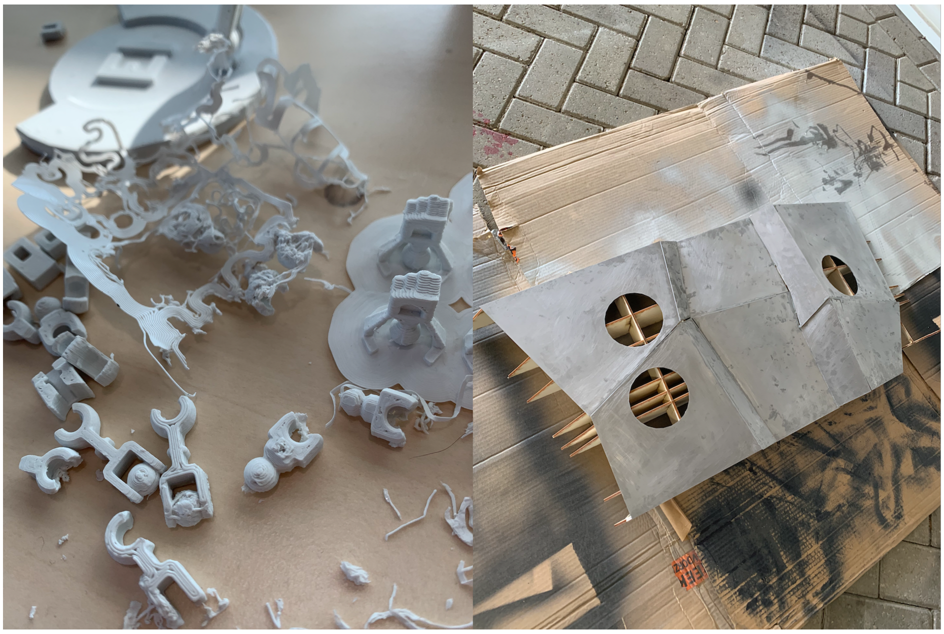

Figure 5.14: Photos of lo-fi prototyping process in the workshop

would represent a person with the height of 1,80 meter. Several small and strong magnets were glued on the hands and feet of the puppet. This allowed the puppet to be placed on the miniature wall, see Figure 5.15.

Test

5.4 Co-design 2: Play It Out!

With the arrival of 'Trial-and-Mirror' multiple assumptions were made that needed validation from testing. The puppet interaction, as well as the climbing pose representation, in the lo-fi prototype can be evaluated in the situated practice of bouldering. Before the co-design session was held, the lo-fi prototype was placed in the local bouldergym to prepare the session. On that day it appeared that the miniature wall with its puppet drew plenty of attention and climbers gathered around it were interested. Therefore, this session was held without recruiting participants beforehand. On top of that, the session was less structured than the previous co-design (Section 4.1). This co-design was intended to observe the spontaneous interactions that would arise to test the design concept. Lastly, ideas were gathered for the development of visual feedback (related to motor feedback), as this would be used in the next design phase.

5.4.1 Aim of the Session

The objective of this session was in three-fold; (1) Investigating the contribution of an interactive distributed representation on the visual inspection of a route (2) Assessing the miniature wall concept with its puppet interaction and (3) Brainstorming on visual feedback to augment. The lo-fi prototype, as description in Section 5.3.1, consist out of a miniature climbing wall with a 3D printed posable puppet that can be attached to each other through magnetism. Due to the newness of this interaction, especially in the context of sports, the interaction required user testing to obtain feedback. An additional drawing tablet, that could be projected on the miniature wall and puppet, facilitated the

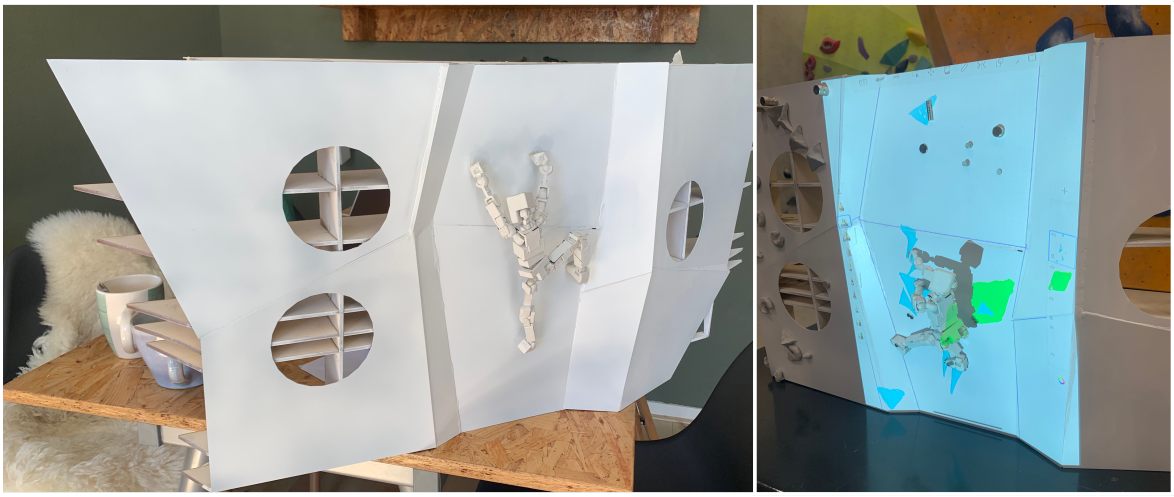

Figure 5.15: Photos of finished lo-fi prototype.

brainstorm for an extra visual layer.

The research question for the co-design session was formulated as follows: **How do climbers experience the puppet-environment concept and what augmented visual feedback would climbers desire during out-of-action route reading?**. The first part of the question to examine the puppet-environment concept will be done by observing the user's behaviour while interacting as well as the social dynamics in situated practice. Once, climbers have interacted with the lo-fi prototype, their experience is discussed with the design-researcher. Furthermore their opinion was asked about the idea of an additional visual layer to augment on top of the wall or/and puppet, that would help with the out-of-action *route reading* practice.The hypothesis is that users will come up with ideas that are based on their experience with lo-fi prototype as well as their bouldering experiences.

The determining factor of implementing a puppet interface in the solution was the active learner role that would be given to the user. Therefore, we are wondering whether this puppet-environment interaction facilitates and invites for exploratory behaviour.

The latest design space hitherto, is still lacking information about *route reading* before any attempt on the wall is made. By investigating this scenario in this co-design session, we aim to obtain new information about the contribution of the 'lived' experience on the *route reading* on the ground. This is essential to know since it will bring us closer to bridging the gap between the 'lived' experience and the 'imaged' experience. What the climber brings to the 'imaged' experience from their 'lived' experience can be externally represented. Plus, we can fill in the missing pieces of information that the climber still needs during *route reading* by augmenting additional visuals.

5.4.2 Method

The focal point of the session is set in the third-person perspective to explore the human-machine interaction. Since the lo-fi prototype aims to map human movements and portray an abstraction of a climbing pose in a simulated environment, the research method should allow us to study the sensemaking of movements. This relates to 'sensemaking' activity nr. 6 (Section 3.5.3).

On top of the individual interactions, the co-design session will be situated in a social environment. Given this, we can make use of the social interaction since the 'Trial-and-Mirror' already facilitates for *distributed collaborative sensemaking*. By adding a drawing tablet and projector, we could enhance this through illustrating ideas on the miniature environment that are coming from the con-

Yellow route: intermediate level route, requires good climbing techniques.

Mint route: intermediate level route, requires good climbing techniques.

Red route: beginner level route, good hand and foot holds but allows for climbing technique training.

Figure 5.16: Setting of co-design 2: The selected three bouldering routes for participants to perform the assignments with.

versations.

In order for us to truly answer the question whether it will invite for exploratory behaviour, we have to leave out instruction and observe spontaneous interactions with the prototype. The design-researcher will therefore take a role as observer to not disturb and in any way guide the user.

Participants

Due to the unscripted characteristic of the co-design session, the participants were not recruited. The users were all climbers that were present by chance in the local bouldergym. In summary, the people that participated and joined on their own initiative were:

- A young boy, estimated age between 8 and 10, experienced climber.
- Owner of the bouldergym, experienced climber and route builder.
- Employee of the bouldergym, experienced climber and beginner route builder.
- 4 regular visitors, experienced climbers.

Setting & Material

As mentioned before, the session was held in the local bouldergym at between 16:00 and 19:00. In the middle of the hall there is a relatively straight section of climbing wall that is quite separate from the rest. This sections was reserved for the session and the miniature wall in the lo-fi prototype represented this part of the wall.

The lo-fi prototype was positioned in front of the wall on a bench (Figure 5.17). A picture of the 'real' wall was made by the tablet and projected on the miniature wall so that the routes would be visible. As preparation the routes were assessed on their usability for this co-design session. The routes are shown in Figure 5.16 with a short description of their characteristics. There were routes

Figure 5.17: Participant interacting with the lo-fi prototype during co-design.

Figure 5.18: Screenshot of tablet where idea sketches (on top of a picture of the route) are visible.

built of various levels which would allow everyone to join the session and perform route reading through the 'Trial-and-Mirror' prototype for their chosen route.

On top of the pictures taken of the wall, markings are made of the hold shape and measurements (Figure 5.16). The reason for this was that the miniature duplicate of the holds on the wall were made of clay with a magnet inside. The miniature holds were placed on the miniature wall for extra dimension.

5.4.3 Results & Discussion

The quotes heard and observations made during the co-design session are listed in Table 5.1. In this section we will discuss the outcome and analyse the observations.

First of all, the aim was to test whether the lo-fi prototype would invite users to interact with. It was noticeable that people immediately gathered around the prototype. This suggest that the prototype in the situated context looks interesting enough for climbers to check it out. Once participants got a glimpse of what was happening and what it was they saw, some started to interact with the puppet and positioning it on the miniature wall. This scaffolding behaviour was not observed by everyone. Some participants only watched how other interacted and were only verbally engaged in the scenario. It was observed that some people seemed to feel uncomfortable to interact with the puppet as well as the drawing tablet. However, both artifacts only allow to be utilised by one person at a time.

The observed interactions with the lo-fi prototype also gave us insights on the intuitiveness of the representation designed. It appeared to be intuitive in the sense that the prototype was used as intended, without the need of instructions from the design-researcher. This also implies that it was clear for users that the prototype represented the wall in front of them and that the puppet represented a climber. Although is was also mentioned that the puppet did not properly represent a human being and that it was "distracting". This implies that the puppet did not provide enough

Quotes & Observations
“I can show you how to do it”, said the young boy to the group who were interacting with the prototype to figure out the ‘beta’.
“I could use this for route building!”, said the beginner route builder to the experienced route builder.
Several people asked the design-researcher what the reason was behind the miniature wall. “Why don’t you just project the puppet on the actual wall?”, is what they said.
“The puppet does not look human to me, this would distract me.”
“I have to constantly switch sight between the wall and the thing”, said a participant referring to the prototype.
Participants manipulated the puppet in a pose that would make the puppet stick to the miniature wall instead of inventing realistic movements.
Once a participant came up with a idea for visual feedback, the rest of the participants built upon this idea instead of suggesting new ideas.
Not all participants felt comfortable to draw on the tablet. It also only allowed for one person to utilise the device.
Not all participants felt comfortable to pick up the puppet and re-model it. It was noticeable that some took more initiative then others.

Table 5.1: List of observational notes taken from co-design 2

immersion for the user. Furthermore, it tells us that users would like to perceive the puppet as a 'surrogate' of themselves.

A related issue with the 3D printed puppet was the limitations in movement. Users could not pose the puppet in every pose possible by humans. On top of that, the pose was adjusted to one that would allow the puppet to stick up the miniature wall due to magnetism. This hindered the route reading process since users were putting more effort into the mechanisms of the prototype. This also limited the facilitation for exploratory behaviour. Performing exploratory movements with the puppet on the miniature wall were almost not observed. People were mostly making sense and scaffolding with the device itself. Besides, the participants that joined the session were so experienced that they probably did not feel the desire to route read for the routes in front of them. They could presumably finish the routes in one attempt.

Besides the puppet, the concept of a miniature representation of the environment had also complications. The idea for the miniature holds as magnets were quickly put aside since they were not feasible. The puppet could not stick on the magnets and a lo-fi solution to make a picture of the actual wall an project it on the miniature wall also facilitated the route configuration representation. A challenge, mentioned by a participants, was the disturbance of having to switch sights between the actual route on the wall and the prototype. This suggests that the actual wall still contains necessary information for route reading that was missing in the prototype. A solution direction, mentioned several times by participants, is to project the puppet on the actual wall.

Another interesting find is the integration of the prototype into the loop of route reading on the wall and on the ground. Participants tried out climbing movements on the actual wall and came back on the ground, manipulated the puppet, and thereby distributed their ideas on the puppet. There was a funny moment when a young boy saw the whole group interacting with the prototype, asked everyone's attention and demonstrated "the way up the wall". You could observe that he did not grasp the idea of route reading yet and though it would be way more fun to "just climb".

After letting participants scaffold and interact with the lo-fi prototype for a while, the design-researcher directed the conversation into a brainstorm session with the question: "What would a beginner climber help in route reading?". This led the conversation into an exchange of experiences and thoughts on what are recurring challenges for beginner climbers. Things that were mentioned:

- Beginner climbers struggle to keep straight arms.
- Beginner climbers often have their feet together which reduces their balance.
- Beginner climbers struggle to keep their hips/CoM close to the wall.
- Beginner climbers can improve their foot and hand positioning on the holds.
- Beginner climbers seem to be "afraid to use the wall", meaning that they tend to keep their hands and feet on the holds, instead of placing their legs aside directly on the wall for more balance .

Ideas for visual feedback to guide beginner climbers in their route reading process were also obtained during the session. Through the drawing tablet, users were invited to draw visual feedback on the pose/environment. One of the sketches from the tablet is shown in Figure 5.18. The initial solution direction from the participants was focused on adding spatial information on the environment. By enhancing the 'structural' properties of holds through color and arrows, the participants believed that this would help beginner climbers to perceive affordances.

5.4.4 Conclusion

From the co-design session it can be concluded that the designed interaction of the 'Trial-and-Mirror' is inviting to use and an intuitive interaction for climbers. However, the puppet in the lo-fi prototype was 3D printed and was perceived to be "not human enough". Another limitation was the magnetism of the system which required users to manipulate the puppet in ways that would work for the prototype instead of what would work in real-life. Therefore, the interactions during the co-design session were focused on the making sense of the prototype and not yet the sensemaking process of the route.

Next to testing the prototype, it also facilitated the brainstorm for what additional visual feedback could be provided to beginner climbers. First of all, five struggles of beginner climbers became apparent that were related to positioning oneself on the wall. However, it was remarkable to see that participants ideated upon solutions that were focused on the environment rather than the pose.

Reframing Design Space

5.5 Design Space 2

The insights obtained during this design phase serves as input for the design space. This section aims to emphasis what findings contribute to our understanding of the problem and solution space and what the effects are on the continuation of this research. The outcome of this design space leads to new questions and research direction for the new design phase.

5.5.1 Problem Space 2

The observations made during co-design session 2 led to insights to enrich the problem space. The first finding is connected the sensemaking behaviour of users. From the first co-design session, we found out that climbers consider route reading as a skill of which some people posses more talent for than others. Although this is based on their experience, it still tells us that time spend bouldering is not solely contributing to climbers' route reading ability. There are way more attributes to the equation such as tendency to explore and scaffold with tangibles in front of them. By facilitating climbers a tangible lo-fi prototype of a puppetry interface, we could observe that the tendency to touch, explore and scaffold upon the device differs per person. This ultimately suggests that the user behaviour not only depends on the design of the system but also their personality or sensemaking tendency/abilities in general.

From the interaction with the lo-fi prototype, it became also apparent the importance of a "human-like" representation of the climber. It seemed that the user immersion into the sensemaking process depends on this feature of the puppet. This gave us the insight that for a surrogate embodied interaction design the "human-like" perception is an important asset since users feel "disturbed" by it otherwise. At least this is the case for route reading but it also imply that this is the case for other contexts where users perform sensemaking of human movements.

Next to the movements sensemaking process of route reading, the users also have to make sense out of the presented device in front of them. Although it can be an intuitive and inviting design, we observed that users need time to grasp the interaction. Therefore, it would be advisable to give them a scaffolding exercise before starting with the assignment of route reading. Another observation was related to the motivation of climbers for performing the task of route reading. During co-design 2, the routes in front of the prototype were relatively easy to very experienced climbers that were participating in the session. Therefore, they seem to be less motivated to start route reading since they would already know how to climb the route.

Additionally, an insight about the ‘situatedness’ of the route reading process was obtained from the co-design session. Participants mentioned that having to switch sight between the miniature wall and the actual wall was disturbing to them. This suggests that route reading on the ground relies on much more information from the environment than initially thought. The environmental information was given to the user by displaying a picture on the miniature wall. Apparently, this is not sufficient for route reading on the ground.

Lastly, we gathered information about the challenges that beginner climbers face in bouldering. The five key challenges are:

- Beginner climbers struggle to keep straight arms.
- Beginner climbers often have their feet together which reduces their balance.
- Beginner climbers struggle to keep their hips/CoM close to the wall.
- Beginner climbers can improve their foot and hand positioning on the holds.
- Beginner climbers seem to be “afraid to use the wall”, meaning that they tend to keep their hands and feet on the screwed on holds (instead of placing their legs aside for more balance).

The first three items relate directly to the climbing pose which we can give feedback upon. The fourth item relates more to climbing techniques that are not obtained through route reading but more on instructions of how the feet and hands should be placed on the holds. The last point related indirectly to the climbing pose since beginner climbers seemingly feel restricted to the holds of the route instead of using the whole environment with action possibilities.

Remaining questions for the problem space are related to the facilitation of a rich learning environment for beginner climbers. How will an interactive system influence the perception-action coupling? How can feedback given on the climbing poses enhance the athlete’s out-of-action sense-making process? This is also closely related to the next section of bridging the gap between the problem space and solution space.

5.5.2 Solution Space 2

From the activities of this design phase, more input can be integrated in the solution space. The visual *2.5-dimensional* (2.5D) representation of a climbing pose on a simulation of the climbing route resulted was the starting point of the second iteration. The investigation continued in embodied and tangible interaction methods to manipulate a climbing pose. Related work on TEI indicated how valuable the solution direction is for a movement-based purpose. A tangible interaction, compared to a traditional GUI, allows for faster navigation, it increases the perception of “visuo-spatial features” and it can reduce the cognitive load by providing a distributed representation.

The framework of Melcer & Isbister (2021) guided our decision making for an embodied design for a learning environment. Their framework consists of seven dimensions where embodied design decisions can vary. In Table 5.2 are the dimensions visible next to their corresponding values. The yellow cells indicate the design choices that are made for our solution space. It begins with the ‘physicality’ of the embodied interface, where we have considered all five in our ideation (Section 5.2). For our problem space it is important that users can easily (re-)model a climbing pose and visualise it on the external representation. Since in-action climbing poses are situated on the wall and not on the ground, the pose cannot be easily directly embodied by the user on the ground.

Group	Dimension	Values				
Physical Interaction	Physicality	Direct Embodied	Enacted	Manipulated	Surrogate	Augmented
	Transforms	PPt	PDt		DPt	
	Mapping	Discrete	Co-located		Embedded	
	Correspondence	Symbolic	Indexical		Literal	
Social Interaction	Mode of Play	Individual	Collaborative		Competitive	
	Coordination	Other Player(s)	NPC(s)		None	
World	Environment	Physical	Mixed		Virtual	

Table 5.2: Final 'surrogate' concept: An overview of the design decisions made upon the various dimensions of embodied interaction.
The table is based on Figure 7.1 of the design framework for embodied learning of Melcer & Isbister (2021) [11]. The framework is explained in Section 5.1 and the yellow filled cells indicate the design choice made for that dimension.

The 'surrogate' option led to the idea of a posable puppet as a tangible interface. The two main arguments for going forward with 'surrogate' method was: (1) a puppet can represent a 3D pose and therefore more spatial information can be included (e.g. hip distance from the wall) and (2) it is a feasible way for users to freeze a pose and have the time to observe the pose from all angles without having to pose themselves.

From the 'surrogate' embodiment concept, the design concept of 'Trial-and-Mirror' was established with its lo-fi prototype. With the puppet as a surrogate of the climber, the idea emerged of a miniature climbing wall and an extra layer of visual feedback could be projected on the in the simulated miniature environment. However, after testing the T-&-M with participants in co-design 2, observations were done that makes us reconsider certain design decisions. For example, the puppet was 3D printed in the lo-fi prototype which made it appear less "human-like" which distracted users. On top of that, not all climbing poses were possible to be represented in the lo-fi prototype due to the magnetism and flexibility of the puppet. This hinders the users to experience the freedom to perform exploratory movements through the puppetry system. On top of the technical issues of the miniature environment, it was also found that there was still a gap of spatial information between the miniature wall and the actual climbing wall. All in all, this leads us to the decision to project the climbing pose in real-size on the actual climbing wall. So, we keep the puppet interface but let go of the miniature wall which also potentially leads to more immersion of the user in the situated practice of bouldering. This relates to the third dimension of 'mapping' (Table 5.2) where the lo-fi prototype still was 'co-located', we now move forward with 'embedded' mapping. This means that the spatial information will not be scattered anymore. It will be visible in one representation which will probably enhance the enactive climbing of climbers at the end.

Another aspect to address in the solution space and to make a conscious decision about is the social interaction aspect. Bouldering, with its route reading, is eminently suitable for a solution that accommodates collaborative sensemaking. We also showed it during our co-design session and it is described in Chapter 2. However, by making a choice to focus the solution design on the collaborative aspect, it makes the design space more complex. Due to time limitations and our aim to focus on the thesis objective (that target's the individual route reading process), the individual 'mode of play' has been picked out. This does not mean we shut off the possibility that climbers can collaboratively interact with the outcome of the solution space. It also does not mean that we deny the benefits of collaborative sensemaking. It basically means that our aim is to enhance the perception action coupling of an individual climber through a tangible interactive system for out-of-action route reading. The perceptual motor learning will therefore not be depending upon the collaboration with another user.

As described in the problem space (Section 5.5.1), during this design phase the five key challenges of beginner climbers became known. To facilitate a learning environment in which their action perception coupling is enhanced, an extra visual layer as output of an interactive system will be added eventually. From the key challenges that beginner climbers face, it is evaluated that three of them are directly related to the improvement of climbing poses (straight arms, legs apart and hips closer to the wall). By designing visual feedback that can be augmented on top of the in-situ projection on the climbing wall, the goal is to stimulate the exploratory behaviour that contributes to perceptual motor development. Further exploration into the most suitable method of visualising feedback for the users route reading practice is needed. The visual feedback will be an abstraction of the lacking motor feedback (present in-action on the wall) to bridge the gap between the 'lived' experience and 'surrogated' experience.

Chapter

06

Design Phase 3

Visualising Motor Feedback to Enrich Out-of-Action Mental Practice

Empathise

Define

Literature Review

Ideate Design Sketching

Prototype Hi-fi Prototype

Test Final User Test

Chapter 6

Design phase 3: Visualising Motor Feedback to Enrich Out-of-action Mental Practice

This thesis aims to explore the potential of interactive technology to enhance perceptual motor skill acquisition. The principle of perceptual motor skill acquisition from the Embodied Cognition theory gave the idea to bring more elements of the in-action (*'lived'*) experience to the out-of-action experience. Therefore, this design phase is determined towards finding a visual translation of motor feedback, based on the given climbing pose, to implement onto the current design concept of 'Trial-and-Mirror'. Moreover, the search for visual motor feedback that can be displayed out-of-action should relate to the insofar investigated design space. This leads to the following research question that will serve as the guide through this design phase:

> *What visual feedback can be augmented on a 2.5D representation of climbing poses to enhance climbers' route reading on the ground?*

This chapter reports on the third design iteration, following the steps of design thinking. The sections of this chapter, together with their design step, occur with the following structure:

- **Section 6.1 Enriching the Surrogated Embodied Experience | *Empathise & Define***
  Investigating literature and related work on visual feedback augmentation to seek forms that fit the out-of-action sensemaking of spatial information.
- **Section 6.2 Ideation: Complementing the External Representation with Visual Feedback | *Ideate***
  Iterating further upon design opportunities derived from literature and output of the two co-design sessions.
- **Section 6.3 Hi-fi Prototype | *Prototype***
  Elaboration on the process towards a hi-fi prototype of the 'Trial-and-Mirror' with the visual augmented feedback on the climbing pose.
- **Section 6.4 Final User Test | *Test***
  Gathering insights on the user interaction with the hi-fi prototype of 'Trial-and-Mirror', and the impact of the design on the *route reading* practice.
- **Section 6.5 Design Space 3**
  Reframing the problem and solution space with the acquired knowledge from this phase.

Empathise & Define

6.1 Enriching the Surrogated Embodied Experience

Bouldering is not based on repetitive movements of the body removed from the context, but is based on the dynamic body-environment interactions where athletes have to self-regulate to develop their motor plans.

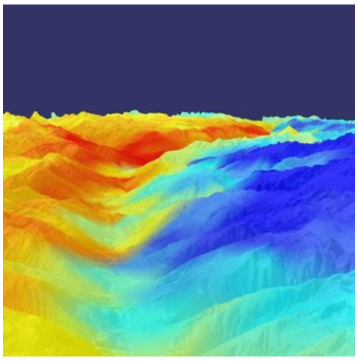

Figure 6.1: Example of 2D texture map as a form of visualising spatial information for depth perception [12].

The identified gap between the direct embodied experience on the wall and the mental practice on the wall has been investigated. Thus far, the interactive puppetry system has been developed to facilitate a learning environment where the puppet serves as the 'surrogate' of the climber. Still, there is a gap between the experience on the wall and on the ground while interacting with the puppetry system. The difference lies in the fact that the out-of-action sensemaking lacks motor feedback. Motor feedback is now received from the actions performed by climbers on the wall and imagined during their mental practice on the ground. To enrich the *route reading* practice on the ground, this section aims to find suitable visualisations of spatial information and motor feedback.

> *"... evolving toward the designer of landscapes that learners (e.g. students and athletes) can interact with, not the conveyors of declarative knowledge about how a problem 'should' be solved. If practice conditions are designed appropriately, learners will actively self-regulate their interactions with a specifically designed practice environment to discover how to best achieve an intended task outcome, based on their current action capabilities. Here, we contend that self-regulation is better understood as an 'active' process, where, through careful task manipulations and informed practice designs, a practitioner works with a learner to guide, direct or nudge (when appropriate) his/her attention toward specific features of his/her environment of use for exploiting actions."*
> [138]

HCI displays often lack the spatial information that is connected to the thing it represents. This can be overcome by visualisations that are intuitive for users to enhance their depth perception. These visualisations are mentioned in literature as 'depth cues' [139]. There are various approaches to enrich 2D presentations with spatial data. One example that is often used in landscape representation is the use of color labels to provide the observer of spatial information. In Figure 6.1 is a texture map visible where the colors of the rainbow are scaled to the depth information of the landscape.

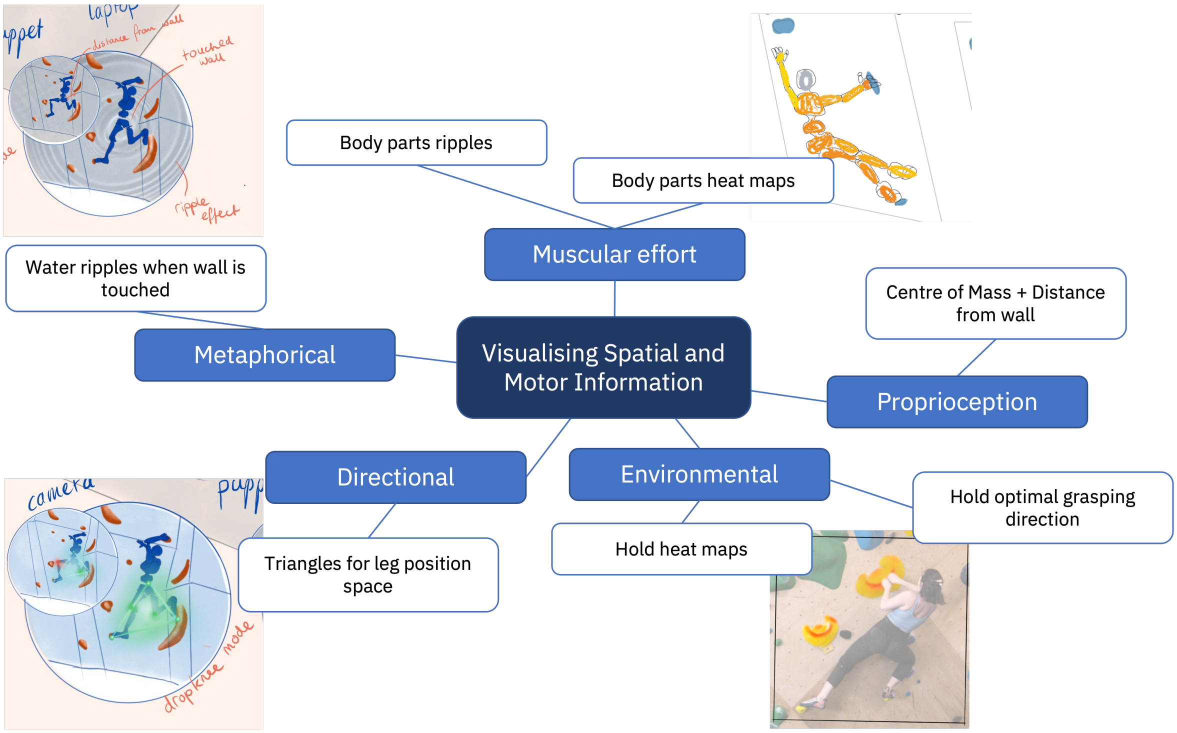

Figure 6.2: Spider diagram of visual feedback design concepts based on five themes: metaphorical, muscular effort, proprioception, environmental and directional

Ideate

6.2 Ideation: Complementing the External Representation with Visual Feedback

From the investigated literature, five themes for visual spatial information design were identified. In Figure 6.2 a spider diagram is visible with the themes ‘muscular effort’, ‘proprioception’, ‘environmental’, ‘directional’ and ‘metaphorical’. During the ideation concepts were created for each type of visual feedback.

In Figure 6.3 is the ideation for the concept ‘triangles for leg position space’ further explored in detail.

Since our design space specifically investigates solutions for beginner climbers, the visual feedback should be accessible an straightforward for a big range of people. We think that the concept of body parts heat maps is the most suitable concept because the common challenges for climbers has mostly to do with muscular effort and motor feedback. They struggle to identify which climbing pose is ‘effective’ to preserve energy.

The concept of “body parts in heat maps” can be a promising visual translation of motor feedback. Since meaning-making emerges in interaction with the world, and in relation to former engagements [140], we can predict that most people have stored the meaning of color-scaling as a medium of spatial information before. Doing so with the colors of red and green would most probably also be recognised by people being “undesired” and “desirable”.

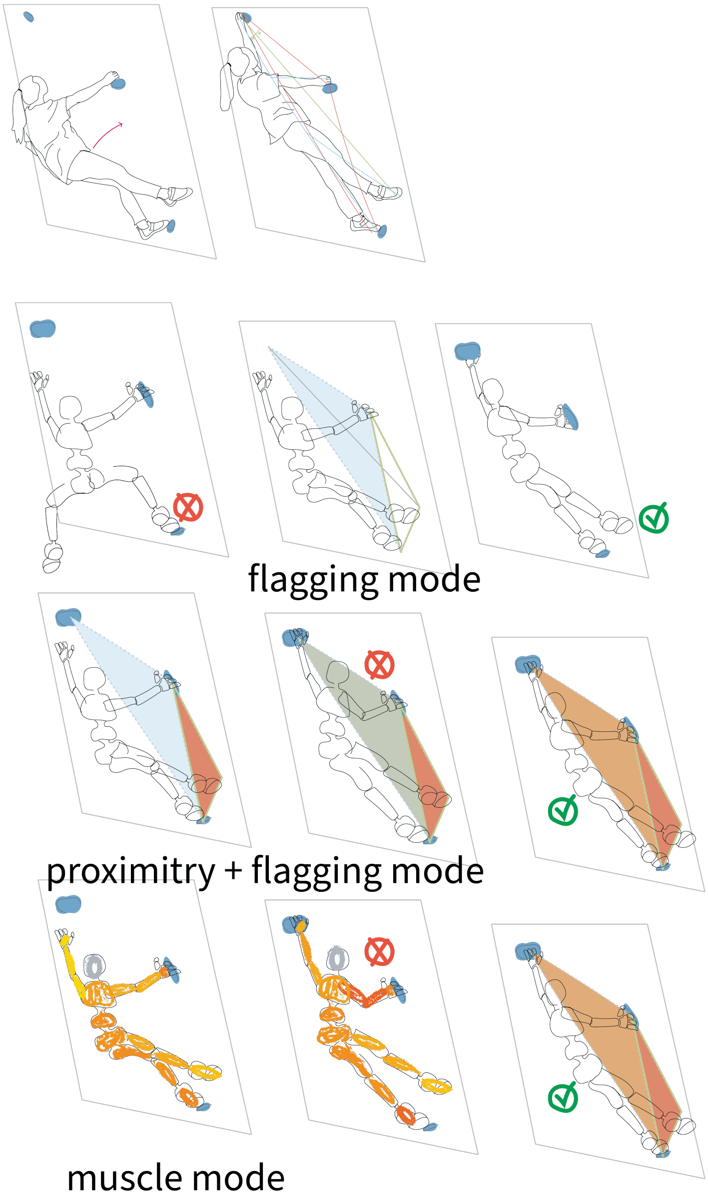

Figure 6.3: Ideation sketches of visual augmented motor feedback to stimulate user's tinkering towards climbing poses with the hips close to the wall

Prototype

6.3 Hi-fi Prototype

The most recent concept of 'Trial-and-Mirror' is transformed into a hi-fi prototype which can be used to test the overall design concept as well as the design space and to develop it further. In contrast to the lo-fi prototype, the hi-fi prototype was focused on the digital domain. From the ideation described in Section 6.2, a conclusion was formed upon which visual feedback on the sensed climbing pose (of the puppet interface) would be most suitable to enhance the *route reading* activity of beginner climbers.

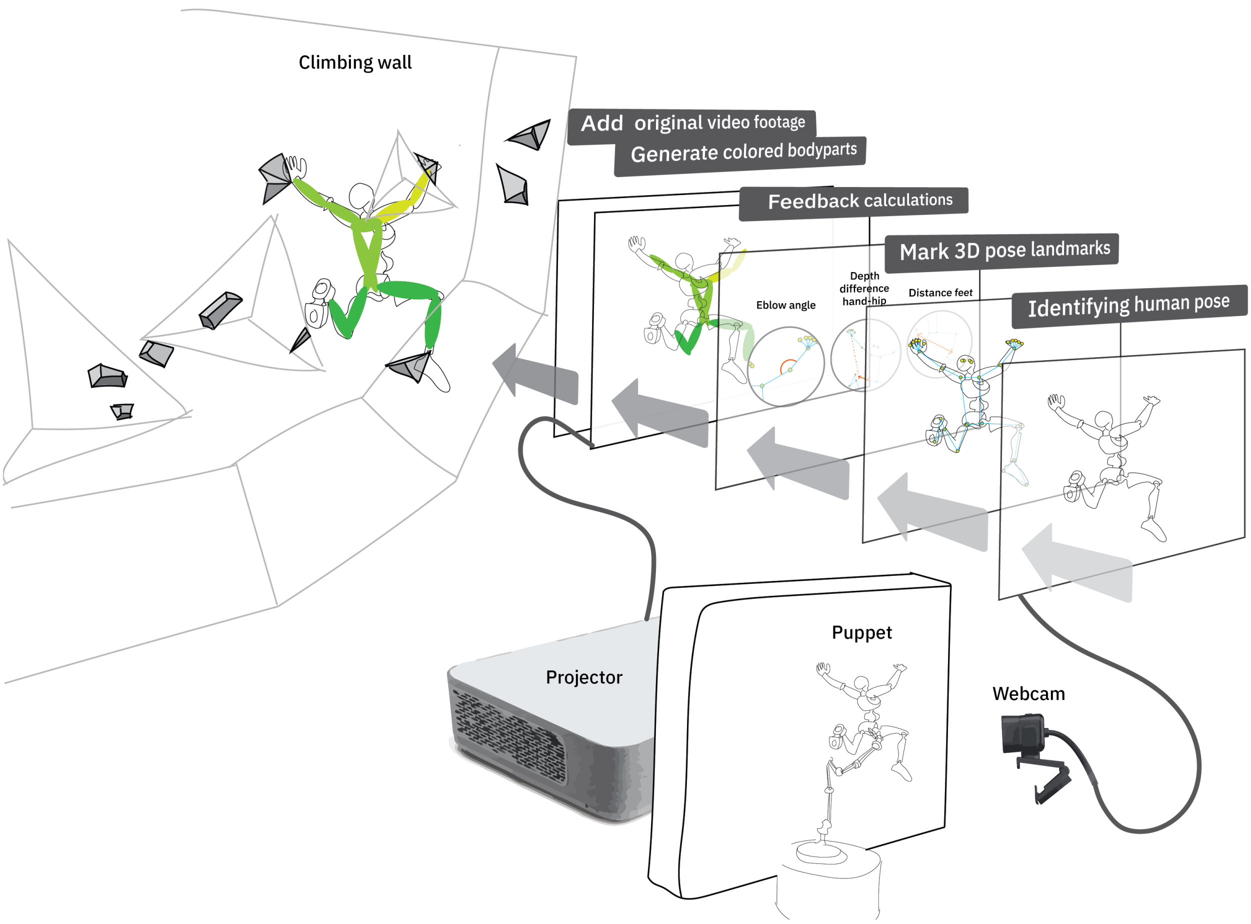

Figure 6.4: Figurative overview of the final Trial-and-Mirror system in the hi-fi prototype. It starts by video footage of the webcam that captures the puppet in a climbing pose invented by the user. The video footage is projected onto the climbing wall (where the user chooses to perform *route reading* on) with the puppet being the size of the users' body. On top of the puppet's footage, the puppet's pose is transformed into visual feedback that is real-time displayed on top of the puppet's image. This is generated by the following steps: (1) The puppet is recognized as a human pose, (2) 3D pose landmarks are placed on 33 placed on the puppet's body and each landmark holds a x, y and z value, (3) The three types of feedback values are calculated: the elbow angles, depth difference between the hand and hip and the distance between the feet, (4) The feedback values are transformed into RGB values and used to generate colored bodyparts (arms, legs and trunk), (5) the original video footage is merged with the colored feedback bodyparts and send to the projector.

The user interface of the hi-fi prototype consists out of the (Stickybones) puppet on a rig with a white background foam board. In front of the puppet stand a tripod with a camera that captures the puppet from the back. The image serves as an input for the system to detect the climbing pose. Through pose estimation, 33 pose landmarks can be detected on the puppet's body. Each landmark contains the position value over the x-, y- and z-axis in relation to the position of the camera. The landmark data is used to calculate three types of values; (1) the elbow angles, (2) the depth difference between the hands and hip center and (3) the distance between feet. The values are translated to a RGB code on the color scale from red to green. Figure 6.5 summarises the feedback given to the user based on the color scale. Thereafter, the color code is used to generate ellipses on top of the corresponding bodypart. For example, the left elbow angle is seen through the color of the ellipse on the left arm. The output of the computer system is the camera capture augmented with the visual feedback on top of the puppet. An overview of the system design is illustrated in Figure 6.4.

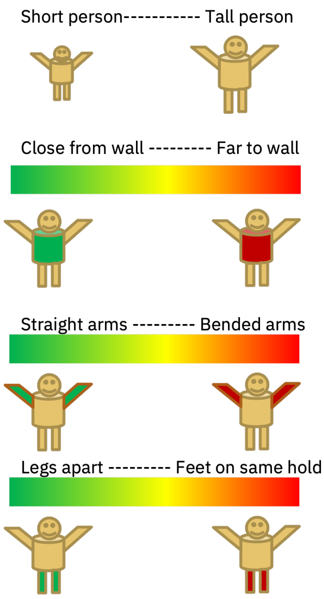

Figure 6.5: Overview of motor feedback implemented in the Hi-fi prototype.

The graphical interface that is produced by the computer is send to a projector that projects the image in-situ on the climbing wall with the chosen route. The frame of the GUI can be moved around the climbing wall so that the puppet is situated in the place of the route where the user chose to 'route read' upon. The size of the image is based on the user's body measurements. At the start of the session, the system needs to be calibrated to the user's height. This way users can perceive themselves in the situation on the wall and receive an answer on the question: "Do I fit there?".

6.3.1 Puppet

Figure 6.6: The stickybones posable puppet with rig.

The puppet is ordered from the company Stickybones and an additional rig was purchased with it as well. In Figure 6.6 the puppet and rig are presented. The target group, where Stickybones puppets are created for, are professional and amateur artists to facilitate their illustration and animation of human figures. Through the flexable joint system, the puppets can be easily manipulated into poses that correspond to the range of motion of humans. The body parts are abstract but are based on the form of human body parts and therefore recognisable as a 'human figure'. The puppet can be placed in the rig for more balance and poses that are situated in air. All in all, the Stickybones products are considered to suit the solution design of 'Trial-and-Mirror'. After receiving the products, the pose estimation program of Mediapipe was tested for puppet pose estimation. Although the accuracy was less than with a real human-being, it was decided to be accurate enough to continue with.

Figure 6.7: Output T-&-M hi-fi prototype: visual feedback augmented on climbing pose.

Figure 6.8: Output T-&-M hi-fi prototype: visual feedback augmented on *flag* pose.

Figure 6.9: Output T-&-M hi-fi prototype: visual feedback augmented on *drop knee* pose.

Test

6.4 Final User Test

The final step of the design process is to examine the final design concept of 'Trial-and-Mirror'. The hi-fi prototype of the system can be used to carry out an user study in the situated practice of bouldering. The observations of users interacting with the prototype enables the evaluation of how the system affects the *route reading* practice.

6.4.1 Aim of the Session

The objective of this session was in two-fold; (1) Examine the user experience and (exploratory) behaviour from the hi-fi prototype interactions (2) Assessing how the 'Trial-and-Mirror' affect the *route reading* of bouldering practice. The user test aims to give an answer to the question: **How does the hi-fi prototype of 'Trial-and-Mirror' affect the *route reading* practice and climbers' sensemaking process?**

It is good to note that one could distinguish ser performance and climbing performance, they are separate things but one relates to the other. For example when the user cannot figure out how to position the avatar into a certain position or they are not find a specific functionality of the system, they can be hindered during the *route reading* process which can affect the execution phase and thereby the climbing performance.

6.4.2 Method

The final user test was performed in the local bouldergym with the hi-fi prototype set-up. Two groups of two participants each were attending the session; a group of experienced and inexperienced climbers. They were recruited and informed about the objective of the session. On the day itself, all four of them signed a consent form which stated that they gave permission to be recorded.

The recordings (video & photo) were taken by the assistant of the design-researcher. This enables the design-researcher to be fully engaged in the session. There were written notes taken after the session to support the recordings with extra observations noticed by the design-researcher.

An overview of the study's set-up is visible in Figure 6.10. At the front of the photographed scenario are two participants; one is looking at the climbing wall and the other is manipulating the puppet. Before the puppet is a webcam on a tripod directed to the puppet and behind the puppet is a white foam board to facilitate a white background of the image. The puppet itself stands on the green rig so that every climbing pose can be represented. The image retrieved from the webcam goes to the computer where the script is running (more in Section 6.3). The design-researcher is standing behind the computer to operate actions of the hi-fi prototype. The output of the system (puppet image + feedback) is displayed in-situ on the climbing wall by a projector. At the start of the session the participants were asked to stand next to the wall to make the puppet appear in their body measurements.

The activities in the session are split up in three parts; (1) Interacting with the hi-fi prototype without visual feedback, (2) Interacting with the hi-fi prototype with visual feedback and (3) Discussing the experiences of both. What is meant with "without visual feedback" is that the output of the system (projected on the wall) is just the captured webcam footage of the puppet's pose (Figure 6.11. Since the participants will interact with both scenarios, with and without the feedback, we can evaluated the individual contribution of the visual feedback on the climber's route reading practice.

The steps taken during the session are listed here:

Figure 6.10: Picture of the final user test set-up in the bouldergym.

Figure 6.11: Picture of the puppet projected without feedback on the climbing wall.

Step 1: Introduction bouldering, route reading and the mechanism of the hi-fi prototype.

Step 2: Participants start their first attempt on the wall of their chosen route.

Step 3: Participants are asked to try to mirror the movements of their attempt with the puppet.

Step 4: Participants interact with prototype on the ground.

Step 5: Participants execute their invented poses on the wall.

Step 6: Step 4 & 5 repeat until they have finished or when they show signs of exhaustion.

Step 7: Introduction of visual feedback system.

Step 8: Participants are asked to figure out what the visual feedback means by playing with the prototype.

Step 9: Participants are asked to improve their 'beta' with the prototype by taking the visual feedback into account.

Step 10: Participants execute their invented poses on the wall.

Step 11: Step 9 & 10 repeat until they have finished or when they show signs of exhaustion.

Step 12: Discuss the experiences together with the design-researcher.

6.4.3 Results & Discussion

In this section the observations from the final user test will be analysed. The highlights of the observational notes, that were taken right after the session by the design-researcher, are listed in Table 6.1.

First of all, the aim was to test whether the hi-fi prototype would be inviting to interact with. From the moment that the participants entered the bouldergym and saw the prototype, they wanted to interact with it right away. This indicates that the hi-fi prototype is inviting as well as intuitive to use. Without having to explain in depth how the puppet can be manipulated, users felt motivated to figure out the device themselves. Another observations was the immediate recognition from users that the puppet would be their 'surrogate' to try out movements.

A finding that contributes to our understanding of beginner climbers' challenges was retrieved. The participants that had almost no experience with bouldering showed that they needed time to grasp the concept of *route reading* before they felt truly motivated to utilise the T-&-M. Once they figured out that *route reading* on the ground helps them to execute the climbing movements on the wall, they understood the added value of the device. This was amplified when the T-&-M augmented visual feedback on top of their invented climbing poses. It was remarkable to see that experienced and beginner climbers gave the visual feedback the meaning that corresponds to 'physical effort' and the 'feeling on the wall'. Although the visual feedback is generated from spatial information, it was fascinating to observe the 'functional' features that users could identify.

6.4.4 Conclusion

If we take the overall impact of the T-&-M, we observed that it fitted well into the situated practice of route reading. The direct impact lies in the ability to distribute the sensemaking process over the external representation and the users' mind. By having an artifact that can represent their ideas, tinker upon them and perceive new action possibilities, the route reading on the ground does not

Figure 6.12: Participants interact with puppet interface during route reading on the ground. The system presents visual feedback to the participants; red on the legs, orange on the trunk, orange on the left arm and green on the right arm.

Figure 6.13: A participants re-enacts the invented climbing pose on the wall. The system present visual feedback to the participant where all body parts are green.

Quotes & Observations
The experienced climbers sat right away behind the puppet to try things out, they almost did not need explanation of the goal and mechanisms of the T-&-M. It took a while for the inexperienced climbers to grasp the concept of route reading and the purpose of T-&-M.
Participants sometimes struggled to pose the puppet in the climbing pose that corresponded to their imagined one.
After two participants discussed first a new climbing strategy, one said: “Oh, I would like to try that with the puppet”.
“Now that I know this, I would like to try it again”, said a participant when realising that he would need less arm strength when keeping his arms straight.
“Finally, I can see if I would fit there!”, said an experienced climber.
All participants still made use of their hands and body to add explanation to the climbing pose and by imagining the pose before going on the wall.
One of the inexperienced participants felt bad towards the researcher that she could not finish the route.
“Aaha! Now I understand what I did wrong the whole time!”, said an ‘inexperienced’ participant when grasping the meaning of the visual feedback.
The participants were very motivated to try the movements on the wall that they had invented on the ground through the t-&-m.
Participants relied on their peer to recall their performed movements on the wall once they were on the ground.
When the system was not working properly (e.g., the rig was detected as a leg), it seemed to disturb the participants’ route reading process.

Table 6.1: List of observational notes taken from final user test

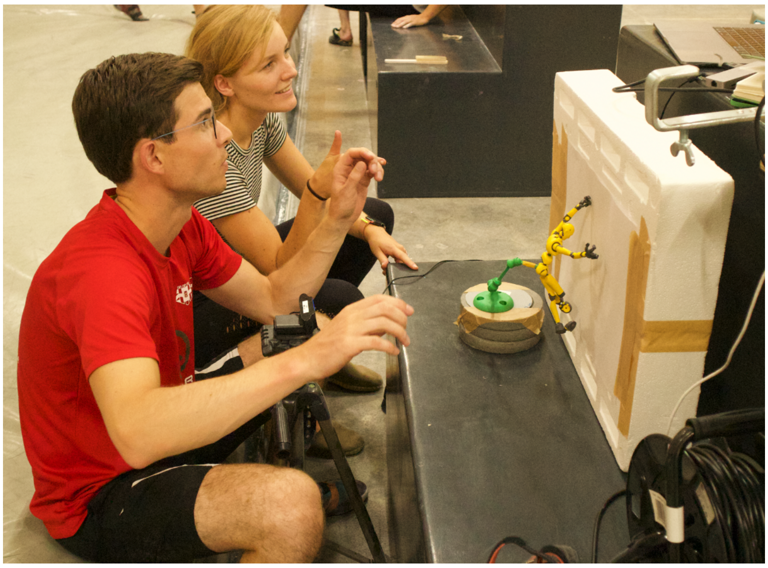

Figure 6.14: A participant imagines the invented move through ‘marking’.

entirely rely on their own motor imagery skills. However, the T-&-M does not cover the whole route reading process on the ground and the user still has to perform mental practice.

The T-&-M system also demonstrated its indirect impact on the overall route reading process with its influence on the users’ behaviour on the wall. The observational findings suggest that the T-&-M, in its current state of prototyping, can stimulate the users’ exploratory behaviour. Users are more likely to explore and try out movements through the puppetry system because of its inviting and intuitive interaction. Moreover, the visual feedback gives users a new perspective on the case (finding their *beta* for their route). Climbers are triggered by visual feedback, on their invented pose when it tells them that certain parts can be improved (red/orange body parts), to perform exploratory movements with the puppet to investigate and invent new poses. Furthermore, once they discovered a new pose, movement or strategy (e.g., finding out straight arms are more efficient) users felt very motivated to re-enact it on the wall in-action.

Due to the variation in climbing experience of the participants, the T-&-M interaction could be investigated by both groups to study the differences. An important finding is that inexperienced climbers first need time to grasp the concept of route reading and bouldering itself. The concept of route reading, and the cognitive task of tinkering upon movements, is something that requires comprehension.

We also implemented variation in the study to split the session up into interaction with the T-&-M **with visual feedback** on the puppet’s pose and **without visual feedback**. We could conclude from our observations that both user groups (inexperienced and experienced) benefit from the additional feedback. The extra dimension motivated them to think further upon their climbing poses and find alternative solutions (when necessary). Especially the inexperienced climbers were helped with grasping the principles of bouldering techniques (e.g., straight arms > less effort).

6.5 Design Space 3

The insights obtained during this design phase serves as input for the design space. This section aims to emphasis what findings contribute to our understanding of the problem and solution space. The outcome of this design space leads to an answer to our research question and contributes to HCI and other research domains.

6.5.1 Problem Space 3

The problem space can be mainly reframed through the outcome of the final user test. The observations of user behaviour and interactions provides the problem space with more insights into (1) the *route reading* process in general, (2) the development of the perceptual motor skill and embodied cognition for bouldering, (3) the influence of an interactive system on this development, and (4) the effect of visual motor feedback on the out-of-action sensemaking process.

The chosen target group for the 'Trial-and-Mirror' is beginner climbers. In order to study the effects of implementing the T-&-M during the beginner climbers' *route reading* activity, a comparison with experienced climbers was desired. Therefore, the participants in the final user test were both experienced and inexperienced climbers. Since *route reading* is situated on the wall (in-action) and on the ground (out-of-action), the study analysed the whole scenario to examine the effects of the T-&-M. The interactive puppetry system was used on the ground but it influences the whole *route reading* process (read more in Solution Space 3).

In addition to the known difference between experienced and inexperienced climbers, we found that beginners need time to grasp the concept of *route reading*. In more words, beginner climbers need time for the meaning-making process of *route reading* as a practice since they are unfamiliar to it. During the final user test, the first step was to explain the the practice of bouldering and *route reading*. And although they seem to understand the concepts, they still needed to experience it to get the 'bodily knowing'. Over the course of the study, when users interacted with the T-&-M, beginner climbers behaved more and more like they understood the *route reading* and the meaning behind it. This suggests that an interactive system, such as the T-&-M, can enhance the sensemaking process of the situated practice to obtain the *situated cognition* (illustrated in Figure 2.7). The requirement of comprehension of the situated practice translates to the effectiveness of the usage of an interactive system. The hypothesis is that this problem can be overcome by giving participants time for scaffolding before the actual user testing starts.

Previously, the differences between experienced and inexperienced climbers were already mentioned in the design space. From the outcome of the final user test it became even more apparent how different the *route reading* challenges are between the groups. As other studies have also shown [**?**] [**?**], inexperienced climbers struggle to perceive affordances beyond the 'structural' properties of the climbing route. In addition to that, we found that beginner climbers also struggle with trust, shame and confidence in their abilities. Between climbing a bouldering route and their embodied cognition, for example climbing a ladder, rests a big gap of unfamiliarity with the affordances. This not only influence the affordance perception in the technical sense, but also the emotional experience of trusting that the perceived affordance is feasible. Even when a peer climbers suggested a climbing pose, and even performed it on the wall to prove the feasibility, the receiver of the advice still doubted their own abilities. This problem could be further investigated in future research.

6.5.2 Solution Space 3

From the activities held in this design phase, more insights were obtained that affects the solution space. An exploration was performed towards suitable visual motor feedback to augment the developed climbing poses of users with additional information. The aim of the extra layer, on top of the in-situ projection on the wall, is to enhance the perception-action coupling and thereby enhance the shift of identifying 'structural' affordances to 'functional' affordances. From the 'lived' experiences on the wall, climbers obtain direct motor feedback from their actions in relation to the environment. However, on the ground this information lacks during *route reading* and the effectiveness of the sensemaking depends on the motor imagery skill of the performer. To bridge this gap, visual feedback can serve as a substitute for the motor feedback ('felt' on the wall) during out-of-action *route reading*.

It was previously determined to equip climbers with distributed representation to aid their *route reading* on the ground. The 'Trial-and-Mirror' concept let users manipulate a tangible posable puppet (as a 'surrogate') into climbing poses and project the puppet on its envisioned position in the route on the wall. During the final user test, this concepts already proved its benefits to the *route reading* process of climbers. The puppet from the lo-fi prototype was exchanged by a more professional one (from Stickybones) in the hi-fi prototype. This improved the usability, intuitiveness and enticement of the user interface which enhanced the overall user experience. Next to that, the puppet was perceived more "human-like" which helps the user immersion by truly utilising the puppet as a 'surrogate' of themselves. On the other hand, the goal of having the puppet represent realistic climbing poses is not totally achieved. There is still a gap between what poses the puppet can perform and what climbers can do. However, during the final user test this was not bothering the users during their *route reading* process. It seemed that they bridged the gap themselves by mental imagery. This implies that the pose representation in the hi-fi prototype was sufficient for users to perform *route reading* activities with.

The in-situ projection of climbing poses facilitates the *route reading* process in the basic sense by giving an answer to the question "Do I fit there?". During the final user test, the basic variant of the T-&-M showed to enhance affordance perception, creative thinking and exploratory behaviour. When comparing the 'basic' T-&-M system (without visual feedback) with the 'augmented' system (with visual feedback), the outcome is that the visual feedback boosts the enhancement of the perception-action coupling even more. The biggest difference was observed by beginner climbers. The reason could be that experienced climbers have their *route reading* skill more developed and can built on top of many 'lived' experienced from the wall. Furthermore, the visual feedback was designed for the main challenges of pose evaluation for beginners. Climbing poses require less effort when performing straight arms, feet apart from each other and hips as close to the wall as possible. This placed one's centre of gravity closer to the wall and ultimately results in needing less muscular activity. The inexperienced climbers (from our user test) showed exploratory behaviour during their T-&-M interaction with the visual feedback. It was intuitive to them what the meaning is behind the color-grading body parts and they translated this into inventing more efficient climbing poses. They were also very motivated, after finding out what works and what does not work, to execute the invented poses on the wall.

Chapter

07

Discussion

Discussion

Conclusion

Chapter 7

Discussion

This final chapter discusses the outcome of the study, including all the elements that contributed to answering the main research question. The research question posed at the beginning of this thesis was: **How to design a tangible interactive system to enhance out-of-action perception action coupling for bouldering practice?** The final answer to this question will be given in the conclusion.

The sections prior to the conclusion first discuss the research outcome and the iterative methodology that was used. The 'Trial-and-Mirror' as a concept will be evaluated as a design concept itself, but also how it embodies the knowledge from the design space. The implications of the user test results will be critically examined to analyse what interaction and experience the Trial-and-Mirror-system provokes.

The chapter continues with a section about the strengths and limitations of this research project. Followed by, recommendations for future work retrieved from the developed understanding of the design space and methodology.

7.1 Research Outcome

We would argue that there are three kinds of research outcomes from this thesis. The first being the developed design space containing knowledge related to the thesis objective. Achieving this through an iterative Research-through-Design process is another form of research outcome. The research activities held were specifically designed to evoke the outcome of information that could then be embedded in the design space. Above that, the designed material (either from co-design session, prototyping or other steps in the process) can be seen as physical manifestations of the knowledge coming from the situated practice (e.g. the athletes' *embodied knowing*) or the understanding within the design space present at the time of composing.

7.1.1 Incrementally Enriching the Design Space

From the initial design space, constructed after preliminary research with literature, the design space has been further developed and enriched with all kinds of knowledge. At the start of the development of the design space, the understanding was still based on related work, theories and assumptions of situated practice. Later on, information was validated, rejected and enriched through the involvement of climbers with the activities held within the situated practice of bouldering. By consciously utilising design in research activities, we could emphasise with and define the topic, ideate solution directions (connected to the topic) and ultimately prototype and test them in the

Figure 7.1: Overview with pieces of knowledge and understanding retrieved in every iteration of the Design Space.

situated practice. This led to receiving richer and more diverse information than traditional methodologies.

Another advantage of incrementally developing the design space, is having the possibility to base the decisions on what research actions to take in every design iteration and on the identified need or gap present in the design space at that particular time. For example, after design phase 1, we established an understanding of what visual representation to provide to climbers when they perform out-of-action route reading. However, it was still unknown what interaction with external representation would be suitable for them to perform exploratory behaviour and how the interaction can facilitate the sensemaking process. This gap led to the activities held in design phase 2 such as: reading upon literature about tangible and embodied sensemaking and creating a lo-fi puppet-wall system.

To summarise the most important pieces of understanding in the design space at the four moments throughout the process, an overview is created in Figure 7.1. It is noticeable that through out the research the design space was more supplied with knowledge about the solution space where as at the start obtained knowledge related more to the problem space. Of course, this has to do with the fact that the solution space is dependent on the understanding of the problem space. There is certain level of understanding required about the situated practice needed before fruitful solutions can be thought of. Additionally, the designed systems became more advanced over time which facilitated the investigation of the solution space with more depth.

By reflecting upon the final state of the design space, we can argue that certain parts of the design space are still ideas, concepts or theories. For example, recognising that the 'guidance effect' can be a pitfall when introducing an interactive technology in the perceptual motor learning process . This theoretical understanding could not yet be tested because the effects of the T-&-M system was tested in a single training session instead of a series of training sessions. This encourages us to critically review the design space that we have established so far.

Due to limited time and resources, many areas were left open to explore. At the beginning, we quickly focused on the visual space. The choice towards the visual space came from the observation that in the current situated practice of bouldering, climbers visually inspect the wall when preparing for the ascend. However, many other senses could enhance an out-of-action route reading act such as through auditory or vibro-tactile feedback. In addition, the 'surrogate' embodied interaction was chosen based on the hypothesis that it was intuitive and inviting to interact with. Although this hypothesis was validated after co-design 2, there were many other fruitful embodied interactions for the design space. Therefore, a recommendation for future research would be to explore the wide variety of embodiments for pose manipulation. Next to this design space, many other areas (e.g. game development) would benefit for more understanding about the effectiveness, user immersion and other aspects.

7.1.2 Movement-based & Participatory Activities

The overall study went through three design phases using the steps of Design Thinking. The activities held in those steps related also the the framework of Loke & Robertson [107]. We specifically designed the activities to gain understanding from all seven "key activities" (Figure 3.4) with the perspectives from the 'Mover', the 'Observer' and the 'Machine'.

The first phase focused on the visual representation of climbing movement based on the the fourth and fifth 'perspective activity' (Figure 3.4). A group of six experienced climbers participated in the co-design session 'Sketch It Out!'. They had to investigate their assigned route in duos and choreograph a *beta* that is executable for the other duo's. They were then told to make a manual for this *beta* using colored pencils and paper. Afterwards, the duos had to re-enact each others' *beta* manual. From switching between the first-person perspective (on the wall) and the second-person perspective (on the ground), and by having to transform those experiences into visual and verbal expressions, a deeper understanding from the *embodied cognition* of expert climbers was obtained.

The *beta* manuals were discussed at the end of the co-design session and also analysed in more detail by the researcher. This gave input for the ideation step to explore options for an external representation of a *beta* for skill acquisition. Ultimately, this lead to the chosen solution direction of *2.5-dimensional* representation of climbing poses.

With the solution space directed towards the distributed (2.5D) representation of a climbing pose, the second design phase addressed the need for an intuitive user interaction. Studies on tangible and embodied interaction design were investigated. This resulted into design opportunities that were further explored in the ideation step. The idea of digital puppetry was born and lead to the development of the 'Trial-and-Mirror' with its lo-fi prototype. The concept was tested in the second co-design where participants could manipulate a puppet on a magnetic miniature wall. The material and setting facilitated the collaborative exploration of the mapping between the 'real' environment and human poses and the representation by the prototype. Furthermore, the projector with drawing tables facilitated a brainstorm on the visual output and feedback that the machine could produce to enhance the affordance perception.

The designed concept of moving a puppet on miniature wall as a 'surrogate' for climbers, served as the base to bridge the gap between the in-action and out-of-action experience. The third design phase dived deeper into the lack of direct motor feedback and how to overcome it through visual feedback produced by the computer. During the ideation, we identified the three most important feedback pillars for beginner climbers: guiding them to climb while keeping their arms straight, stay with the hips close to the wall and keep feet apart. Visual feedback, in the form of a color, was given on the hips, arms and legs. The color was altered to the puppets position and varied between green, yellow and red to guide the user towards a more preferable position. The concept was implemented in a hi-fi prototype through developing a computer vision script.

Taking the perspective of the 'machine' in all three design iterations on various levels, facilitated the translation between the 'human' situated practice to the digital space. In order to design an interaction that would be of use in the situated practice this translation goes both ways. Since it was also necessary for the users to interpret the output the machine. Furthermore, the activities held throughout the thesis forced the participants and researcher to abstract/visualise/make tangible a 'lived' and 'imagined' experience. This led to a deeper understanding of those experiences themselves.

7.1.3 Design Outcome

The aim of all that was designed was to investigate and develop the design space. By making pieces of knowledge tangible and/or visual by prototyping within a co-design session (e.g. through making *beta* manuals in Co-design 1) enabled the possibility of quickly receiving more practice-based knowledge and validation. Additionally, the main design outcome of the concept of Trial-and-Mirror (through its physical manifestation of the lo-fi and hi-fi prototype) is another outcome of this thesis.

The 'Trial-and-Mirror' (T-&-M) system was evaluated in its lo-fi and hi-fi form. The main improvements that were made from the lo-fi prototype were: changing to a easier posable and more "human-like" puppet and by projecting the puppet's pose plus visual feedback in-situ on the actual climbing wall.

The current version of the T-&-M was evaluated by observations made during user interactions with a group of experienced and inexperienced climbers. The interactive system demonstrated its indirect impact on the overall route reading process with its influence on the users' behaviour on the wall. The observational findings suggest that the T-&-M, in its current state of prototyping, can stimulate the users' exploratory behaviour. Users are more likely to explore and try out movements through the puppetry system because of its inviting and intuitive interaction. Moreover, the visual feedback gives users a new perspective on the case (finding their *beta* for their route). Climbers are triggered by visual feedback, on their invented pose when it tells them that certain parts can be improved (red/orange body parts), to perform exploratory movements with the puppet to investigate and invent new poses. Furthermore, once they discovered a new pose, movement or strategy (e.g., finding out straight arms are more efficient) users felt very motivated to re-enact it on the wall in-action.

Due to the variation in climbing experience of the participants, the T-&-M interaction could be investigated by both groups to study the differences. An important finding is that inexperienced climbers first need time to grasp the concept of route reading and bouldering itself. The concept of route reading, and the cognitive task of tinkering upon movements, is something that requires comprehension.

We also implemented variation in the study to split the session up into interaction with the T-&-M *with visual feedback* on the puppet's pose and *without visual feedback*. We could conclude from our observations that both user groups (inexperienced and experienced) benefit from the additional feedback. The extra dimension motivated them to think further upon their climbing poses and find alternative solutions (when necessary). Especially the inexperienced climbers were helped with grasping the principles of bouldering techniques (e.g., straight arms > less effort).

Although the designed augmented feedback in the T–M informed climbers about the context and supplemented the visual perception of the climbing pose with a visual form of motor feedback; it was still lacking a 'lived' experience. Technically speaking, the augmented feedback only reached the visual sense. However, people were able to translate and (motor) imagine this part. Beyond their ability to translate the visual feedback to its meaning related to motor and spatial information, participants also expressed that the visual feedback made them "feel" what would happen on the wall.

Although the meaning of the augmented feedback can be interpreted in the intended way, it could be that users struggle to perceive the meaning on the first encounter. The beautiful thing is that the augmented feedback can be explored through active engagement of the user due to its interactive characteristic. Users could manipulate the puppet in various ways to perceive the changing colors on the body parts and over time make couplings between the person's action (puppet's pose) and meaning (motor feedback).

7.1.4 Bridging the Gap between Wall and Ground

The advantages from the 'lived' experience on the wall were described in in Table 2.1. This resulted in the design challenge of enriching the on the ground situation with a form of immediate motor feedback and enhancement of kineasthetic awareness. The underlying intention of bridging the gap stems from the thesis objective to stimulate climbers' perception-action coupling. From our investigation we know that spatial information together with the proprioceptive sense contribute to the affordance perception and validation of invented movements.

By offering climbers a distributed representation of their invented climbing poses from their mind to the outside world, part of the cognitive load is presumably reduced. Once the invented pose is represented in the puppet, immediate visual feedback can be given by the Trial-and-Mirror system.

The visual feedback was perceived by users during the final test as feedback on their pose in terms of difficulty in execution, required strength and feasibility. One participant mentioned that "when seeing the arms of the puppet turn red, I can feel the pain myself". This implies that climbers experience receiving the feedback on top of the puppet as something 'bodily'. Furthermore, it suggests that climbers identify themselves with the puppet and can thereby test and evaluate their invented poses through the puppetry system.

Of course, the goal of bridging the gap was never to fully substitute the in-action experience since we acknowledge the value of direct embodied interaction with the environment in the perceptual motor coupling. Nonetheless, we suggest that an enhanced out-of-action experience (through the 'machine') can contribute with a new type of 'lived' experience to goes beyond the motor imagery. It would thereby fit into the situated embodied sensemaking illustrated in Figure 2.12.

7.2 General Strengths & Limitations of the Project

This study is larger than an average graduation project due to the combination of two master studies into one big thesis. Therefore, more time could be invested in the research which contributes to outcome of the study and the opportunity to involve a wide range of design and research aspects. In more words, often a thesis objective has to focus on one aspect of design or research, such as prototyping or user testing. This study went through all the steps and through several iterations. This resulted in the outcome of thesis being less limited by time than it would have otherwise. Despite this, the graduation period is still limited and therefore restricting the objective to be researched to its full extent.

Next to that, the amount of users that participated in the co-design sessions and user test are bound to the regulations of the local bouldergym, recruitment process and resources. Although rich qualitative results were obtained, we are unable to generalise it to the general population. This is also partly caused by the chosen methodology where the focus lies on the quality instead of quantity of user involvement.

A major strength of the study, again has to do with the double master thesis, is the fact that the design-researcher has the knowledge from interaction technology as well as the design practice. For example, this technological skill set facilitated the participatory design methods with interactive movement-based material. At the same time, the design concept is based on a deeper understanding of its users and situated practice through utilising participatory design methodology and applying the embodied cognitive perspective. Next to the strength, the study is still a one-man show in the sense that one design-researcher has executed it (of course with supervision and guidance). This results in an inevitable bias on the case and limitations on what the design-researcher could accomplish within her abilities.

7.3 Conclusion

This study investigated the design space in the intersection of bouldering, perceptual motor learning and sports-HCI. The design space was further explored through three design iterations, including literature research, co-designing, self-reporting, conceptualisation, prototyping and testing. A deeper understanding of *route reading*, its cognitive processes, *situated practice* and other aspects compliment existing literature on the matters. On top of that, this thesis contributes by demonstrating how movement-based interaction design methods and user participation can support design-research.

The thesis objective of designing a tangible interactive system for out-of-action route reading is established through researching the activity of route reading through (participatory) design activities with tangible design material (prototypes and probes) in the situated practice. Through perceiving design as a facilitation tool to research and to obtain a deeper understanding within the design space we (1) helped to decide upon research activities that effectively could enrich the current understanding of the design space and (2) develop physical and visual manifestations of the present knowledge in the design space with the purpose of understanding, reflecting and validating that knowledge.

In this thesis, this lead to the design of Trial-and-Mirror with its lo-fi and hi-fi prototype. The interactive system consists out of a puppet interface which the user can manipulate into climbing poses. This 'surrogate' embodied interaction facilitates users the perform exploratory behaviour (movements) on a distributed representation. The puppet's pose will be displayed real-time with the body measurements of the user on the climbing route in front of them. This image will be augmented with visual feedback in the form of colored body parts (arms, legs and trunk) that represent the (otherwise lacking) motor feedback.

Initial test results imply that exploratory behaviour is provoked by the Trial-and-Mirror interaction. Climbers seemingly perceive new action possibilities and more 'functional' affordances with the system than they would have without technology. The additional visual feedback layer brings the 'lived' experience (on the wall) and the 'imagined' experience (on the ground) even closer to each other. Therefore, we would argue that a novel embodied interaction concept is established with the visually-enriched 'surrogate' experience. In order for us to answer the part of the research question about enhancing perception-action coupling, more research is needed. However, the research outcome of this thesis is promising since the initial results on the enhancement of exploratory behaviour and affordance perception are positive and these are indicators for perception-action coupling on the long run.

7.4 Closing Thoughts: Never Oversimplify the Situatedness

Regardless of whether the interactive system will increase athlete's performance, development or other objectives, it is naive to think that technology can solve it all. From this study we can only imply that our interactive design benefits the route reading in the sense that climbers perceived new action possibilities on the ground and felt motivated to try them on the wall afterwards. Through the help of technology, the climbers can receive a new perspective and experience that otherwise would not have been possible. It helped that the system was designed to fit in the current practice and was based on the *embodied cognition* of experienced climbers.

On the other hand, technology can also invent new problems by oversimplifying the route reading cognitive process and "situatedness". The situated practice of bouldering appeals to people because of its "just go up there" mentality. The bouldergym is a place where experienced climbers train but at the same time people enter to try it out with a group of friends. The openness and inviting atmosphere, as was also described in the Preface. The social aspect of the sport is highly appreciated by visitors of the bouldergym. These elements were all considered during the research. However, it still remains unknown how such a technological intervention will affect the situated practice of bouldering. It could be that technology, by bringing in an extra layer, can put users in the "bubble" with the machine which takes them away from "real life".

To prevent the interruption of the situated practices by HCI, I would like to invite researchers and designers to be critical about their creations. Not only think about the "happy flow" but also find cases where other solutions or no solutions is the better option.

The final words are dedicated to my thoughts on combining design practice with research. From my perspective, every part of HCI, "human", "computer" and "interaction", need an equal amount of attention and appreciation in research. Due to the paradigm of the Cartesian split, the focus in technological research remained on the “computer” aspect for a long time. I am pleased to see, as a designer, student and user, that a shift is taking place towards “human” and especially the “interaction”. Many people around me hold a pessimistic view of a technological future. I believe HCI design-research, by bridging the gap between humans and technology through interaction, can change that by developing experiences that built onto the human experience instead of stepping away from it.

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Appendix A

Ethics forms

Boulder Co-design Session 1 – "Sketch It Out!" – Information Brochure

Thank you for considering participating in this co-design session. Before you decide to officially participate, it is important to have all the information about participating in the co-design session. Please read this information brochure carefully, before you decide if you want to sign the consent forms.

Background

This co-design session is part of a graduation assignment from the University of Twente that combines the studies "Interaction Technology" and "Industrial Design Engineering". The research objective is to design and evaluate a system that uses interactive technology to enhance the perceptual learning of climbing during route reading. In other words, the system should enable climbers to investigate, invent and choreograph sequences of climbing movements on the ground to cut down on the physical load required for doing so on the wall.

Due to the complexity of the research objective, co-design sessions will be held to gain more insights from the practical experiences of climbers. By executing co-design sessions, participants will be lead through exercises that would stimulate their creativity and evoke ideas and interesting insights for meaningful discussions.

Goals of this sessions

- Gain insights into the social interaction while figuring out the "right" boulder sequence of movements
- Get inspiration on how to translate boulder sequence of movements to a visual understanding/documentation and how to communicate this understanding visually to peers
- Get an understanding of how peers interact with visual explanation of climbing movements
- How this visual interaction between peers influences a climbing session
- Have fun with each other!

Participant criteria

- Experience with bouldering
- Climbing level is at least 5a
- Sufficient level in English

Practical information of the session

- Every participant is asked to bring everything they need for a bouldering session (shoes, sport clothes, water bottle etc.)
- The session will take about 2 hours.
- The session takes place at CUBE bouldergym

Safety

In the current times of covid-19, we make sure to follow the pertinent rules and guidelines regarding health and safety. The current rules and regulations can be accessed on the website of the Dutch Government. The most important aspect is that if you experience any covid-19 symptoms, inform the researcher (information at the end of this form).
During the co-design session, participants will be asked to climb on the indoor boulders. To protect any harm from happening, the safety guidelines from CUBE Bouldergym apply. This also means that participants are responsible for their own risk for injuries to happen.

Collecting, using & storing data
During the co-design session, interviews and activities will be recorded by video, audio and photographs. This enables the researcher to document the results without missing important information. The data will only be accessible to people involved in the research project. The recordings will only be used for documentation of the research held. Audiovisual material on which persons are present will not be used for publication and/or presentation, unless separate permission is given for this. If relevant captured data is planned to be used for publication and/or presentation, the person(s) visible on that data will be asked for a separate consent after previewing the fragments.

The data will be securely stored according to UT GDPR rules. Your data is used for academic research and potentially for any commercial purposes in the future.

At any time during the data collection you are allowed to refrain from further participating in the data collection. You do not have to give any reason for this. You are allowed to obtain/keep a copy of this document and informed consent form. In addition you can always request for us to delete your data on our secure and encrypted server/local drive afterwards.

Signing documents
If you agree to participate in the data collection and with the terms we just explained, you can read through the consent form that needs to be signed before data collection and the consent form for sharing your data. Please take your time and let us know if you have any questions or concerns. If you want to participate and agree to sharing the data you will be asked to give your consent at the start of the co-design session. Make sure to keep a personal copy of the information brochure and consent forms.

Contact information for questions and feedback
If you have questions or feedback about anything you read so far or later on, you can contact the researcher organizing this session.
Amy de Lange, University of Twente
a.n.delange@student.utwente.nl
+31 6 31 04 61 87
Supervised by: Dr. Ir. Dennis Reidsma

For any complaints about the content or execution of this research the ethical committee of the faculty EEMCS-HMI can be contacted: Petri de Willigen, +31534892085, ethicscommittee-cis@utwente.nl

Thank you very much for reading and hopefully you will participate and enjoy the experience.

Informed Consent Form (Before Co-design session)

About

The University of Twente is researching the use of interactive technology to enhance the perceptual learning of climbing during route reading. To gain insights from climbers, this co-design session will be held in CUBE bouldergym in Enschede. More information is given in the information brochure attached to this form.

Researchers

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Research: Boulder Co-design Session

☐ Hereby I declare to be well informed about the research through the information brochure. The aims of the co-design session are explained to me, and I had enough time to make a decision about participating and my questions are satisfactorily answered.

☐ I voluntarily agree with participating in this co-design session. I thereby retain the right to withdraw my consent without giving any reason, which will result in my data being deleted from the secure and encrypted servers and drivers owned by the University as specified in the information brochure.

☐ I understand and give consent that my data will be used by researchers as part of this research project.

☐ I give my consent for photographs, video and audio recordings to be used for research purposes.

The data will be securely stored according to UT GDPR rules. Your data is used for academic research and potentially for any commercial purposes in the future.

☐ I am aware that my data will never be used shown public. Only if separate consent is asked for after previewing the data.

Date: Place:

Name: Signature:

Informed Consent Form (After Co-design session)

About

The University of Twente is researching the use of interactive technology to enhance the perceptual learning of climbing during route reading. To gain insights from climbers, this co-design session was held in CUBE bouldergym in Enschede. More information has been given before in the information brochure.

This consent form is to reassure that you agree to have personal data recorded during the co-design session to be used for more than research purposes.

Researchers

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Research: Boulder Co-design Session

☐ Hereby I declare that I have previewed the personal data that is gathered during the co-design session of ________________________.

☐ I voluntarily agree that my data, recorded during the co-design session from_____________________, can be shown during presentations and publications (offline and online) where my identity will be visual to the public.

The data will be securely stored according to UT GDPR rules. Your data is used for academic research and potentially for any commercial purposes in the future.

Date: Place:

Name: Signature:

Bouldering prototype testing round – Information Brochure

Thank you for considering participating in this user study. Before you decide to officially participate, it is important to have all the information about participating in this user study. Please read this information brochure carefully, before you decide if you want to sign the consent forms.

Background

This user study is part of a graduation assignment from the University of Twente that combines the studies "Interaction Technology" and "Industrial Design Engineering". The research objective of the graduation assignment is to explore the use of interactive technology to enhance exploratory perceptual-motor activity during mental practice of bouldering training. In between physical attempts on the climbing wall, athletes observe the wall and perform motor imagery to prepare themselves for the new attempt.

The final prototype is an interactive puppetry system where a tangible puppet interface enables climbers to enact climbing movements visualized in-context through a projector. The climbing poses set by the users are detected by computer vision, augmented with visual proprioceptive feedback, and projected on the selected part of the wall. By investigating climbing movements on the ground, climbers prevent early physical fatigue and over time develop the perceptual motor skill beneficial for bouldering.

This interactive system will be tested by a group of (mostly beginner) climbers. The aim is to gain insights in the user experience, behavior and discuss with participants the potential of the tool. Participants will be grouped in pairs and be climbing bouldering routes where in between attempts they can interact with the prototype. During the assignment, video recordings and observational notes will be made and after the assignment, a short conversation will be held to discuss the experience.

Participant criteria

- Sufficient level in English
- Physically able to climb

Practical information of the session

- Every participant is asked to bring everything they need for a bouldering session (shoes, sport clothes, water bottle etc.)
- The session will take about 1,5 hours.
- The session takes place at CUBE bouldergym.

Safety

In the current times of covid-19, we make sure to follow the pertinent rules and guidelines regarding health and safety. The current rules and regulations can be accessed on the website of the Dutch Government. The most important aspect is that if you experience any covid-19 symptoms, inform the researcher (information at the end of this form).
During the user study, participants will be asked to climb on the indoor boulders. To protect any harm from happening, the safety guidelines from CUBE Bouldergym apply. This also means that participants are responsible for their own risk for injuries to happen.

Collecting, using & storing data

During the user study, interviews and activities will be recorded by video. This enables the researcher to document the results without missing important information. The data will only be accessible to people involved in the research project. The recordings will be used for documentation of the research held. Parts of the recording can also be used for publication and/or presentation if participants give consent for this.

The data will be securely stored according to UT GDPR rules. Your data is used for academic research and potentially for any commercial purposes in the future.

At any time during the data collection you are allowed to refrain from further participating in the data collection. You do not have to give any reason for this. You are allowed to obtain/keep a copy of this document and informed consent form. In addition you can always request for us to delete your data on our secure and encrypted server/local drive afterwards.

Signing documents

If you agree to participate in the data collection and with the terms we just explained, you can read through the consent form that needs to be signed before data collection and the consent form for sharing your data. Please take your time and let us know if you have any questions or concerns. If you want to participate and agree to sharing the data you will be asked to give your consent at the start of the user study. Make sure to keep a personal copy of the information brochure and consent forms.

Contact information for questions and feedback

If you have questions or feedback about anything you read so far or later on, you can contact the researcher organizing this session.

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Thank you very much for reading and hopefully you will participate and enjoy the experience.

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Research: Boulder User study

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☐ I voluntarily agree with participating in this user study. I thereby retain the right to withdraw my consent without giving any reason, which will result in my data being deleted from the secure and encrypted servers and drivers owned by the University as specified in the information brochure.

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