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WaterHCI: Water in Human-Computer Interaction

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Contents

WaterHCI: Water in Human-Computer Interaction

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ABSTRACT

Over recent years, there has been an increase in the coming together of interactive technology and water, leading to the emergence of WaterHCI, a distinct subfield of human-computer interaction (HCI). However, there is little work that aims to paint a comprehensive picture of the work around WaterHCI experiences so far, limiting the opportunity to identify directions for future research. This monograph aims to address this through an articulation of prior WaterHCI works structured using two frameworks that aim to offer a better understanding of the design of aquatic experiences through four key user experiences across six different degrees of contact with water. This articulation allows us to

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highlight underexplored areas that could guide WaterHCI researchers in identifying what to research next in order to bring the field forward as a whole. Ultimately, our work aims to help so that more people can profit from the many benefits that combining interactive technology and water affords.

Keywords: Water; aqua; aquatic interfaces.

1

Introduction

Over recent years, there has been an increase in attempts to place interactive technologies into aquatic settings (Oppermann *et al.*, 2013, 2016; Pell and Mueller, 2013a), not least in the human-computer interaction (HCI) field (Clashing *et al.*, 2022a). For example, there have been developments to place augmented reality goggles into public pools (Oppermann *et al.*, 2013, 2016), interactive water projections into bathtubs (Koike *et al.*, 2013), virtual reality headsets into water-based rehabilitation exercise settings (Quarles, 2015), and robots to interact with into the ocean (Novitzky *et al.*, 2019). In the HCI field, these efforts have been called WaterHCI (Clashing *et al.*, 2022a; Mann, 2021, 2022) and a set of grand challenges have been proposed (Mueller *et al.*, 2024). However, these water-human-technology interactions have not yet been formally collated, even though there is work emerging that goes beyond technical implementation and also considers the associated user experience. In particular, there is work that not only considers instrumental, but also experiential aspects of being in, on and around water, such as the enjoyment that being in bodies of water can facilitate (highlighted in many recreational water activities) that can now be supported by interactive technology (Clashing *et al.*, 2022b; Mann, 2022; Pell and

Mueller, 2013b). In response, in this monograph, we align with a general trend that appreciates a heightened experiential focus in HCI and hence go beyond instrumental systems to also consider the experiential aspects of WaterHCI. In particular, we review systems by employing a user experience framework (Clashing *et al.*, 2022a) in combination with a water contact framework (Raffe *et al.*, 2015). With this, we can identify gaps in the WaterHCI design space. This articulation is hopefully inspiring as it can show what the underexplored opportunities are in the coming together of water and interactive technology.

We hope that our monograph can assist researchers in identifying what to research next. Similarly, we hope that for academics not working in the field of WaterHCI our monograph offers guidance and orientation on how to get into the WaterHCI field. For people within HCI, we hope that our monograph can shed light on discussions around WaterHCI. We also hope that developers can learn about the various technologies employed in WaterHCI and be inspired to push beyond what has already been achieved. Furthermore, aquatic educators might also benefit from our work as they may gain awareness of the different kinds of interactive systems that exist and be inspired to collaborate with WaterHCI experts.

To achieve our objectives, we examined prior work that looked at the WaterHCI field more holistically, as well as individual projects that made use of water properties (hence we excluded projects that solely focused on waterproofing existing systems). We believe that these water properties are important to consider because aquatic activities are subject to properties that are less pronounced or not even present in land-based activities, resulting in very different experiences. Shmeis (2018) listed a set of water properties, namely: depth, temperature, pressure, visibility, light, sound, water flow, non-open water environment, and open water environment. When compared in land-based activities, these water properties affect our sensory perception, physical movement, and physical abilities (Pell and Mueller, 2013a). Previous research positioned these effects as potential constraints for the human body during aquatic activity (Li *et al.*, 2016). However, prior work also advocated viewing these water properties as opportunities (Kajastila *et al.*, 2016; Kosmalla *et al.*, 2016; Mueller and Young, 2018) and we similarly believe that they provide opportunities for interaction design (our framework described below frames water as both a problem and an opportunity). Furthermore, we note that, without the necessary skills, such as the ability to swim, many aquatic environments can be dangerous (e.g., participants can drown). We, therefore, believe that designers must consider how to harness or mitigate the impact of water's properties through informed risk assessment and the establishment of acceptable margins of safety.

We also learned from prior work around technology supporting water experiences more generally. These previous research endeavors highlighted that water is a difficult medium to design for because it often requires the waterproofing of electronics (Bellarbi *et al.*, 2013; Cejka *et al.*, 2021; Lin and Xie, 2010; Quarles, 2015). Therefore, based on the high electrical conductivity of the impurities in water, interactive technologies can be seen as not really suitable for aquatic environments (McCleskey *et al.*, 2011). As a result, recreational interactive systems are typically unsafe or impractical in wet environments while wireless components face interference challenges when trying to communicate through water (Niu *et al.*, 2019; Verzijlenberg and Jenkin, 2010). Furthermore, water's dynamic movement adds complexity to the use of technology in relation to bodily activity when compared to the relative predictability of moving through lower-density air (Ranson *et al.*, 1996). In this regard, we note that prior investigations around the use of technology to support aquatic activities have typically taken the form of technical papers detailing sensor deployment in the aquatic domain (Davey *et al.*, 2008; Reyes *et al.*, 2016). In addition, given that these deployments historically required extensive technical knowledge and resources, they were predominantly focused on supporting elite sporting performances (Delgado-Gonzalo *et al.*, 2016; Hagema *et al.*, 2013; Stamm *et al.*, 2012).

While these prior works showed that technology can support people in the aquatic domain, we believe that recreational activity participants should also be supported, not just elite athletes, especially now that technological advances make low-cost prototyping more feasible. Taken together, we found that prior work mostly focused on technical challenges (and how to address them) when it comes to combining interactive technology and water. The resulting developments have advanced the WaterHCI field by mostly showcasing that interactive systems can work within water settings. Furthermore, we note that much of the prior work in WaterHCI does not mention user experiences, and even if they do, they do not offer much insight through, for example, a study. This is a shortcoming within the WaterHCI field that future work should address. As such, it seems imperative to note that we believe what the field is still missing is a comprehensive overview of the field and, in particular, an investigation into the experiences of such interactive systems in water settings. Without such an investigation, we believe that the field will continue to simply waterproof existing land-based systems, missing out on the opportunities that water offers to human experiences. With such an investigation, however, we hope that the field can delve deeper into utilizing the many affordances water brings to our lives. Furthermore, such an investigation could extend our understanding of experiences with technology more broadly as it moves from land-based HCI to a more comprehensive perspective to also consider interactive experiences in oceans, lakes, pools etc.

1.1 Contribution and Benefit Statement

Our work makes the following contributions:

- We present an overview of the WaterHCI field that is concerned with the coming together of interactive technology and water. This overview might be useful for people aiming to get into the field and would like to gain a broad impression of what the field has achieved so far and what the current status quo is. The overview might also be useful for researchers interested in other sub-fields of HCI, such as SportsHCI (Elvitigala *et al.*, 2024), FoodHCI (Khot and Mueller, 2019), and NatureHCI, as it allows to compare the state of their sub-field to other sub-fields in HCI in order to assess progress and inspire next steps (Mueller *et al.*, 2020).
- Our work presents a comprehensive structured analysis of prior WaterHCI projects based on the consolidation of two existing frameworks. This analysis could be useful for WaterHCI researchers aiming to identify where their own work sits in relation to prior work in order to gain guidance on what to work on next. It could

also be useful for junior researchers who would like to venture into the field but do not want to repeat investigations already being conducted. It could also be useful for researchers in other areas that look for inspiration about how one can structure an analysis of prior works. Finally, our consolidation of the two existing frameworks could also be helpful for researchers who are looking for examples on how to combine existing theory to structure survey works.

- We also present a table with underexplored areas within WaterHCI based on our aforementioned analysis. This table highlights opportunities for future work, which could be useful for PhD candidates looking for dissertation topics. Furthermore, these underexplored areas could be useful for funding agencies who are looking to support "the next big thing". Also, they could be useful for researchers who aim to direct larger research endeavors and hence can use them to structure such endeavors around WaterHCI. Lastly, these underexplored areas can be useful for industry practitioners already working on WaterHCI development projects to guide them in what to work on next to facilitate innovation and to advance the field as a whole.

With our work, we aim to provide the WaterHCI field with an overview of what has been achieved so far to highlight what has been underexplored and, hence, might deserve further attention. With this articulation, we can prevent the field from repeating existing work and consequently stagnating. Instead, we aim to advance the field as a whole by providing a structured understanding of what the underexplored areas are and hence guide what opportunities researchers and practitioners might want to focus on next so that more people can profit from the many benefits that combining interactive technology and water affords.

In the next section, we discuss the two aquatic frameworks from which we drew (Section 2). We discuss each (Sections 3 and 4) and then, in the subsequent section (Section 5), combine the two; the result is a table that allows us to place prior WaterHCI systems (Section 6). We go through the table, column by column, to detail these prior

WaterHCI systems. In the following section (Section 7), we present design gaps identified through the frameworks and what this can mean for future work (Section 8), before we present the limitations of our work (Section 9) and our conclusion (Section 10).

2

Two Aquatic Frameworks

In this section, we extend prior work by outlining and then combining a two-dimensional experiential framework for WaterHCI systems called "Going into depth" (Clashing *et al.*, 2022b) with Raffe *et al.*'s (2015) "Six degrees of water contact" framework.

We combine these two frameworks, for the first time, to paint a more vivid picture of WaterHCI. This allows examining the opportunities and challenges that water poses to technology, as derived from framework one ("Going into depth") in reference to the "Six degrees of water contact" of framework two in order to better understand what the opportunities and challenges are for interaction designers when aiming to support the whole gamut of water interactions across the entire spectrum of possible water contact. This combining of the two frameworks also allows us to identify underexplored areas that researchers might find useful to know about when ideating possible future research projects.

The reasons for using these two frameworks are manifold. First, these two frameworks are explicitly concerned with water interactions and hence appear to suit our intention quite well. Other, more tangential frameworks, such as those concerned with tangible (Hornecker and Buur, 2006), bodily (Mueller *et al.*, 2011) or contextual (Abowd *et al.*, 1999) factors, might also be suitable, however, they could miss out on the unique affordances of water relevant to interactions, such as buoyancy. Second, they have been published in HCI venues, and hence, it could be implied that HCI researchers find them useful and, consequently, possibly also WaterHCI researchers, speaking to our intention to produce value for WaterHCI researchers.

Third, framework one, “Going into depth” is concerned with water *experiences*, so focusing on the user experience, while framework two, “Six degrees of water contact” appears to come from a more technical grounding, and hence could provide a focus on the technical systems aspects of these user experiences, hence complementing each other nicely. Fourth, some of the authors of this monograph have been involved in these prior works, hence have an intimate knowledge of them and were able to answer any clarification questions. Fifth, these frameworks are relatively recent, and hence, we thought it might be useful when there is a need to consider any latest advancements in interactive technology developments, such as miniaturization. Sixth, we acknowledge that we were limited in available frameworks that could guide such investigations. With the advancement of the WaterHCI field, more frameworks might emerge, which could be useful for future investigations involving the creation of new combinations of frameworks or additions to our combined framework, see below. As such, we encourage future work to consider additional frameworks to complement our work.

3

Framework One: Going into Depth

The framework "Going into depth" was derived from a survey of WaterHCI systems (Clashing *et al.*, 2022b). It focused on ACM, IEEE and SportDiscus as source because prior survey work also started there (Hornbaek and Hertzum, 2017; Koelle *et al.*, 2020; Schneider *et al.*, 2018; Terzimehić *et al.*, 2019). To achieve a manageable result size, the search was limited to publications between 2010 and 2021. The search resulted in a total of 1,512 papers. This included only original, peer-reviewed research. Screening comprised a two-step process. First, papers were excluded that did not involve leisure and recreational activities around water. For example, papers that modeled the flow of waterways but did not relate back to human experiences were excluded (Ben-Daoud and Sayad, 2020; Hirsch, 2010). The papers were then screened to exclude topics such as sustainability, nutrition, conservation, physiology, water management and virtual reality (VR)/augmented reality (AR) simulations of water that did not involve any contact with physical water. This includes projections of where water might be in the future given climate change (Biggs and Desjardins, 2020). To account for publication venues not included in the databases, a backward-chaining process was employed, additionally examining all papers referenced by these 212 works (snow-balling principle; Wohlin, 2014). This activity yielded 101 additional papers. After removing duplicates, 257 papers remained for further screening. In the next step, enabling theories and technologies without clear interaction opportunities (e.g., computer vision algorithms, wireless communication assessments, development of physiological or biomechanical models; Cecchi *et al.*, 2020) and non-digital systems (e.g., more efficient swimsuits; Beckett, 2008) were excluded. The final set of 48 papers was coded using an open coding process, and observations regarding the activity the paper addressed, the system's feedback loop, and how water was incorporated, were noted. Common themes were extracted from these observations and iterated over. These themes indicated that water presented unique challenges and opportunities for interaction when compared to similar land-based scenarios.

3.1 Considerations of the Properties of Water

It was suggested that water can be both an opportunity and also challenge for technology; in particular, it was found that designs that explicitly consider the properties of water could affect or enhance the technology (Dietz *et al.*, 2014; Mann *et al.*, 2006a; Pell and Mueller, 2013a; Quarles, 2015). In other words, such properties can act as a challenge or an opportunity for WaterHCI systems in contrast with their on-land counterparts. For example, a liquid can be easily deformed without changing its volume (Campbell *et al.*, 2015; Geurts and Abeele, 2012). When not disturbed, a liquid settles into a smooth surface between itself and air, maintaining this boundary through surface tension (Sylvester *et al.*, 2010). This quality offers opportunities to delineate two different usable regions (one of air, one of water) (Koike *et al.*, 2013; Lee *et al.*, 2013), while also presenting an issue of limited and distorted "visibility" through the surface (Bächlin *et al.*, 2009; Bruno *et al.*, 2019; Cejka *et al.*, 2021; Kiss *et al.*, 2019; Sylvester *et al.*, 2010; Szczepan *et al.*, 2016; Ukai and Rekimoto, 2013). While this issue is always present due to the refraction of light at the air-water boundary, it can be worsened underwater due to limited light penetration at depth or opacity due to particles and dissolved materials (Muehlbradt *et al.*, 2017; Yamashita *et al.*, 2016). Furthermore, immersion in water changes the forces that a user experiences, resulting in pressure increasing with depth (Bächlin *et al.*, 2009; Coppo *et al.*, 2014; Förster *et al.*, 2009; Muehlbradt *et al.*, 2017; Quarles, 2015; Seibert and Hug, 2013).

In addition, it was pointed out that without the need to support oneself on the ground, and due to a general lack of obstacles around them, people usually have more freedom of movement while being immersed in water (Baldwin *et al.*, 2019). Furthermore, buoyancy affects the human exertion often required, with water exhibiting greater drag than air, resisting a person's body movements through it (Quarles, 2015). Furthermore, water's inertia and viscosity, which cause drag, also present opportunities for propulsion via paddling or propellers (Novitzky *et al.*, 2018; Schaffert and Mattes, 2015), along with tactile feedback or wetness when someone is sprayed with a jet of water (Hoste and Signer, 2014; Mann *et al.*, 2006a,b; Richter *et al.*, 2013) or feels water's weight when lifting it (Koike *et al.*, 2013). Also, jets and currents represent a flux of water rather than a constant quantity, so flow rate can be used in much the same way as electrical current (Campbell *et al.*, 2015; Dietz *et al.*, 2014; Mann *et al.*, 2006a,b; Pares *et al.*, 2005). Despite this similarity, the electrical conductivity of water can dampen wireless network communication, while water can damage any insufficiently waterproofed circuitry (Bellarbi *et al.*, 2012; Oppermann *et al.*, 2016). Nor are users safe from the dangers of water. For example, access to life-sustaining air is limited in many aquatic contexts (Lin and Xie, 2010; Oppermann *et al.*, 2016).

Taken together, these opportunities and challenges that water poses for technology have led to a 2-dimensional design space that we describe in the next section.

3.2 Water as Problem and Opportunity

While the unique properties of water can be seen as problematic (for users and technology) in some situations, these unique properties can create opportunities for novel interactive experiences in other situations. Based upon this dichotomy, a two-dimensional framework was derived, shown in Figure 3.1, with each axis ranging from water being a "problem" to an "opportunity" for either users or technology.

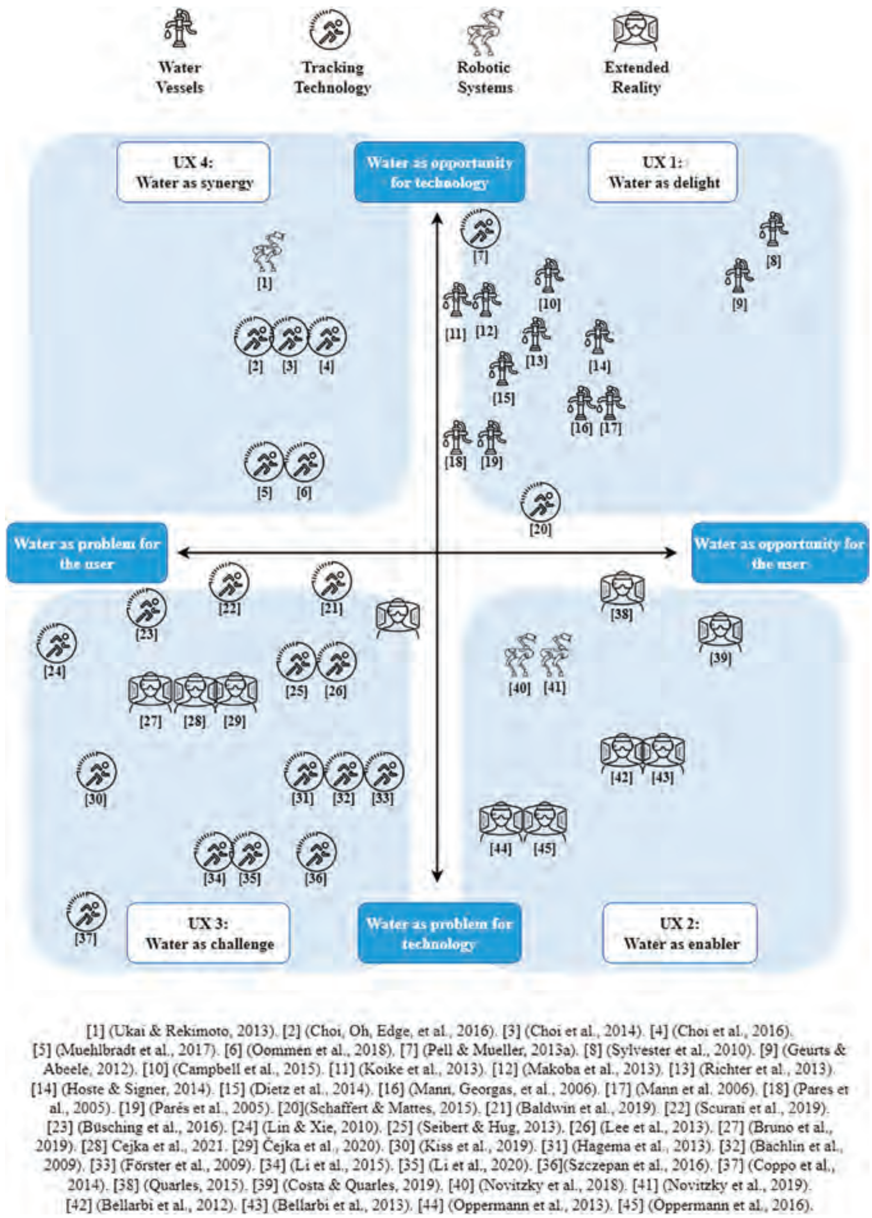

Figure 3.1: Design space where water as a problem or opportunity for users is plotted on the X axis, and water as a problem or opportunity for technology is plotted on the Y axis, allowing to depict different user experiences: first quadrant, water as delight; second quadrant, water as enabler; third quadrant, water as challenge; and fourth quadrant, water as synergy.

The interplay between water's problems and opportunities, for users and technology, allows depicting different aquatic user experiences across the framework axes. The following sections describe how water can be a problem or opportunity for users or technology, and the user experiences associated with different combinations of these two factors.

3.2.1 Water as a Problem

From the user's perspective, "water as a problem for the user" means that the air supply for breathing is restricted within the recreational activity. "Water as a problem for technology" generally refers to technology requiring some form of waterproofing due to its electrical components (although we acknowledge that fluidic computers could address this issue; Lu *et al.*, 2023).

3.2.2 Water as an Opportunity

On the other hand, "water as an opportunity for the user" uses water's properties, such as buoyancy, to create a more engaging experience, such as facilitating floating. "Water as an opportunity for technology" refers to the system aiming to leverage water's unique properties, such as its tactility (e.g., wetness, weight, and temperature), to achieve something that could not be done on land.

3.3 Four Different User Experiences

There are four different combinations of water as a problem or opportunity for users or technology, and each of these supports a different aquatic user experience. When water is an opportunity for both users and technology, systems may elicit "Water as Delight" through pleasurable or surprising water contact. When water is an opportunity for the user but a problem for technology, we find the "Water as Enabler", whereby the properties of water (e.g., buoyancy) enhance a user's capabilities, often through expanded freedom of movement. When water is a problem for both users and technology, we see "Water as Challenge" whereby technology tries to reduce the limitations imposed by water on users (e.g., difficult locomotion) at the same time as the system must overcome its own challenges (e.g., networking issues). Finally, when water is a problem for users but an opportunity for technology, we see "Water as Synergy", whereby the system leverages the unique properties of water (e.g., predictable pool features) to support users in their aquatic activities.

3.3.1 Water as Delight

"Water as delight" systems are located in the upper-right hand quadrant of the design space. Here, water is experienced as an opportunity for technology and for users. According to a common definition in HCI, delight is the combination of pleasure and surprise elicited from a user's interaction with a system (Mirza and Tabak, 2017). "Water as delight" elicits a combination of pleasure and surprise when the user interacts with water.

3.3.2 Water as Enabler

"Water as enabler" systems are located in the lower-right quadrant. Here, water is experienced as a problem for technology but as an opportunity for users. In HCI, "enabler" means offering support through interactive means for the execution of a task (Marcos *et al.*, 1998; Markosian *et al.*, 1994; Prasolova-Førland *et al.*, 2013), most often for persons with special needs (Edwards *et al.*, 1994). In this regard, water is an enabler primarily because it is a medium that can give users an increased sense of agency over their bodies (Limerick *et al.*, 2014).

3.3.3 Water as Challenge

"Water as challenge" systems are located in the lower-left quadrant. Here, water is experienced as a problem for technology and for users. Water is a challenge because the interaction with it represents a task with different obstacles to overcome. For example, efficient movement through water, and the need for air in a timely manner, present challenges for users. In HCI, the notion of challenge has been considered in relation to "flow," or the "optimal experience" (Csikszentmihalyi and Csikszentmihalyi, 1988). When a user's abilities match the challenge of an activity, a positive state of "flow" can occur (Csikszentmihalyi and Csikszentmihalyi, 1988). Conversely, a user may experience boredom, frustration and anxiety if their abilities exceed the skills required by the activity (Hurd *et al.*, 2021).

3.3.4 Water as Synergy

"Water as synergy" systems are located in the upper-left quadrant. Here, water is experienced as an opportunity for technology and a problem for users, referring to user experiences where the interactions between the properties of the aquatic environment and the interactive system produces a combined effect greater than the sum of those properties were they to stand alone. Therefore, "water as synergy" systems explore the interactions between the properties of the aquatic environment, such as black line patterns in a pool, and the technology, such as computer vision algorithms, to produce a solution that substantially enriches user experiences, such as a swimming guiding computer vision system based on the pool patterns (Muehlbradt *et al.*, 2017).

4

Framework Two: Six Degrees of Water Contact

Raffe *et al.*'s (2015) "Six degrees of water contact" framework is presented in Figure 4.1. To help the design of future WaterHCI systems, the authors applied the "exertion framework" (Mueller *et al.*, 2011) to water interactions to identify six degrees of water contact with the human body and the implications of each degree of contact for the design of interactive systems. These degrees of contact were described as "vicinity", "sporadic contact", "on top of water", "partially submerged", "floating" and "underwater".

The degree and nature of physical exertion required during water-based activities have consequences for how associated systems could be designed and for the experiences linked with them. For example, when a person is partially submerged in water, their body experiences buoyancy, which means that the water provides some support for their weight. This buoyancy reduces the amount of physical exertion required to perform certain activities, such as swimming. On the other hand, when a person is fully submerged in water, they experience greater resistance to movement, which can increase the amount of physical exertion required to perform the movement. As with these two examples,

Figure 4.1: Six degrees of water contact proposed by Raffe *et al.* (2015).

each change in the degree of contact with water changes the design considerations.

4.1 Six Degrees of Water Contact

We now describe the six degrees of water contact. These degrees refer to the extent to which the player interacts with water. They have a notable impact on the abilities and performance of both the user and the technology involved. These degrees form a linear spectrum ranging from proximity to water to being fully submerged, with the addition of being on top of the water using a flotation device.

4.1.1 Vicinity

At this level, there is no direct physical contact between the user and the water. Nevertheless, water can still influence the overall experience. The sight and sound of water can evoke feelings of relaxation and vitality. For instance, the mesmerizing sight and sound of ocean waves at a beach or the rushing water sounds at a water park can immerse visitors in a water-related ambiance. Additionally, observing others unexpectedly getting wet or engaging in water-based activities while remaining dry can be entertaining.

4.1.2 Sporadic Contact

Here, no part of the body is fully submerged, but there is contact between the user's skin and water. This contact may occur through rain, showers, playing with water guns and balloons, running through garden sprinklers, or sliding down a water slide. A distinguishing feature of these experiences is that water is typically dispersed and in motion, colliding with the user rather than requiring the user to enter a body of water.

4.1.3 On Top of Water

Being on top of the water represents a combination of the Vicinity and Floating categories. It shares characteristics with the vicinity degree, as there is no direct physical contact between the user and the water. However, the user is situated on the water's surface and not in contact with solid ground, similar to "floating". The key feature here is the indirect contact between the player and the water facilitated by a flotation device, such as a surfboard or boat.

4.1.4 Partially Submerged

This category encompasses a range of experiences, from having a single extremity (e.g., a hand or foot) submerged to submerging the entire body up to the neck. Regardless of the specific level of immersion, the common element is that a portion of the player's body is in contact with water, while the head remains above water and the player stands on solid ground, whether inside or outside the body of water. This distinction sets Partially Submerged apart from Sporadic Contact, as the player is now entering a body of water. Additionally, unlike in the Floating state, the player's limb movements, vestibular senses, and oxygen availability are more similar (though not identical) to the previous degrees of water contact. Of note here is that Partially Submerged is a broad category that includes both minimal hands-only submersion and deeper bodily immersion.

4.1.5 Floating

Here, most of the user's body is underwater, with only a small portion remaining above water, including the face to enable breathing during recurring intervals. It is comparable to the upper limit of the Partially Submerged category, but the player is no longer in contact with solid ground. Therefore, the Floating category encompasses situations where the user is treading water or swimming on the water's surface.

4.1.6 Underwater

Here, the user is completely submerged, holding their breath or utilizing a breathing aid, and typically employing different swimming techniques compared to those used when floating on the water's surface.

5

Combining the Two Frameworks

We can combine the two frameworks by depicting the four different user experiences from the first framework as rows, and the six degrees of water contact from the second framework as columns in Table 5.1. This allows us to systematically describe existing WaterHCI systems.

We selected these WaterHCI systems based on the results from the first framework, “Going into depth”, and checked it with the referenced systems from the second framework, “Six degrees of water contact”. This allowed us to draw from a large pool of systems that appears to span a wide range of experiences that we believe map the WaterHCI field quite well. However, we acknowledge that this is only a snapshot in time and might miss some work. Furthermore, although the original survey work utilized back-chaining, allowing the capture of older works, the initial focus was on works from after 2010. Hence, we acknowledge that the systems discussed below will come from a perspective focused on more recent works. However, we believe that this can be adequate as we are aiming to inform future WaterHCI work, and hence, a deep engagement with current works seems promising.

Through our attempt to systematically describe existing WaterHCI systems, we can identify what aspects of water interactions have been

Table 5.1: WaterHCI exemplar systems discussed are mapped across two frameworks

Degree of Water Contact/Water User Experience	***Vicinity***	***Sporadic***	***On Top***	***Partially Submerged***	***Floating***	***Underwater***
Water as delight	Fluid user inter-faces	Pump-Spark Soap bubbles Water ball Z Splash Controllers LiquiTouch Hydraulo-phone using Water Jets as Pixels Water games		Gravity Well Aquatop		
Water as enabler			Aquaticus	3D Pointing	DOLPHYN AREEF	Shark punch
Water as challenge			Rowing Sonification		Clair-buoyance AquaCAVE Aqua-trainer Swim-Master Swim Train Auditory Swimming Coach Iswim Wearable Visible Light Communication Video Replay Training LED strip speed	Drowning Prevention Swimming Cap AR Heritage AREEF (no snorkel) Smart Spa
Water as synergy			Rapid Scout CoOP		Goby MobyDick Swimoid	

more, and which ones have been less explored, possibly aiding any decisions on what to focus next in the WaterHCI area. In the following sections, we go through the table and fill it with WaterHCI exemplars in order to paint a more complete picture of what the current state of the art in WaterHCI is.

6

WaterHCI Exemplar Systems

We now go through Table 5.1, starting with the "vicinity" column. For each column, we then investigate "water as delight", "water as enabler", "water as challenge" and "water as synergy". For every cell, we describe exemplar systems, noting that for some cells, there are no exemplar systems, at least to the best of our knowledge. We provide an overview of our exemplar systems in Table 5.1.

6.1 Column 2: Vicinity

"Vicinity" systems refer to WaterHCI systems that bring users close to, but not in contact with, water. We found only one cell with systems: they facilitate "water as delight".

6.1.1 Water as Delight Through Vicinity to Water

We now discuss *Fluid user interfaces*, a WaterHCI system concerned with water as delight through users being in vicinity to water.

The *Fluid user interfaces*, or *Fl. UI*, system (Figure 6.1) consists of a set of liquid-based touch surfaces that use computer vision to detect and interpret a range of tactile user inputs (Campbell *et al.*, 2015). The

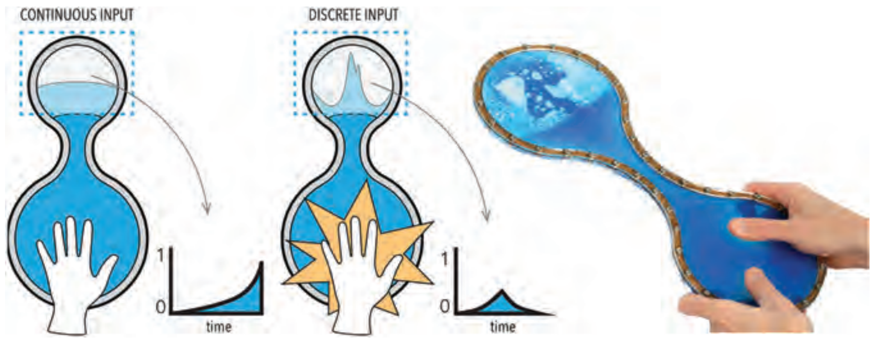

Figure 6.1: The input modalities of the *Fluid user interfaces* system (Campbell *et al.*, 2015).

shape of the surfaces mimics standard pressure vessels and consists of a layer of liquid between two layers of plastic that are sealed with a cork gasket. A camera is placed in front of the plastic layer to detect the fluid movement that is akin to a button being pressed. The designers of the system aimed to propose novel surface interaction techniques. Thus, the system allows users to interact and trigger digital events by pressing a malleable surface. Depending on the surface material, the user can utilize light touches but also hard slams to generate input to the system.

We believe that this system allows for a "water as delight" user experience by providing a touch display that enables users to find pleasure when interacting with a computational system, given that touching water can be associated with pleasure. We categorized this system as "vicinity": while users do not experience direct contact with water, they can still manipulate it. We learned from this prior work that pressure interfaces can be rapidly prototyped, using low-cost materials and commercially available equipment (Campbell *et al.*, 2015). Moreover, the flow of water into the interface's vessels creates temporary buttons that allow for dynamic interactions. The work suggested that liquid-based touch surfaces enable unpowered interfaces that can allow designers to use them in areas where electricity is not readily available, such as in remote outdoor (water-proximate) areas.

6.2 Column 3: Sporadic

In this section, we discuss WaterHCI systems that bring users into sporadic (occasional) contact with water. We found exemplar systems only in the "water as delight" cell.

6.2.1 Water as Delight Through Sporadic Contact

We now discuss WaterHCI systems that are concerned with water as a delight through sporadic contact. We classified seven systems under this category (Figure 6.2): *PumpSpark* (Dietz *et al.*, 2014), *Soap*

Figure 6.2: Water as a delight through sporadic contact systems. (A) The components of the PumpSpark development kit and an example of its use (Dietz *et al.*, 2014). (B) User manipulating a soap bubble on top of the liquid interface (Sylvester *et al.*, 2010). (C) Type of receptacles that can be created for Splash Controllers (Geurts and Abeele, 2012). (D) Water jets are activated based on a user performing playful fighting actions with the Water Ball Z system (Hoste and Signer, 2014). (E) The water jet of the LiquiTouch system is activated by a user's touch (Richter *et al.*, 2013). (F) Children using Water Jets as Pixels to play the Hydraulophone (Mann *et al.*, 2006a,b). (G) Water Games fountain installation (Pares *et al.*, 2005).

Bubbles (Sylvester *et al.*, 2010), *Water Ball Z* (Hoste and Signer, 2014), *Splash Controllers* (Geurts and Abeele, 2012), *Liquitouch* (Richter *et al.*, 2013), *Water Jets as Pixels* (Mann *et al.*, 2006a,b) and *Water Games* (Pares *et al.*, 2005). We consider that all these systems highlight the potential of water to offer "water as delight" experiences through sporadic contact, evoking pleasure, surprise, and engagement through the unique properties of water, such as flow, sound, and touch. For example, the *PumpSpark* (Figure 6.2(A)) development kit provides a versatile toolkit for prototyping fluidic user interfaces, enabling high-resolution control of water streams. Moreover, *Soap Bubbles* (Figure 6.2(B)) employs ephemeral interfaces using soap bubbles for playful digital interactions, leveraging the temporal nature of bubbles. *Water Ball Z* (Figure 6.2(D)) combines virtual combat with physical water feedback, using water jets to simulate punches and kicks in a safe, playful manner. Particularly, *Splash Controllers* (Figure 6.2(C)) use a variety of water-filled receptacles as interactive controllers, adding challenge and fun through the risk of splashing. *LiquiTouch* (Figure 6.2(E)) integrates water jets with touch screens to provide haptic feedback, enriching user interactions with virtual objects. Finally, *Water Jets as Pixels* (Figure 6.2(F)) and *Water Games* (Figure 6.2(G)) utilize water jets in playful installations, providing multi-sensory feedback to engage users, particularly children, in interactive experiences.

Overall, the systems concerned with water as a delight through sporadic contact water can be leveraged in various interactive systems to create customizable, playful, and engaging experiences. We note several takeaways from analyzing these systems: Toolkits like *PumpSpark* can simplify the creation of water-based interfaces, supporting diverse applications. Ephemeral interfaces with water, like *Soap Bubbles*, offer unique, unpredictable interactions that require focused user control. Water can transform physical actions into safe, playful experiences, as seen in *Water Ball Z*, combining multimodal feedback for user delight. As demonstrated by *Splash Controllers*, water's movement can be used to design novel, tactile, and challenging interactions. Water can enrich digital content, providing haptic cues and enhancing touch interactions, as shown by *LiquiTouch*. Water jets can replace traditional feedback systems, supporting multi-sensory, educational, and social experiences, particularly for children, as seen in *Water Jets as Pixels* and *Water Games*.

6.3 Column 4: On Top

"On top of water" systems are those that allow the user to be on the surface of water and typically use crafts such as surfboards and kayaks. We now present WaterHCI systems that have users on top of water offering user experiences of enablement, challenge, or synergy (but not the first one, delight).

6.3.1 Water as Enabler on Top

We now present *Aquaticus*, a WaterHCI exemplar system where water is regarded as an enabler on top of water.

Aquaticus is an "on top of water" system that leverages water as an enabler, offering a unique setting to explore human-robot interaction, communication, and trust. Particularly, *Aquaticus*' designers chose water for its safety benefits when conducting human-robot tests. *Aquaticus* reinvents capture-the-flag into an aquatic game by placing two players in motorized kayaks in a river alongside two robots in separate autonomous surface vehicles (Novitzky *et al.*, 2019). Each human teams up with a robot to capture the opposing team's flag (Figure 6.3). Communication between players and robots is facilitated by speech recognition software and dual-radio headsets.

Aquaticus demonstrated that water provides a versatile environment for testing technological concepts and relationships that might be more challenging on land. Although the game explored robot interactivity "on top of water", We believe there is more room to explore human-robot interaction in water. For instance, integrating capabilities for the robots to submerge and resurface could have enhanced the game mechanics by taking full advantage of water's dynamic properties.

Figure 6.3: *Project Aquaticus* uses headsets to support communication between human and robot teammates in motorized kayaks (Novitzky *et al.*, 2019). Upper image: Overview of the kayak course. Lower image, left: Person on water communicating via a headset. Lower image, right: Communication options.

6.3.2 Water as Challenge on Top

Here we present *Rowing Sonification*, a WaterHCI system categorized in water as a challenge, as explained next.

Rowing Sonification transforms on-water rowing training by using Sofirow, an acoustic feedback device, to sonify a boat's acceleration (Schaffert and Mattes, 2015). Traditional CoxBox loudspeakers used by coaches to give verbal feedback to rowers on the water are transformed to provide athletes with real-time acoustic feedback at crucial stages of the rowing stroke (Figure 6.4). Synchronizing the four stages in Figure 6.5 is critical for the crew's performance.

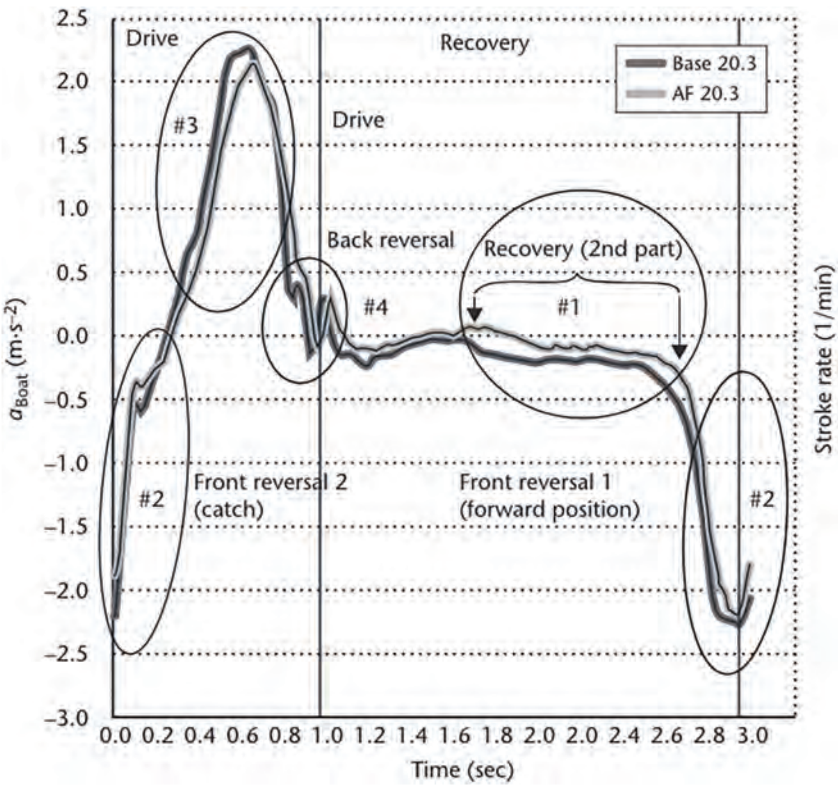

Figure 6.4: The *Rowing Sonification* project: The rowing boat acceleration averaged over 30 rowing cycles, with the acoustic feedback line (where acoustic feedback is provided) compared to the baseline movements (Schaffert and Mattes, 2015).

Rowing Sonification is an "on top of water" system that offers the user an experience of "water as challenge", since moving through the water requires skill and exertion. This project demonstrated that auditory non-verbal feedback effectively reinforces cues during rhythmic movements on water. Additionally, it showcases the potential to repurpose existing tools like the CoxBox in innovative ways, providing users with a greater variety of feedback.

Figure 6.5: Water as synergy on top of water systems. (A) The hardware components of the *Rapid Scout* system (Ranson *et al.*, 1996). (B) The rudder assembly of the CoOP system is seen in the larger photo and the transmitter that controls the rudder is in the smaller photo (Baldwin *et al.*, 2019).

6.3.3 Water as Synergy on Top of Water

We now discuss WaterHCI systems that are concerned with water as synergy on top of the water. *Rapid Scout* (Ranson *et al.*, 1996) and CoOP (Baldwin *et al.*, 2019) are pioneering systems designed to enhance the experience of paddlers in water-based activities. Both "on top of water" systems emphasize a "water as synergy" user experience, leveraging technology to create safe, engaging, and enriched water-based experiences that harness the natural rhythms of the activity and the collaborative potential of aquatic environments.

Rapid Scout (Figure 6.5(A)) is a GPS tracking system tailored for white water paddlers to inform upcoming rapids along a river route (Ranson *et al.*, 1996). Integrated into a neoprene belt, it features a magnetically sensitive touch screen activated by a glove with magnetized fingertips, overcoming water-related challenges for traditional touch screens. The system provides paddlers with various viewpoints, such as aerial views and graphical representations of the river's dynamics, including current changes. This information is accessed during calm sections of the river. *Rapid Scout* was designed with these paddling and river rhythms and patterns in mind, to provide the paddler with information and support a non-distracting, enriched, "water as synergy" scouting experience. *Rapid Scout* illustrates how natural aquatic rhythms can inform and predict recreational experiences, providing interaction designers with a reliable framework for creating synergistic water experiences.

CoOP (Figure 6.5(B)) (Baldwin *et al.*, 2019) is a cooperative outrigger paddling system that shares steering control between sighted and visually impaired paddlers using servo motors. The system's rudder (the steering mechanism) is controlled remotely by a sighted paddler via a handheld radio frequency transmitter. This "on top of water" system also offers a "water as synergy" experience due to its collaborative nature, ensuring safety and facilitating enjoyment for visually impaired paddlers. The *CoOP* system demonstrates the effectiveness of co-design and collaborative approaches in designing water activities for specific populations. It highlights the advantages of using technology to distribute control remotely, enhancing users' enjoyment by allowing them to focus on those aspects of the activity in which they have greater capabilities.

6.4 Column 5: Partially Submerged

We now present WaterHCI systems that can be characterized by partial submersion of their participants in water and offer user experiences of delight and enablement (but not challenge nor synergy).

6.4.1 Water as Delight Partially Submerged in the Water

Gravity Well (Pell and Mueller, 2013b) and *AquaTop* (Koike *et al.*, 2013; Matoba *et al.*, 2013) are innovative systems that leverage the unique properties of water, such as flow and touch, to create engaging and delightful user experiences through interactive play and novel interfaces while partially submerged in water.

Gravity Well (Figure 6.6(A)) features a system of underwater robotic "baby fish" that react collectively to a user's interactions with a robotic "mother fish." The fish are contained in clear water containers, allowing users to see and interact with them by immersing their hands. Actions such as pushing the mother fish to the bottom of the tank cause the baby fish to exhibit anxious movements, creating a playful and immersive experience. This system highlights the potential for interactive aquatic

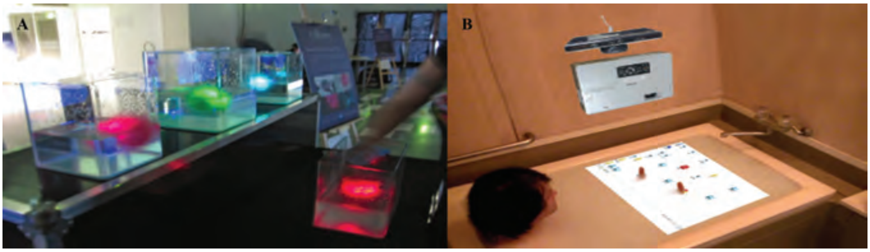

Figure 6.6: Water as delight partially submerged systems. (A) Two partially submerged players interacting with the *Gravity Well* system's "mother fish" (Pell and Mueller, 2013b). (B) User in a bath using the *AquaTop* system, which projects images onto the water's surface (Koike *et al.*, 2013; Matoba *et al.*, 2013).

designs to motivate users to engage with water, partially submerging their hands, in delightful ways thanks to the visual and touch stimuli. *Gravity Well* uses water's characteristics not merely as challenges but as integral elements of the interaction.

AquaTop (Figure 6.6(B)) is an interactive display system that uses an opaque water surface for both input and output. Images are projected onto the water's surface, and users interact with these images through hand gestures tracked by a depth-sensitive camera. This system introduces playful computer interactions into the bathroom setting, allowing users to perform tasks such as watching videos or playing games by manipulating the water surface. *AquaTop* promotes delight through the physicality and novelty of water-based gestures, showcasing the potential use of water's permeable surface to facilitate intuitive and engaging interactions.

We highlight a clear takeaway from these systems: *Gravity Well* and *AquaTop* each capitalize on the unique properties of water—its density, fluidity, permeability, and ability to facilitate sensory experiences—to create innovative and enjoyable user interfaces. These systems illustrate the potential for water to serve as a medium for interaction, offering new opportunities for designing playful and immersive user experiences.

6.4.2 Water as Enabler While Partially Submerged in Water

The *3D Pointing system* (Figure 6.7) consists of a head-mounted, waterproofed smartphone for visual output and head motion tracking,

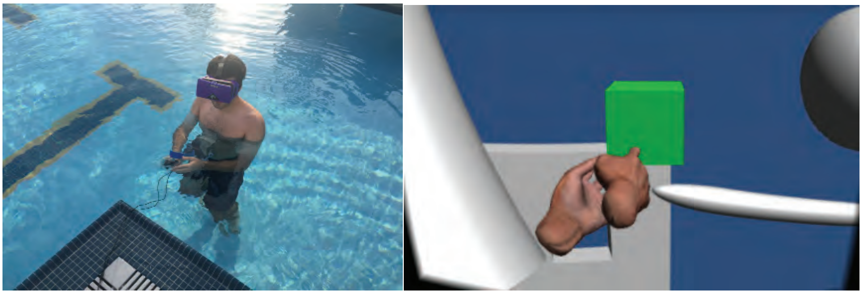

Figure 6.7: A user interacting with the *3D Pointing* system while partially submerged in a pool (left). A virtual image of the user's actions while interacting with the *3D Pointing* system (right) (Costa and Quarles, 2019).

alongside Razer Hydra controllers for tracking hand orientation and trigger input (Costa and Quarles, 2019). This system allows users to explore input in VR while underwater. Users are immersed in a virtual scene composed of polygons, where they are tasked with selecting target shapes either by pointing at them with a virtual hand or by positioning their virtual hand within the boundaries of the target. The system was designed to compare the usability of these object selection methods in both terrestrial and aquatic environments.

3D Pointing elicits the experience of "water as an enabler" where the partial submersion of the user in water reduces the physical fatigue typically associated with repetitive VR object selection tasks. The authors believed that a system with this effect would enable users with motor challenges to use VR applications for longer, which was confirmed in their study results. This research highlights the potential of aquatic environments to enhance user comfort and extend the usability of VR applications.

6.5 Column 6: Floating

We now present WaterHCI systems that can be characterized by their users floating on water and offer user experiences of enablement, challenge, and synergy (but not delight).

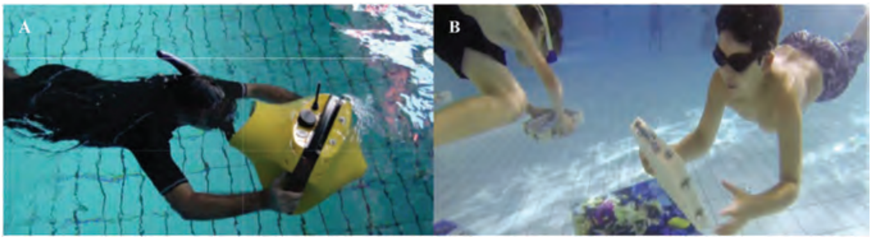

Figure 6.8: Water as enabler while floating systems. (A) The *DOLPHYN* system used in a swimming pool (Bellarbi *et al.*, 2012, 2013). (B) Two children playing *AREEF* in a pool (Blum *et al.*, 2009).

6.5.1 Water as an Enabler While Floating

DOLPHYN (Figure 6.8(A)) (Bellarbi *et al.*, 2012, 2013) and *AREEF* (Figure 6.8(B)) (Blum *et al.*, 2009) are underwater augmented reality systems that transform conventional swimming pools into immersive oceanic environments, leveraging the properties of water to enhance user interaction and engagement through gamified experiences. Both systems exemplify a "water as enabler" experience since the water's buoyancy supports users to float while maintaining the safety and convenience of a pool environment.

DOLPHYN allows users to float on the surface and play a first-person shooter game using a waterproof device (a tablet, a webcam, joysticks, flow sensors, and a Wifi module), where they must protect marine life by targeting virtual submarines. Similarly, *AREEF* uses a custom waterproof passthrough head-mounted display to overlay virtual ocean scenes of shells and fishes onto the pool environment, enabling users to snorkel while solving interactive puzzles. These systems highlight the challenges of underwater input mechanisms and demonstrate the potential of serious games to promote environmental awareness and learning about marine environments through enhanced immersion in water. Moreover, both systems demonstrate how the sensory nature of floating in water and the physicality of being partially submerged add depth to the virtual interactions that are difficult to replicate on land. Finally, we note that *AREEF* illustrates how a system can evolve and occupy different design spaces over time. By transitioning through various stages of development, *AREEF* demonstrated that systems could offer different experiences and degrees of interaction with water, from delight to enabler, thereby adapting to different user needs and contexts.

6.5.2 Water as a Challenge While Floating

In this subsection we describe 10 systems that offer a user experience of "water as challenge". Each system addresses distinct challenges faced by swimmers when floating in the water, such as navigation in open water, training efficiency, and real-time feedback, thereby transforming the aquatic environment into a platform for both recreational enjoyment and competitive improvement. Water presents a significant challenge to swimmers due to its dynamic nature, including waves, currents, and the need to navigate without clear visual landmarks. Traditional swimming often requires frequent interruptions as swimmers lift their heads to orient themselves, disrupting their stroke rhythm and consuming additional energy. Systems like *Clairbuoyance* (Kiss *et al.*, 2019), *AquaCAVE* (Yamashita *et al.*, 2016), *Aquatrainer* (Coppo *et al.*, 2014), *SwimMaster* (Bächlin *et al.*, 2009), *Swim Train* (Choi *et al.*, 2016a), *Auditory Swimming Coach* (Seibert and Hug, 2013), *Iswim* (Li *et al.*, 2020), *Wearable Visible Light Communication* (Hagema *et al.*, 2013), *Video Replay Training* (Scurati *et al.*, 2019), and *LED Strip speed feedback system* (Szczepan *et al.*, 2016) aim to mitigate these challenges by providing real-time feedback, enhancing technique, and improving performance.

Clairbuoyance (Figure 6.9(A)) introduces LED-embedded goggles that guide swimmers with color-coded directional cues, eliminating the need for frequent head lifts in open water. *AquaCAVE* (Figure 6.9(B)) utilizes stereoscopic projections within a pool to simulate underwater environments, enhancing training realism for SCUBA divers and competitive swimmers alike. *Aquatrainer* (Figure 6.9(C)) leverages cloud-based platforms to monitor multiple swimmers in real time, offering tailored coaching and performance metrics during training sessions.

SwimMaster (Figure 6.9(D)) integrates wearable sensors and feedback devices to provide auditory, visual, and tactile cues for stroke

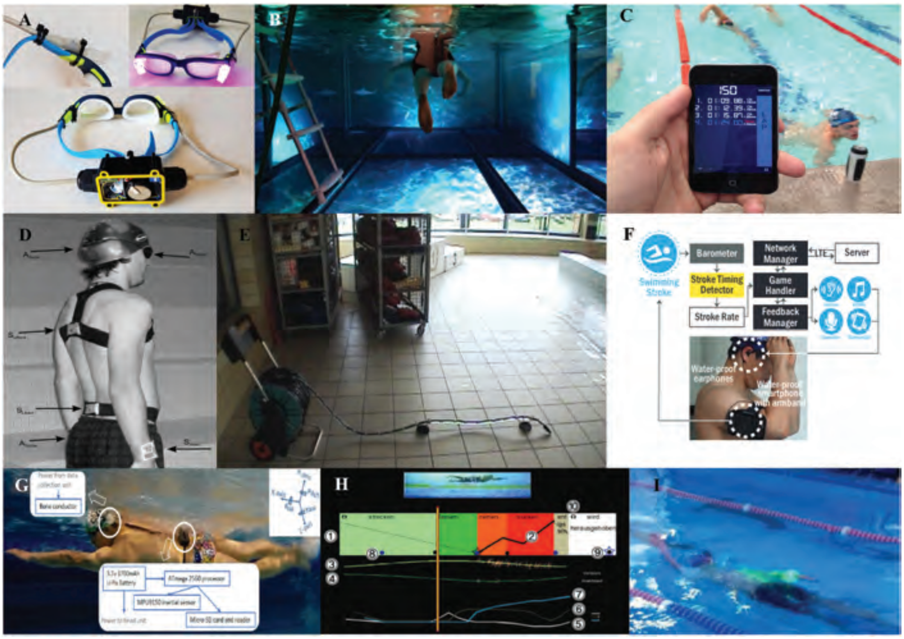

Figure 6.9: Water as challenge while floating systems. (A) The *Clairbuoyance* system: the control button (right), the device working in the ACF mode (right) and a detail of the hardware (bottom) (Kiss *et al.*, 2019). (B) Person swimming in the *AquaCAVE* system with multiple stereoscopic projections on surrounding acrylic walls (Yamashita *et al.*, 2016). (C) *Aquatrainer*'s mobile app (Coppo *et al.*, 2014). (D) *SwimMaster* system worn by a swimmer (Bächlin *et al.*, 2009). (E) LED strip speed feedback running system (Szczepan *et al.*, 2016). (F) *Swim Train*'s software and hardware architecture (Choi *et al.*, 2016a). (G) Diagram of the *Iswim* system worn by a swimmer (Li *et al.*, 2020). (H) *Auditory Swimming Coach* guide for musical improvisation (Seibert and Hug, 2013). (I) Swimmer using the wearable visible light communication system (Hagema *et al.*, 2013).

improvement, promoting efficient technique and reducing drag. *Swim Train* (Figure 6.9(F)) gamifies group fitness swimming through auditory cues, fostering collaboration and stroke rate management among participants. *Auditory Swimming* (Figure 6.9(H)) translates swimming strokes into musical scores, offering rhythmic guidance to enhance stroke timing and efficiency.

Iswim (Figure 6.9(G)) utilizes fuzzy logic-based feedback to monitor and improve body rotation during freestyle strokes, optimizing hydrodynamics and stroke efficiency. *Wearable Visible Light Communication* employs wrist-worn accelerometers and LED feedback to maintain optimal swimming pace, enhancing real-time stroke rate control and performance adjustment. *Video Replay Training* supplements traditional coaching with video feedback, allowing swimmers to analyze and refine their technique from a third-person perspective. Lastly, the *LED Strip speed feedback* system (Figure 6.9(E)) provides visual feedback on swimming speed, aiding swimmers in adjusting their stroke intensity for improved performance and efficiency.

Overall, these systems exemplify how technology can transform the aquatic experience by supporting swimmers in overcoming the inherent challenges of water, thereby enhancing enjoyment, safety, and performance in aquatic activities. For example, passive and wearable technologies, such as *Clairbuoyance* and *SwimMaster*, are particularly beneficial as they allow for natural, uninterrupted swimming. Immersive environments like *AquaCAVE* and innovative feedback methods, including auditory and visual cues, significantly improve training and technique retention. Moreover, leveraging IoT and mobile devices, as seen in *Aquatrainer*, facilitates real-time monitoring and coaching of multiple swimmers. Finally, the adaptability of simple commercial technologies, such as video replay, and the use of vibrant visual feedback systems like the *LED Strip Speed Feedback System* underscore the importance of user-friendly and versatile solutions in aquatic contexts. These insights collectively highlight that water as a challenge can be addressed through the mentioned design decisions.

6.5.3 Water as a Synergy While Floating

We now present three WaterHCI exemplar systems of "water as synergy" user experience while floating in water (Figure 6.10). *Goby* (Figure 6.10(A)) is a smartphone app designed to support the independence of visually impaired swimmers while they are lane swimming in a pool (Muehlbradt *et al.*, 2017). The app utilizes the camera and gyroscope embedded within the smartphone and requires waterproof Bluetooth earphones. The phone is placed in a standard waterproof case attached to the user's waist. When the user is swimming in a standard-sized lap

Figure 6.10: Water as a synergy while floating systems. (A) A swimmer is wearing the *Goby* system in a pool while *Goby's* wearable camera tracks a lane marker at the bottom of the pool to be used as a guide (Muehlbradt *et al.*, 2017). (B) Swimmer wearing the *MobyDick* system and *MobyDick*'s network configuration diagram (Choi *et al.*, 2014). (C) *Swimoid* system travelling below a swimmer to offer them visual feedback regarding their stroke technique (Ukai and Rekimoto, 2013).

pool, they receive voice alerts if they drift away from their lane's black line or are approaching the end of the pool (Figure 6.11). Interestingly, an almost identical system (Oommen *et al.*, 2018) was independently developed at the same time, and due to their similarity, we will treat them as one system.

MobyDick (Figure 6.10(B)) offers swimmers a mentally stimulating yet physically engaging activity that incorporates all four swimming strokes (Choi *et al.*, 2014). *MobyDick* transforms swimming into a multiplayer game where in which swimmers collaboratively hunt an underwater monster. Swimmers are equipped with waterproof smartphones and headphones to synchronize their swimming towards a main goal, so they have to work together synergistically. On the other hand, *Swimoid* (Figure 6.10(C)) is a buddy robot that swims below its user allowing athletes to view their movements from a 3rd person perspective on its attached screen (Ukai and Rekimoto, 2013). *Swimoid* facilitates real-time coaching, allowing its user to view and adjust their technique while they are swimming. The robot also features a game mode where players dive down and tap the camera when enemies appear on the screen. *Swimoid* leverages the consistent color of the water surface as a background for color-based swimmer tracking.

Overall, these systems work synergistically with the environmental features to operate effectively in the water. *Goby* uses the standardized layout of swimming pools, *MobyDick* transforms the repetitive nature of swimming strokes into game mechanics, and *Swimoid* utilizes the consistent color of the water surface for swimmer tracking. Taken together, specifications and patterns of a standardized aquatic environment can be leveraged by systems to improve their effectiveness and support an experience of "water as synergy".

6.6 Column 7: Underwater

We now discuss WaterHCI systems that are characterized by their users being underwater and having experiences of enablement and challenge (but not delight nor synergy).

6.6.1 Water as Enabler While Underwater

Shark Punch (Figure 6.11) is a VR game played while underwater in a pool (Quarles, 2015), where players must defend themselves from a virtual 3D shark by executing punching movements. These movements are tracked by an accelerometer embedded in a smartphone attached to the player's waist, enabling real-time interaction within the game environment (Quarles, 2015). *Shark Punch* was developed as a serious game for physical rehabilitation, focusing on building muscle strength and joint mobility. The game leverages the buoyant properties of water to facilitate free movement without the need for assistive devices, such as canes or wheelchairs, thereby expanding the range of motion and allowing users to engage in therapeutic exercises in a more engaging and motivating way.

This system exemplifies the concept of "water as an enabler" while underwater, demonstrating how the buoyancy of the aquatic environment can be harnessed to reduce the physical demands of rehabilitation, particularly in terms of balance and exertion. The integration of VR in aquatic settings, as seen in *Shark Punch* and the *"3D Pointing" system* mentioned above, suggests a promising avenue for further exploration, particularly in understanding the role VR can play across different quadrants of aquatic experiences.

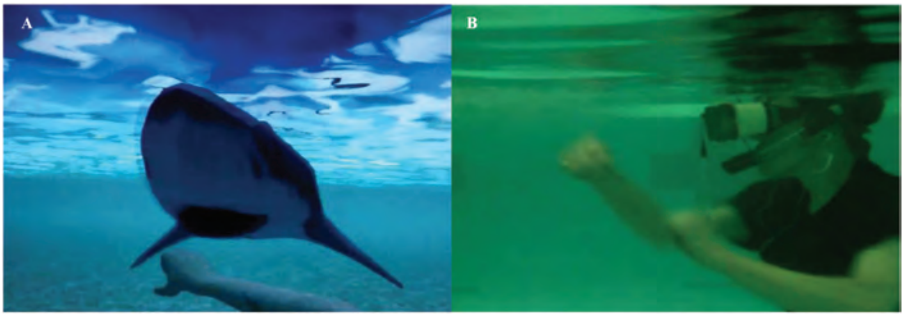

Figure 6.11: The *Shark Punch* system. (A) Virtual image of a shark displayed in the system. (B) The user is underwater in a swimming pool, wearing the *Shark Punch* system, and performing a punching action (Quarles, 2015).

6.6.2 Water as a Challenge While Underwater

Here, we present four WaterHCI systems—*Drowning Prevention Swimming Cap* (Lin and Xie, 2010), *AR Heritage* (Čejka *et al.*, 2020), *AREEF* (no snorkel) (Oppermann *et al.*, 2013, 2016), and *Smart Spa* (Büsching *et al.*, 2016)—that demonstrate the challenges that water presents when designers aim to use interactive technologies while users are underwater. These systems highlight how some water's environmental features, such as limited visibility, the necessity for periodic surfacing for air, and the difficulties in communication and tracking underwater, can serve both as obstacles and as opportunities for innovation.

The *Drowning Prevention Swimming Cap* (Figure 6.12(A)) system can detect if its wearer is drowning and alert lifeguards or other bystanders of the need for rescue (Lin and Xie, 2010). Although most pools and popular beaches employ lifeguards to watch for drowning incidents, a variety of factors can make it difficult for them to see submerged patrons who may be drowning. Hence, this system contains a pressure sensor that triggers a red LED when the user's head goes more than one meter underwater. The *Drowning Prevention Swimming Cap* system addresses the drowning challenge that water bodies can create, only making its presence felt when intervening for safety.

The *AR Heritage* system (Figure 6.12(B)) facilitates an augmented experience for divers at underwater archaeology sites, allowing them to visualize the ancient buildings that once existed there (Čejka *et al.*,

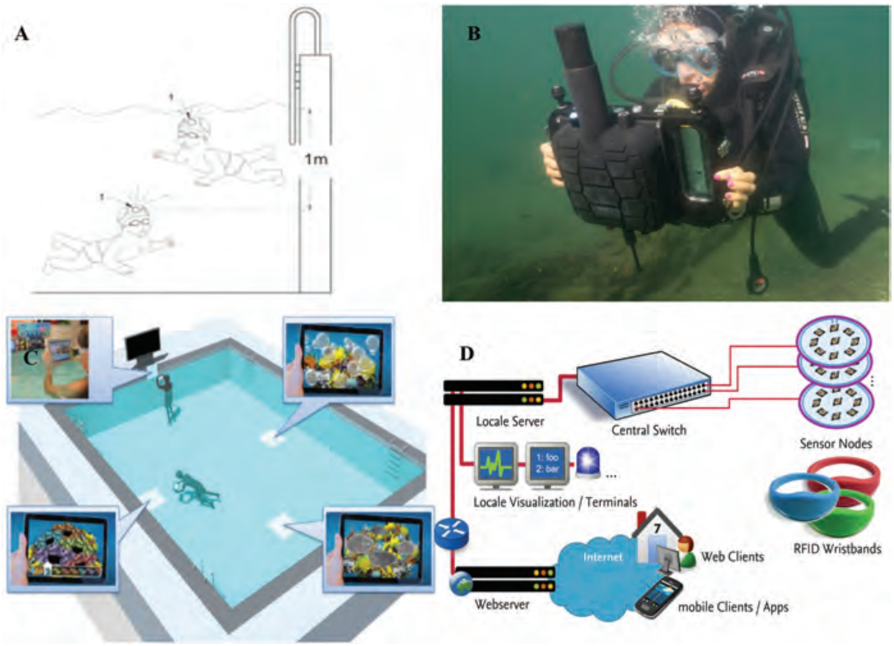

Figure 6.12: Water as a challenge while underwater systems. (A) Operation diagram of swim cap (Lin and Xie, 2010). (B) Diver using the AR underwater case coupled with the acoustic localization system (Čejka *et al.*, 2020). (C) *AREEF (no snorkel)* configuration in a pool. Markers spread about the pool showing different content on the tablet when the players approach, and the base station at the pool side (Oppermann *et al.*, 2013, 2016). (D) *Smart Spa* system configuration (Büsching *et al.*, 2016).

2020). This system addresses water as a challenge for both the technology and the user while they are diving underwater. Users have difficulty maintaining orientation and visual clarity underwater; while the AR system guides them, it has to rely on acoustic localization.

AREEF (no snorkel) (Oppermann *et al.*, 2013, 2016), is an upgraded version of the *AREEF* system presented in "water as an enabler while floating" section. *AREEF* (no snorkel) (Figure 6.12(C)), allows users to dive underwater using tablets in waterproof casings to play a treasure game, where users see virtual fish and corals as they pass over visual markers in a pool, "collecting" them for points. After collecting a target, players swim over to a base station on the edge of the pool to update their score (via Wi-Fi) and receive a new target creature to collect. *AREEF* (no snorkel) tackles the challenge of intermittent air access during underwater gameplay, using this necessity as a design feature to synchronize device communication.

The *Smart Spa* system (Figure 6.12(D)) is a prototype for turning a regular swimming pool into a multipurpose interactive space by attaching RFID wristbands to users and positioning RFID readers around the facility (Büsching *et al.*, 2016). The readers feature LED lights of different colors so games such as "Connect Four" and "Capture the Base" can be played by interacting with them. The *Smart Spa* system faces the technical challenge of waterproofing and adapting land-based games to an aquatic environment, highlighting the range of recreational experiences that can be supported with a single system: The same sensors and wristbands used for playing games in the diving tank are also used to track laps swum by people training in the other pool.

7

Design Gaps Identified Through the Frameworks

Having presented our WaterHCI systems, we can now identify and discuss the WaterHCI design gaps based on the empty cells in our table.

7.1 Design Gaps

Table 7.1 summarizes the cross-referencing of systems with Raffe *et al.*'s (2015) six degrees of water contact and Clashing *et al.*'s (2022b) four aquatic user experiences. We highlighted the empty cells in grey. We then elaborate on these underexplored areas in relation to the aquatic user experiences, i.e., the rows.

7.2 Water as Delight

We observe that with respect to the UX of water as delight, there are three degrees of contact with water that we did not find systems for (on top, floating, underwater). We invite designers to ask how they would design for delightful interactivity (i) on top of water, (ii) floating in water and (iii) underwater. Clashing *et al.*'s (2022b) framework suggests strategies for creating such experiences using water as delight. However, we acknowledge that these strategies are based on prior work, and

Table 7.1: The grey cells highlight underexplored areas in the design of WaterHCI systems

Degree of water contact/ Water user experience	Vicinity	Sporadic	On top	Partially submerged	Floating	Underwater
Water as delight						
Water as enabler						
Water as challenge						
Water as synergy						

we encourage designers to consider taking inspiration from emerging technologies and other aquatic-related fields and industries. In addition, designers could leverage water as delight to create playful aquatic systems since playful attitudes can emerge from stimulating the senses in new ways (Lucero *et al.*, 2014; Lucero and Arrasvuori, 2010, 2013). For example, the empty cells regarding "delight" inspire us to envision interactive systems that use jets to pump water of different salt and mineral content at people in water spas to facilitate different wellness experiences: the user will be treated with different water coming from the jets, where the water's origin corresponds to visuals the user sees through the head-mounted display they are wearing. Such as, seeing scenery from the black sea will result in water from the black sea being jetted at the user to massage their muscles while they are floating in a water spa. We can envision similar jets mounted on a stand-up paddle board, spraying water at the paddler on top of the board, where the water temperature is a response to the user's body temperature: if too hot from paddling, the water is meant to cool down if getting cold, the water is warmer. Similarly, when under water, divers could enjoy different water jets coming from the base of the pool during training where the water temperature responds to their body temperature to support a delightful training session.

7.3 Water as Enabler

Similarly, regarding the UX of water as enabler, there are two degrees of contact with water that we did not find systems for (vicinity, sporadic). We invite designers to ask how they would design for water as an enabler in contexts such as (i) vicinity to water and (ii) sporadic contact with water. We believe that there is an opportunity to utilize land-based technologies in the building of such systems given that waterproofing and pressure control are probably of less concern in these two contexts. Moreover, designers can design playful aquatic systems by utilizing water as enabler, since an enabler system can provide a sense of agency to users thanks to the water. For example, an enabler system can facilitate playful attitudes when supporting the user in the water activity allowing them to enjoy being in the water and explore the sensations that water creates. Such a system could take the form of very large water tanks mounted on self-driving robotic wheels with only a small dome at the bottom that allows a person to inhabit this large aquarium, enabling fish-like experiences where everything they see they experience through a large body of water. Such a surreal human-in-an-aquarium-like experience could facilitate enhanced empathy for the life of fish in captivity.

7.4 Water as Challenge

Regarding the UX of water as challenge, there are two degrees of contact with water that we did not find systems for (vicinity, sporadic). We therefore invite designers to question how they would design for water as challenge in the contexts of (i) vicinity to water and (ii) sporadic contact. Here, we suggest that there are opportunities to design systems that allow users to experience water as a challenge in natural environments where water dynamics are less predictable. Furthermore, we found only one system responding to each of the "on top" and "partially submerged" degrees of contact, which indicates that these contexts could also be further explored. Water as challenge could also be considered by designers who are interested in developing playful aquatic systems that present user challenges that facilitate a flow state (Csikszentmihalyi, 2014; Csikszentmihalyi and Csikszentmihalyi, 1988), thereby keeping the users motivated and engaged in their water activity. Challenges in aquatic environments can be leveraged by designers because their work to overcome these challenges can encourage a sense of enjoyment and pleasure and facilitate a playful attitude (Csikszentmihalyi, 2014; Csikszentmihalyi and Csikszentmihalyi, 1988; Lucero *et al.*, 2014; Sinclair *et al.*, 2009). For example, we can envision sports training systems of land-based athletic activities that consider the predicted weather forecast at the upcoming competition venue: if rain is predicted, the system will automatically turn on the sprinklers in order to provide the athlete with the most similar wet conditions to optimize their training.

7.5 Water as Synergy

The UX of water as synergy presented the most design gaps, with four degrees of contact not identified in our survey of systems (vicinity, sporadic, partially submerged, underwater). In this regard, we suggest that designers consider how they would design for water as synergy in scenarios of (i) vicinity to water, (ii) sporadic contact with water, (iii) being partially submerged in water and (iv) underwater. We hope that designers are able to see opportunities that utilize the unique features of aquatic environments to promote a synergetic collaboration between the users, the technology and the water. There are a variety of useful features to choose from in each of these vicinities; for example, an exertion-based application on a beach might consider guiding users near the waterline when they are overheating so that they may be cooled off by waves on their ankles and ocean spray on their bodies. Another idea is a partially submerged system in the form of an additional arm for a swimmer to collect floating garbage as they swim in the ocean, with the technology leveraging buoyancy to keep the garbage at the surface and the swimmer experiencing the concentration of waste as a sustainability problem. WaterHCI systems such as this could bring SustainabilityHCI (Knowles *et al.*, 2018) to the water through the synergy quadrant. Another system we can envision would help people train in aerial acrobatics using augmented reality: through the headset, users could receive instructions and guidance, including how to perform certain tricks depicted through slow-motion videos. However, during land-based training, the user cannot perform many tricks, such as back-flips, in slow motion to check if their movements match the video. However, the augmented reality headset would also support underwater usage, allowing the user to perform the backflip at the same speed as the video to allow for accurate comparisons with the instructional video.

Since water as synergy systems produce a combined effect greater than the sum of their parts, designers can take advantage of the playful attitude that arises when users collaborate with each other (Lucero *et al.*, 2014; Lucero and Arrasvuori, 2013) and, in this case, with the aquatic environment and the technology to achieve a goal.

Taken together, the aforementioned investigations highlight that there are many opportunities for HCI practitioners as well as researchers who are interested in WaterHCI systems and developments. However, we also believe that our work highlights opportunities from within the WaterHCI field that could advance the interaction design area more broadly. For example, we find that many of the results from investigating user experiences with interactive technology on and around water could also inform the design of land-based systems that might be used near water settings, therefore expanding the possible application locations these systems might be used in. Furthermore, underwater investigations might expand our understanding of land-based HCI experiences by enabling comparisons that could highlight what makes land-based HCI unique to other environmental settings. These settings could include air-based settings, such as is common in most HCI projects, but also air-less environments, like outer space. Lastly, we believe that a better understanding of the coming together of interactive technology and water might also enhance our understanding of HCI theory. For example, we are inspired by prior work that found that interactive experiences in water can align not just with one, but multiple relations (such as embodiment, background and immersion relations) suggested by postphenomenology [to appear]. This highlights for us that land-based technology experiences might also benefit from being examined through multiple postphenomenological relations at the same time rather than through just one, as so often previously done, elevating the potential impact interactive systems can have on people's lives. With such an enhanced view on theory, we might gain a more comprehensive understanding of interaction design more broadly, we believe.

8

Future Work

Our analysis indicated that various design aspects appear to be underutilized across the literature, and we are concerned that the absence of some of these design aspects can slow the progress of interactive aquatic design. In this section, we discuss our concerns relating to these design aspects and encourage future work.

8.1 Use and Development of Frameworks

We begin by noting that it appears that there is a shortage of frameworks to guide the design process and system development for WaterHCI systems. By offering a theoretical contribution to design work, frameworks can influence the development and implementation of new systems, particularly for novel interaction styles (Girouard *et al.*, 2018). However, only two of the aforementioned prior works made use of existing frameworks: Splash Controllers (Geurts and Abeele, 2012) used the MDA framework (Hunicke *et al.*, 2004), and Siebert *et al.* (Seibert and Hug, 2013) used Haverkamp's multisensory design framework (Haverkamp, 2009). While Gravity Well (Pell and Mueller, 2013a) developed a design guidance framework, the work focused only on informing future work in partially submerged and underwater contexts. Because frameworks typically reflect, expand upon, or compare existing frameworks (Girouard *et al.*, 2018), we suggest that future WaterHCI research might benefit from considering additional frameworks when it comes to the development and implementation of new systems, even including frameworks from outside the field.

8.2 Use of User Experience Evaluations

We also noted that there appears to be a shortage of user experience evaluations of WaterHCI systems. Within HCI, the value of user studies is central to the creation of an optimal system that suits user needs (Sharp *et al.*, 2019). We suggest that future WaterHCI systems should be designed with an experiential foundation, where technology is only the material to develop "meaningful, engaging, valuable, and aesthetically pleasing" experiences (Hassenzahl, 2011). We note that less than one-third of our systems was accompanied by an evaluation assessment of users' experiences. Within those, the authors exhibited varying levels of interest in user experience, ranging from the iterative development of a design based on the experiences of users (Baldwin *et al.*, 2019; Choi *et al.*, 2016a; Osone *et al.*, 2017; Ranson *et al.*, 1996), to the assessment of user experiences through interviews (Choi *et al.*, 2014; 2016b; Oppermann *et al.*, 2016; Schaffert and Mattes, 2015; Seibert and Hug, 2013) to a focus solely on testing the functionality of the device (Dietz *et al.*, 2014; Li *et al.*, 2016; Oommen *et al.*, 2018). We therefore point to the potential for future work to make use of user experience frameworks in order to help to better understand the user experience of WaterHCI systems, which in turn can support the development of future systems, ultimately benefiting the WaterHCI field as a whole.

8.3 Use of Established Design Processes

We also would like to note that there appear to be only minimal descriptions of the design process when it comes to WaterHCI systems. Following a design process has been shown to have value because it allows design teams to perform more efficiently (Gericke *et al.*, 2012). Only a few studies reported that their design process was based on participatory design (Baldwin *et al.*, 2019), field observation (Ranson *et al.*, 1996), user experience design (Quarles, 2015), or an iterative design approach (Muehlbradt *et al.*, 2017). In considering design approaches such as the human-centered design approach (Quarles, 2015), we suggest that designers of WaterHCI systems can consider not only the users' needs and requirements but also those of the water. This is because water, as a body with physical properties, could be considered another agent that requires the same attention as users from a methodological standpoint. For example, water in a fluidic interface cannot simply be placed on a table like a keyboard and mouse: it requires an appropriately shaped and sized vessel to contain it (Campbell *et al.*, 2015). We therefore suggest that design researchers engage with a particular design process and document their practice so that they (and others) can learn from it in the future, ultimately helping to build on each other's work that guides and informs upcoming developments in the aquatic domain.

8.4 Use of Underlying Values

We also note that there appears to be an underutilization of underlying values when it comes to WaterHCI. Within "value sensitive design", values are defined as what people consider important in their lives (Friedman *et al.*, 2013). While value sensitive design has been used in the HCI community (Borning and Muller, 2012), few of the WaterHCI works appeared to consider the role of values. Some studies did consider values such as accessibility by all cultures (Pares *et al.*, 2005; Parés *et al.*, 2005), cultural heritage preservation (Bruno *et al.*, 2019; Cejka *et al.*, 2021; Čejka *et al.*, 2020), ocean education (Bellarbi *et al.*, 2013; Oppermann *et al.*, 2013, 2016), water safety (Lin and Xie, 2010), and the desire for socialization (Choi *et al.*, 2014, 2016a; Lee *et al.*, 2013; Mann *et al.*, 2006a,b; Pares *et al.*, 2005; Parés *et al.*, 2005; Pell and Mueller, 2013a). However, we believe that there is room for improvement and hence encourage the greater use of personal or shared values (Borning and Muller, 2012) when it comes to future WaterHCI designs. Researchers should be explicit about their cultural standpoints when expressing values that inform WaterHCI designs because these values can differ from culture to culture. For example, some cultures revere water and recognize water bodies as persons (Australia, G. of., n.d.; Maclennan, 2007). To aid these developments, we direct researchers to consider the "virtues" of recreational activities, as explored in, for example, Mueller and Young's "10 Lenses" approach to sports design in HCI (Mueller and Young, 2018).

9

Limitations of Our Work

We acknowledge that our work has limitations, as does all work that aims to provide an overview of a sub-field of interest. In particular, we acknowledge that our results have not yet been validated through additional design work. We believe that there is an argument that our work is valid through the fact that it is based on two existing frameworks that have been peer-reviewed by the community; however, we acknowledge that further validation, such as through the design of new systems via the use of our table above, could be valuable. Furthermore, we believe that our work has value as it could already serve as a starting point for designers interested in creating novel WaterHCI systems as we can point them directly to opportunities for innovation. Furthermore, we point out that there appears to be not much other guidance available (with exceptions, like by Mann *et al.*, 2021). Hence, our work might be appreciated as initial advice on where to start. We encourage future work to validate our results, for example through workshops with designers who can report how useful they find our work in helping them develop new WaterHCI experiences.

We also recognize that combining only two frameworks in order to paint a picture of an entire sub-field of HCI has limitations. Considering additional frameworks could supplement our work, and so could the consideration of alternative ways of combining frameworks. Furthermore, completely new frameworks could be developed to structure similar investigations in the future. Nevertheless, we believe that our work can offer value as the combination of the two frameworks we selected is novel and might serve as a starting ground for future investigations. As such, we see our combining of the two frameworks not as a suggestion that this can be the ultimate approach to understanding WaterHCI, but rather as a first attempt to offer structure towards more comprehensive investigations. We encourage future work towards such investigations.

Furthermore, we recognize that we have relied on prior work as initial source to pool our systems from, therefore limiting the extent to which we were able to discuss prior work, potentially missing out on some systems. Nevertheless, we believe that this initial source was quite comprehensive, and our (informal) conversations at WaterHCI workshops and seminars (Clashing *et al.*, 2022b; Mann *et al.*, 2021, 2022) suggest that we are somewhat knowledgeable about the key works known amongst the community.

We also acknowledge that new technologies will change the WaterHCI field, just as new technologies, such as wing foiling, have enabled new watersports. With these changes, the field will face new opportunities and challenges. It is, therefore, important to view this monograph not as a conclusion, but as a current examination of the state of a field that will continue to evolve.

We have focused on academic works that are reported in HCI-focused articles and hence acknowledge that our view can be tainted by this perspective. We encourage future work to expand this perspective, by, for example, surveying commercial works. This might also include systems where users are concerned with water interactions but do not get in contact with water at all, such as remote-controlled underwater robots/submarines. The consideration of such systems and associated land-based experiences could also be useful for WaterHCI researchers, and we hence look forward to future work to also examine these.

We also acknowledge that our discussion of underexplored areas is entirely based on our table, which might suggest that these are the only areas worthy of exploring in the future. This is not the case; we merely present these areas to highlight opportunities for innovation and stress that future work should continue exploring the other areas as well. Together, this will allow bringing the WaterHCI field to the next level, we believe.

It is also important to note that our approach to begin with combining frameworks takes a particular stance on how knowledge is constructed and what role theory plays in this. We acknowledge that other approaches are certainly possible and recent HCI work suggests alternative pathways forward (for example, see Frauenberger, 2019). As such, any articulation of a sub-field like WaterHCI should, therefore, be seen as coming from a particular viewpoint that might need updating with emerging developments, speaking to the fact that HCI itself is a relatively new discipline that is constantly evolving (Harrison *et al.*, 2007) and benefits from the consideration of additional perspectives as the field matures (Harrison *et al.*, 2011). Technological advances, such as the emergence of big data, can also play a role in the way that knowledge is constructed (Kitchin, 2014), which in turn can then also affect how we understand knowledge (and hence works such as ours) within the WaterHCI field. Hence, any WaterHCI research should always be on the lookout for recent developments that will require an updating of the knowledge assembled so far in order to keep up with any advancements. This can be time-consuming but will ultimately lead to enhancements in and of the field.

We furthermore acknowledge that we may have a more positive view of WaterHCI's future and that the field could also take a dark turn, leading to technologies that distract people from the benefits of water engagement, as has already been suggested by the current prevalent use of mobile phones on beaches, with the technology engaging people at the expense of their engagement with the water. In this respect, the WaterHCI field has important research to do to ensure that interactive technology helps people profit from the many benefits that engaging with water can provide, rather than disengage from those benefits. To achieve this outcome, HCI researchers and practitioners may need to work with people outside the field, especially those with water expertise. We hope that our monograph provides useful information to inform such future investigations to steer the field into a positive future.

10

Conclusion

We believe that the coming together of water and interactive technology is an exciting new area within HCI that is increasingly gaining interest under the term WaterHCI. This increasing interest is fueled by technological advances, such as smaller, more rugged, and, of course, waterproof sensors. However, simply waterproofing devices is not doing full justice to the opportunities that water can bring to our interactions with technology.

Our investigation into what has been achieved so far in the WaterHCI field has identified numerous individual systems, often aimed at improving watersports athletic performance. While systems that support the joy of being in and engaging with water are less common, they are emerging, and they highlight that interaction design can support both the instrumental and the experiential aspects of water interactions.

We also find that more conceptual work is relatively underexplored in WaterHCI. The few works that exist aim to provide a more structured approach to how interaction designers can engage with the different ways that users can encounter water, and we have engaged with some of these prior works.

We hope that this monograph provides a better understanding of the characteristics of the WaterHCI field, its achievements so far, the opportunities it presents and the challenges that lie ahead. Furthermore, we hope that we have been able to excite emerging researchers about working with water and encourage and enable established WaterHCI researchers to expand and enrich the scope of their work.

We stress that the WaterHCI field is not only facing technical questions. There are, of course, many other questions (especially societal and ethical) still to be explored. We hope that our work provides a starting point for others to structure and begin those investigations. We believe it is also pertinent to point to the significant challenges related to water that the world faces, such as insufficient fresh water supplies, severe water events such as floods and storms as a result of climate change including rising sea levels, etc. Furthermore, we note that there are also many environmental pollution issues that come out strongly in the aquatic domain, such as the massive amount of garbage in today's ocean or noise coming from human structures in the ocean affecting marine life (Kunc and Schmidt, 2019). These issues significantly overlap with the problems already identified by the SustainabilityHCI (Knowles *et al.*, 2018) community and concerted efforts are needed to address them. We believe that WaterHCI researchers are probably very sympathetic to SustainabilityHCI efforts and that advances in one area will likely be beneficial to the other and vice versa.

Furthermore, we hope that interaction design efforts can help mitigate and address some of these negative issues and we are thankful for the projects emerging from the community to investigate these societal challenges, such as the "high water pants" (Biggs and Desjardins, 2020). The "high water pants" make cyclists aware (through mechanically shortening the pants) of rising sea levels when cycling through an area that is projected to be impacted by climate change. Such provocation research might have a significant effect on people's awareness of rising sea levels, and we encourage future work in this area. Nevertheless, we did not consider such works in our monograph as the system does not support aquatic activity (instead, it supports cycling), nor does the user, we would argue, have a water experience or come in contact with any water. Similarly, we did not include in our scope, for example, CO_2-awareness apps that aim to make people aware of rising sea levels.

We are very excited about the potential of the coming together of water and interactive technology. We believe that the resulting WaterHCI field can offer many advantages, helping people profit from the myriad benefits of water engagement. However, we also believe that, in turn, water can help advance the HCI field by enhancing and enriching our interactions with technology. We hope that our monograph provides interested readers with a better understanding of how the WaterHCI field can help them and provides insights into what WaterHCI offers to the users they aim to support. Ultimately, with our work, we aim to support researchers and practitioners to contribute to the coming together of interactive technology and water.

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