Grand challenges in WaterHCI

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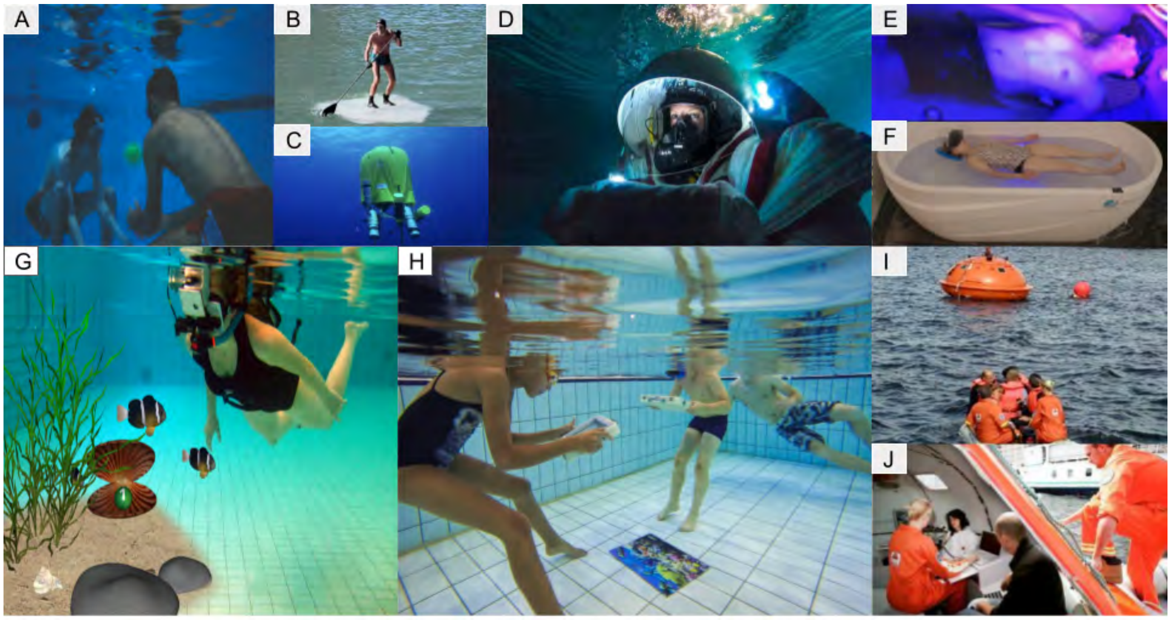

Figure 1: A collage of WaterHCI works: a) "Gravity Well" fosters aquatic play through robotics [143]; b) "Growlerboarding" is an interactive icewater paddling video game on a wearable display [87]; c) "Ocean Space Habitat" is a portable inflatable station to augment lengthy in-water decompression stops for divers [76]; d) "Project Moonwalk" conducted human-robotic cooperative lunar-analogue underwater trials; e) Extended reality in floatation tanks: "Sensory-reprivation tank" [92] and f) "Fluito" [106]; g) Augmented reality under water [135]; h) Playing with "AReef" in public pools [134]; i) "LifeBoat" is a biological laboratory and psychological profiling station (contained within an off-shore platform lifeboat), visa and passport processing terminus [53]; j) Inside "LifeBoat" [53].

ABSTRACT

Recent combinations of interactive technology, humans, and water have resulted in "WaterHCI". WaterHCI design seeks to complement the many benefits of engagement with the aquatic domain, by offering, for example, augmented reality systems for snorkelers, virtual reality in floatation tanks, underwater musical instruments for artists, robotic systems for divers, and wearables for swimmers. We conducted a workshop in which WaterHCI experts articulated the field's grand challenges, aiming to contribute towards a systematic WaterHCI research agenda and ultimately advance the field.

CCS CONCEPTS

• **Human-centered computing**; • **Interaction design**;

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1 INTRODUCTION

Interactions at the intersection of water, humans, and technology date back to the invention of vessels and rafts, leading to the claim that "vessels were the first cyborg prostheses" [85]. More recently, these have been complemented by a rich array of systems and investigations around the coming together of interactive technology and water, collectively referred to as "WaterHCI" [30, 31, 90, 92, 94].

Early examples of WaterHCI systems include: "SWIM" ("Sequential Wave Imprinting Machine") used cathode-ray oscillograph displays for exploring underwater acoustics and collaborative multi-swimmer video gameplay [192]; "Aqua-Syntauri", an interactive musical water fountain, allowed participants to interact with a

Table 1: A summary of our Grand Challenges, based on four groupings, and derived from the process detailed in section 3 "Process of identifying the Grand Challenges".

Technology for water environments	Users engaging with water	Designing water experiences	Ethics around water
Waterproofing technology	Evaluation framework for WaterHCI experiences	Designing implicit aquatic interactions	WaterHCI for and as sustainability
Developing materials for WaterHCI interactions	Supporting human senses in aquatic environments	Designing shared agency with aquatic tools	Applying WaterHCI safely
Water as interaction material	Sharing aquatic experiences	Overcoming aquatic environment constraints	Overcoming the divide in terms of accessibility to water
Toolkits for prototyping WaterHCI devices	Transitions in and out of the aquatic environment		Addressing cultural factors

computer by touching water jets [78]; and "Hydraulophone" [95], an interactive musical instrument, required physical contact with water in order to play it [83]. Recent WaterHCI examples range from: devices to help rafters navigate rivers [152] and avoid rocks [91]; novel force feedback modalities using water [57, 153]; virtual reality (VR) headsets for waterslides [10]; underwater camping tents that provide support for human-robot assistance [76]; to water pumps for interactive wet spectacles based on quantified-self data [65, 66] and augmented reality used in swimming pools to learn about marine life [135].

The aquatic arts tradition has also inspired performance research [140], for example involving the artist submerging in a tank filled with 17,000 liters of water to perform variations of John Cage performance instructions, including "Water Walk" and "Water Music" [139]. There have been underwater concerts [169], as well as a lecture by an underwater wheelchair performance artist [137, 172]. Mann et al. also created WaterHCI devices for other artists to use [84] based on their experiences of introducing interactive showers in art gallery settings [78, 81].

There are myriad opportunities for interactive technology to enhance water-based experiences and support the many benefits – improved physical and mental health as well as social relationships [127, 171, 176, 177, 183] – that engaging with water can provide. However, these examples also reveal that HCI has mainly engaged with water through one-off designs, without a structured overarching research agenda, limiting opportunities to advance the field. To consolidate ad-hoc research and discovery, we conducted a workshop with WaterHCI experts to articulate the field's Grand Challenges, spanning four categories: technology for water environments; users engaging with water; designing water experiences; and ethics around water. Grand Challenges are defined as major existing or potential limiting factors, and they are used to steer the direction of future research fields [168]. Our collaborative approach was inspired by prior work that aimed to advance diverse sub-fields of HCI via Grand Challenges in: social robotics [175], information retrieval [13], crowdwork [69], humanistic intelligence [104], shape-changing interfaces [5], human-computer integration [121], and immersive analytics [44]. Table 1 illustrates a summary of our Grand Challenges, based on the groupings above, and derived from the process that we detail in section 3 "Process of identifying the Grand Challenges".

Introducing interactive technology into aquatic environments can result in unique "in", "on", and "under" water interactions (all promoting specific benefits [127]) that are uncommon to normal terrestrial interactions. WaterHCI researchers are uniquely equipped to address these. For example, in rehabilitation settings, they apply technical and design expertise to develop devices to make repetitive exercises more engaging and accessible through waterproofing virtual reality headsets, gamification techniques, and leveraging water's buoyancy [150]. Furthermore, they understand the methods to evaluate associated first-person felt experiences of being in water [56] and physiological changes that occur during aquatic immersion [12].

As a result, WaterHCI is more than simply an application domain for HCI. WaterHCI offers distinctive opportunities (unique experiences such as floating, tactile sensations, etc.) as well as significant challenges (skin pruning, drowning, visual and acoustic distortion, etc.) that span experiences from everyday showering to space simulation in pools. These considerations demand their own dedicated research effort to keep abreast of blue economies [184], epistemologies [59], and the sensorium of oceanic embodiment technologies [103] to respect that we are made of water, that we come from water (in the womb) [50], and that we require a lifelong water-body practice [131] to survive while embracing its many benefits.

While other sub-fields of HCI can contribute to WaterHCI (such as wearable computing helping to reduce the size of swimming devices), WaterHCI has unique hydrodynamic design requirements (such as the need for waterproofing and pressure resistance). In turn, WaterHCI can give back insights to other sub-fields of HCI, for example, we believe that "immersion" for VR experiences can be better designed if we understand the design of immersion in water better [106]. Furthermore, as WaterHCI allows us to understand interactions with technology in saturation environments, the translation of principal insights can also inform the research and design of general-HCI experiences for humans in different density, viscosity, hydrostatic pressure, and specific gravity environments, such as on mountains [126], underwater habitats [76] and excursion activities on the Lunar surface [58, 141, 142].

When it comes to the similarities and differences between the challenges WaterHCI and general-HCI researchers face, we refer to prior work that listed Grand Challenges for HCI [168]. Some of the

Table 2: Contributions and benefits to expectations, stakeholders, and application areas.

Contributions	Benefits	Expectations	Stakeholders	Application areas
Identification of gaps in knowledge in WaterHCI	More people working in WaterHCI, advancing the field and hence more people profiting from water's benefits	Helps bringing non-WaterHCI researchers into the field by aiding them identify where they can contribute	HCI researchers not working in WaterHCI	Research that advances the coming together of interactive technology and water
Larger research agenda in the form of four Grand Challenge categories	External partners gain a better understanding of how projects contribute towards the societal goal of engaging people in aquatic activities	Helps WaterHCI researchers situate their work within a larger research agenda	External partners, like funding agencies	Funding applications that ask for articulating how projects contribute towards larger goals
Grand Challenges articulation	Guiding PhD students in selecting research topics that advance WaterHCI as a whole	Working on Grand Challenges advances the field more than incremental research	Higher degree by research candidates such as Master's and PhD students	Thesis contributions
Summary of Grand Challenges	Prepares industry what trends to expect	Helps practitioners anticipate what future WaterHCI experiences emerging interactive technologies can enable	Practitioners such as pool operators, aquatic leisure park designers, watersports equipment developers, etc.	Better aquatic infrastructure
Articulation of benefits if Grand Challenges are solved	Motivates HCI researchers to work on topics that support end users	Helps people profit from the many benefits of engaging in aquatic activity	End users	Physical, mental and social health and wellbeing
Articulation of relation of Grand Challenges to aquatic interventions	Accelerated advancements in aquatic interventions thanks to interactive technology	Helps organizers to utilize latest developments to advance their aquatic interventions	Participants in interventions such as aquatic rehabilitation, swimming classes, surfing therapy [99]	Enhanced intervention outcomes, such as increased safety around beaches

authors' general-HCI Grand Challenges (such as ethics, health, and human-environment interactions) are more specific to WaterHCI and our work may aid in solving them in part (as evident in, for example, our "WaterHCI for and as sustainability" challenge). Equally, some general-HCI Grand Challenges ("Democracy") have a lesser specific equivalent in WaterHCI. The same applies to other HCI subfields: for example, "Grand Challenges for Immersive Analytics" [44] asks for "Establishing an Evaluation Framework for Immersive Analytics" which speaks to our "Evaluation framework for WaterHCI experiences", while "Assessing Collaborative Work" does not seem to be specific to WaterHCI. As such, we believe that addressing WaterHCI is worthwhile, distinct, and specific compared to both general-HCI and other sub-fields of HCI. In response, we now outline our contributions and benefits to expectations, stakeholders, and application areas (Table 2).

2 BACKGROUND

By providing an overview of the evolution of the WaterHCI field, we aim to establish a basis on which we articulate our Grand Challenges. A few prior research efforts have tried to go beyond one-off designs and looked at WaterHCI from a more holistic perspective. The results included survey work, broader frameworks for WaterHCI design, and community-building efforts such as conferences, which informed the Grand Challenges discussed in this article.

A recent survey tried to synthesize the findings of the increasing number of WaterHCI publications. The survey (with six of the authors attending our workshop) conceptualized two dimensions: the first dimension being water as an "opportunity or challenge for the user", and the second being water as an opportunity or challenge for the technology [31]. This led to the articulation of four different user experiences that WaterHCI designers can pursue: "water as delight"; "water as enabler"; "water as challenge"; and "water as synergy" [31]. Our "Users Engaging with Water" category considers various modes in which designers can engage with water to facilitate different user experiences.

Frameworks have also been developed to help researchers better understand the opportunities they have when introducing technology to existing water-based activities. For example, Raffe et al. (with two of the authors attending our workshop) proposed to consider "six degrees of water contact", namely "vicinity, sporadic contact, on top of water, partially submerged, floating, and underwater" [151]. The authors noted that these degrees of water contact affect a technology's "networking, acting, sensing, and state" features. Our "Technology for Water Environments" category considered challenges relating to these features across the six degrees of water contact.

Prior work also resulted in frameworks relating to the use of water (supplemented by technology) in artistic experiences [7, 81]. The authors made two arguments: first, that locating the "body aquatic" in all stages of design is significant to Grand Challenges [70, 155]; and second, that a designer's conceptual choices must acknowledge the agency of water bodies [20]. Our discussions regarding "Designing Water Experiences" touched upon these challenges.

Prior works also tried to facilitate community building. For example, since 1988, the annual "WaterHCI" event [80] has explored WaterHCI culture, technology, engineering, science, philosophy, and art. These explorations have led to the development of a taxonomy that focuses on interfaces where water enters the human versus the human entering water, when technology enters the human versus the human entering technology, and when water enters technology versus technology entering water. This taxonomy embodies three dimensions along which WaterHCI systems could be placed, namely: "water+user", with water as an opportunity or challenge for the user and vice-versa; "water+technology", with water as an opportunity or challenge for the technology and vice-versa; and "user+technology", with technology as an opportunity or challenge for the user and vice-versa. The result is three planes: the water plane, the user plane, and the technology plane [86]. Our workshop discussions also considered the three elements of water, human, and technology, and how they intersect. However, with our workshop, we tried to go beyond descriptive conceptualizations and instead aim to inform the development of future systems.

In 2021, a hybrid conference and associated events (which included swimming) identified four WaterHCI challenges: first, water "priveillance", which involved the consideration of privacy, surveillance, and sousveillance while bathing or using the toilet in an environment that might contain sensors such as video cameras [93]; second, "vironmentalism", which is concerned with the interplay between the environment and the "invironment" in WaterHCI; third, water justice and human rights in WaterHCI; and fourth, reliability, meaning the difficulty associated with getting sensing and computation to work well when wet or underwater. Our workshop discussions regarding "Ethics Around Water" addressed the first three of these challenges and our "Technology for Water Environments" addressed the fourth. Furthermore, a symposium [92] proposed four challenges for WaterHCI: the aforementioned "priveillance", fairness (for example, human rights to limited water resources), technology (for example, water presents unique challenges such as waterproofing) and health (for example, positive health benefits as a result of engaging with water but also dangers such as drowning). Several of our workshop participants took part in the events above, thus their outcomes also informed our discussions on the Grand Challenges.

In summary, although prior efforts have produced surveys, frameworks, etc., there is still only limited knowledge that could form a basis for a future research agenda. As such, we aim to begin answering the research question: "What are the Grand Challenges that WaterHCI is facing that could form a basis for a future research agenda?" Without knowing what the Grand Challenges are, we have limited chances to solve them. In contrast, with an articulation of Grand Challenges, we have a basis for a future research agenda that could begin solving them. Ultimately, this will help drive the WaterHCI field forward.

3 PROCESS OF IDENTIFYING THE GRAND CHALLENGES

This section outlines our process, inspired by prior works that also aimed to articulate Grand Challenges for an HCI sub-field: shape-changing interfaces [5], human-computer integration [121], and immersive analytics [44].

3.1 Participants

During a premier HCI conference, 17 participants (Table 3) took part in a workshop. Participants were recruited through the website of the HCI conference. We also designed our website and promoted the workshop widely on HCI-relevant e-lists and socials as well as through word of mouth. Potential applicants had to write a position statement that included their aquatic background, their personal experiences with the interaction between water and technology, and a discussion on water-based systems that they have worked on or are aware of in industry or research. This statement also needed to include images that illustrated their positive or negative experiences with water. The workshop spanned 2 days, lasting in total 6.5 hours plus regular breaks, with an additional asynchronous mapping activity of prior water-based systems in between. Participants had to register for at least one day of the conference and pay for the workshop registration. There was no compensation provided.

We chose a workshop format based on prior work that also used a workshop to arrive at Grand Challenges [5, 44]. Alternative formats are possible, such as seminars [121] or reflection [13], however, we leave these for future investigations to complement our work. Our participants have had experience designing, evaluating or analyzing WaterHCI systems, and several are leaders in the field, with expertise spanning augmented reality in water, aquatic art, toolkit design for water, and augmented human in water. In particular, they had designed underwater augmented reality 3D games, studied the effect of water immersion on vection in virtual reality, investigated accessible virtual SCUBA experiences for people with impairments, designed a platform for artists to create interactive water-based shows via autonomous watercrafts, explored water-based interaction techniques that exploit the electrical and optical properties of water for sensing user interactions, designed an interactive fountain that recedes when approached by human hands, invented pump toolkits and designed a harp-like musical instrument with strings made of flowing water, amongst others. The combined credentials included having organized over 20 WaterHCI events, developed more than 30 WaterHCI systems and written over 40 papers on WaterHCI. This was supplemented by their backgrounds such as a commercial occupational diver, a PADI dive master, an experienced underwater photographer, sailing with blind sailors over large distances, and rowing across oceans. The participants possessed varying levels of water competence, too, with two non-swimmers and fifteen with swimming abilities. The participants' personal water experiences included water polo, underwater hockey, surfing, wing foiling, stand-up paddle boarding, and kayaking among others.

Table 3: Participant demographics: participant; age; gender (female, male, non-binary, self-described); work experience in years; WaterHCI experience in years; WaterHCI experience domains; disciplinary background; affiliation: academia (uni), industry, or both; country.

#	Age	Gender	Experience	WaterHCI experience	WaterHCI experience domains	Disciplinary background	Affiliation	Country
1	43	m	19	1	Accessibility, sensing and sensors	Tangible computing, accessibility, computational toolkits	Uni	AU
2	34	f	15	1	Literature review	Swimming, diving, sports development	Uni	AU
3	41	m	20	5	Aquatic virtual reality	Virtual reality, augmented reality, mixed reality	Both	USA
4	52	m	29	20	HCI for underwater habitats & diving, art/installations	Affective & context-aware computing, learning sciences, creativity research	Uni	USA
5	47	f	17	2	Water-based interactions, water spectacles, interactive fountains, water-based drones	Tangible & embodied interaction, interactive surfaces, embodied cognition, creativity & expression	Uni	CA
6	-	f	43	23	Underwater performance, aquabatics, undersea analogue	Human performance, live art, commercial diving, human factors	Both	AU
7	52	f	25	4	Inclusion	Accessibility	Uni	AU
8	29	f	6	2	Playful design, virtual environments, biosignals	Engineering physics, biophysics, games for health, virtual reality applications	Uni	AU
9	61	m	30	25	Interactive fountains, displays, prototyping tools	Electrical engineering, HCI	Uni	CA
10	44	m	16	3	Sport, games, boating	HCI, mixed reality, games	Uni	CA
11	29	m	6	2	Swimming, athletic performance	HCI, feedback design	Uni	CA
12	48	m	20	17	Underwater AR, mixed reality, game, entertainment, edutainment	Computer science, media informatics, pervasive games, mobile, mixed reality	Both	DE
13	45	m	20	2	Swimming, waterproofing, cold	Computer science, HCI	Uni	UK
14	26	m	10	2	Robotics, sensing, swarm robotics	Computer Science	Uni	CA
15	43	m	15	18	Blindsailing, seamark, wind feeling, non-visual representation	User experience	Uni	FR
16	25	m	4	2	Robotics, human-water interaction	HCI, narrative-based interaction, interaction design	Uni	CA
17	-	m	25	6	UX, design, theory	HCI	Uni	AU

3.2 Discussion process

Our discussion process (including tools employed) (Figure2) was inspired by workshops with analogous aims [44, 121] where participants were invited to write down before the workshop their past experiences with the topic, both positive and negative, to fuel thinking about Grand Challenges early on. The organizers also shared papers beforehand outlining what other HCI sub-fields have done to articulate Grand Challenges [5, 44, 121].

The workshop began with presentations about participants' past WaterHCI research and the challenges they encountered. During the talks, participants were encouraged to note down any thoughts on a shared online whiteboard that could be useful for the articulation of the Grand Challenges. This led to an initial articulation of Grand Challenges and a grouping that were then discussed in groups before the results were shared amongst the entire cohort. The groups were organized to help give less vocal participants a chance to have their opinions heard. A representative of each group presented their findings. Then, participants were asked to give names to each grouping and also turn the short post-it descriptions into fuller and richer textual explanations. After an initial structured draft emerged, groups worked on the individual Grand Challenges, which continued beyond the workshop where participants arranged their own synchronous and asynchronous online discussions that led to a further refinement of the Grand Challenges. This collaborative writing approach was supplemented by editing sessions where it was decided which challenges were so grand that they needed to stay, in comparison to those that could be cut for brevity purposes. We reminded participants that we needed to identify challenges that are "grand", i.e., that are challenging for

Figure 2: Each step of our process and tools employed.

the field and are probably not easily solved with, for example, a small student project.

We considered prioritizing some Grand Challenges over others, however, found an ordering in terms of, for example, urgency or implementation difficulty, not very useful. There was no formalized methodology for the discussions, but rather, the approach was discursive and informal, where the quality of the output was a function of the expertise of the participants. We also discussed various alternative grouping options to ultimately decide on our four categories, inspired by the four categories identified in prior Grand Challenges work [5, 44, 121].

4 GRAND CHALLENGES IN WATERHCI: TECHNOLOGY FOR WATER ENVIRONMENTS

4.1 Waterproofing technology

WaterHCI interactions rely on interactive devices that are suitable for use in an aquatic environment, i.e., are waterproof. Such waterproofing must prevent electric shocks to protect the device but also the user, all while not hindering the intended interactivity.

4.1.1 Waterproofing to protect interactive devices and users through IP ratings. Even though prior work has highlighted that waterproofing is not the panacea for all WaterHCI challenges [30, 31], waterproofing is still one of the field's Grand Challenges because interactivity and water do not mix well: if we want to support interactions with water, we need to consider interactive devices, which mostly rely on electronic circuits. Getting these electronic circuits wet can produce shorts, which can not only damage the device but also lead to injury and even death. One aspect of waterproofing is therefore to keep participants safe while also protecting the interactive device. Another aspect is to ensure that the device remains usable and offers the expected interactivity (e.g., traditional touchscreens do not work well, if at all, when wet).

Unfortunately, "waterproof" is not clearly defined although frequently used in advertisements for devices like smartphones. IP ratings remain the only clear indicators of a device's capacity to resist moisture ingress. In general, a device's IP rating consists of two digits, occasionally followed by a letter denoting specific materials, hazards, or testing scenarios. The first digit between 0-6 indicates the degree of protection from ingress of solid objects (such as dust or dirt). The second digit between 0-9 denotes the quality of resistance to moisture ingress at varying intensities, angles, depths, and pressures of exposure or immersion. Ratings that feature an "X" denote that a numerical rating has only been provided for one of the two main ingress types. Hence, IPX7 will indicate a moisture resistance rating of 7, but no assigned rating against foreign body ingress. The ratings widely accepted as "waterproof" for most general purposes are IP65, IP66, and IP67. However, one common misconception is that water resistance is "higher" if a device's rating is above IPX6. In fact, IPX7, IPX8 and IPX9 relate to a device's immersion properties, which means that these devices do not necessarily meet the criteria for pressurized water jet resistance, while devices rated IPX5 and IPX6 do. Furthermore, there are many different IP ratings that vary internationally; in the UK, IP codes are assigned in accordance with British standard BS EN 60529:1992, in Europe, the codes fall in line with IEC standard 60509:1989, and in other countries, the codes conform to EN 60529 certification [156]. These variations make it difficult for interaction designers to source and compare components.

Fortunately, devices such as smartphones and Bluetooth speakers increasingly come with an IP rating. There is even nanotechnology spray that claims to be able to achieve an IPX7 rating when sprayed on phones [73]. However, common interaction design components, such as microcontrollers and sensors, do not have an IP rating, making prototyping challenging as the researcher does not know how waterproof these devices are without trying them out, often breaking them in the process [55].

4.1.2 Waterproofing, yet not hindering interactivity. Constructing a waterproof case might not solve all problems, as there can be additional challenges of operating terrestrial interfaces underwater. Analogous to the difference between a waterproof microphone and a hydrophone, there is often a need for custom-sensing, for example, lidar and infrared depth cameras do not work underwater without modifications. We note that there are opportunities to utilize marine-grade and industrial technology fittings that work underwater, including sonar, rubber electrical lugs, pressure-release housings, and hydrophobic inert biomedical components. There is also an opportunity to create novel experiences by taking advantage of what has traditionally been seen as technological limitations associated with water exposure. For example, in a videogame about war, droplets were dripped onto a tablet using a mechanical contraption, making the touchscreen increasingly prone to inaccuracies [101]. These inaccuracies became a feature: the water was colored with red ink to remind players of the blood of war, and the increasingly difficult gameplay was linked to the increasing difficulty of operating a touchscreen covered in "bloody" droplets.

4.2 Developing hardware suitable for WaterHCI interactions

WaterHCI devices are enhanced by hardware optimized for use in an aquatic environment. This hardware should support designing for buoyancy, robustness and connectivity.

4.2.1 Buoyancy. Buoyancy (the upward force exerted by water that opposes the weight of the partially or fully immersed device) is an important factor in WaterHCI hardware design. It complements more traditional HCI hardware factors such as weight and size, for example, with the desire to make wearables light and small. The challenge is to develop hardware that allows designers to easily create various levels of buoyancy. This allows WaterHCI devices to either sink or float (inspired by underwater cameras [9]) as needed for the interactions that they support. Because light refracts when it enters water, users can more readily see and interact with a device that is buoyant enough to float, rather than fully submerged. Depending on size, and adherence to standardized safety features, a device could also serve an additional function as an emergency floatation aid (however, should never be seen as a substitute for swimming ability [145, 159]).

Three factors impact buoyancy: displacement, gravity, and water density. Designers can engage with displacement and gravity by considering the size of the WaterHCI device as well as its material to affect weight. When it comes to density, designers need to consider the characteristics of the water the device is being used in: More salt, for example, would increase water density (often measured by salinity).

We envisage an opportunity to develop hardware that builds upon various buoyancy support on demand via gas, for example through inflatables [157, 158]. These features enable designers to create a device that features negative buoyancy when supporting divers in descending (e.g., functioning like a weight belt), and positive buoyancy to facilitate divers' ascent (or device retrieval if lost). Designers should also factor the hydrodynamics that can influence the user's experience in and their movement through water. Recent research in deformable hardware that can change shape on demand [5] could be a useful starting point for such endeavors.

4.2.2 Robustness. WaterHCI devices need to be able to withstand the impacts of harsh aquatic environments, including exposure to salt, sunlight (UV light), and pressure (pressurized water in the form of water jets or pressure underwater), but also the impacts of often forceful interactions due to an exerting activity [109, 112, 119, 120, 124], such as when exhaustingly grabbing onto a WaterHCI device after having successfully swum to it. The challenge is to develop hardware that allows designers to easily create robust WaterHCI devices while supporting interactivity.

Sodium chloride (NaCI) in water can not only cause electronics to short out, but also form chemical bonds with different device surface materials. These bonds are formed immediately upon wetting of the surface, and they leave a corrosive salt residue that damages electrical connections and produces equipment faults. However, corrosion is not the only risk. For example, even if a device sensor is IP67 rated, saltwater can still cause problems if salt residue forms on the sensor, resulting in erratic data. One way to neutralize the salt is to use isopropyl alcohol >90% [4].

WaterHCI devices are often exposed to direct or reflected sunlight and associated higher temperatures; these can cause damage. For example, semiconductors and batteries are prone to be negatively affected by high temperatures, while ultraviolet light can damage LCD displays and plastic device casings.

A device and its electronic components need to be able to withstand water pressure when the device is submerged. Work in the field of pressure-tolerant electronics [17] suggests that WaterHCI researchers need to know whether any electrolytic capacitors have either air or fluids that are susceptible to compression under water. Selecting the right components is challenging when pressure tolerance is not part of datasheets [166]. One solution might be to turn to marine-related equipment that often comes with pressure tolerance data, however, these systems are often costly, narrowly accessible, and closed, hindering prototype development.

4.2.3 Connectivity. WaterHCI researchers face "connectivity" challenges mostly due to wireless hardware being only suited for terrestrial use. Connectivity can be desired in situations where WaterHCI devices need to communicate with other devices (e.g., to support the social aspects of the aquatic interaction [21, 27, 28]) or the cloud (for example, to download security updates or outsource power-demanding tasks). Wireless connectivity is often preferred because cables can produce physical entanglement hazards. The wireless signals that interaction designers commonly use (WIFI, Bluetooth) die rapidly in water. Furthermore, commercial cellular coverage such as 5G extends only a short distance from many shorelines. Research projects such as "Aqua-WIFI" [164] have not yet progressed beyond the proof-of-concept stage and are hence not yet readily available; however, advances have been made to reach larger wireless distances [42] and reduce power consumption [61].

4.3 Water as interaction material

With respect to prior work that proposed that HCI designers should have a "material concern for interaction" [189], we find that utilizing water as a material for interaction – where the interactivity stems from interacting with the water itself, rather than with an interactive device in or near water – has huge potential. However, the challenge is the development of technology that allows water to be treated as a material for interaction.

4.3.1 *Sensing water displacement.*

To utilize water as a material for interaction, WaterHCI researchers will benefit from technology that can sense water displacement. For example, researchers might want to know how much water, in which direction and with which force, their device or users have displaced because of their movements. There are not many sensors available that can readily sense such water displacement (mainly sensors that measure water flow from the plumbing domain, or prototype devices with constraints on how water can be displaced [23]) and are easily integrated into interactive designs as they are often closed systems. Kiss et al. described these challenges in their work around attempting to introduce sensors into a swimming pool to guide swimmers [68]. Similar challenges were faced in the early days of ubiquitous computing that also tried to advance the placement of sensors in the environment [1]. This was picked up by ubiquitous computing advocates who have begun to develop suitable sensors to help interaction designers [72]. We hope that similar developments will emerge that will help WaterHCI researchers. Such work might benefit from the fact that many bodies of water, especially indoor pools, are quite standardized. For example, prior work utilized the black lines featured in most pools that help swimmers stay straight: the authors have utilized these black lines to improve their vision system's performance [108].

4.3.2 *Enhancing the human body's predisposition to water.*

To utilize water as a material for interaction, WaterHCI researchers will also benefit from technology that enhances the human body's predisposition to water as it makes it easier for the user to directly interact with the water. There are already (non-interactive) technologies that enhance the human body's predisposition to water, such as snorkels that allow people to put their mouth under water for longer, swim fins that enable divers to move faster, and athletic swimsuits [190] that trap air for buoyancy to help swimmers achieve faster lap times. We believe that HCI can contribute to these developments. For example, researchers could learn from prior work on wearables, as wearable design appears to share similar goals, such as low weight and being always available [79, 88]. However, researchers need to also consider the drag the additional device might produce. We also note that watersport participants can form very intimate bonds with their equipment, to the point where the device becomes an extension of their body [167]. Consequently, researchers could learn from prior work on human-computer integration [46, 110, 121] when it comes to enhancing the body's predisposition to water as "integration" research aims for a fusion between users and devices [111, 114, 121].

4.3.3 *Altering the materiality of water.*

If WaterHCI researchers had the technology to interactively alter the materiality of water, we believe that they would be much better equipped to utilize water as an interaction material. Such technology could, for example, interactively change the water's density (affecting buoyancy on the fly), change the water's color (via interactively adding ink), or change the shape of bodies of water on demand (turning them into shape-changing interfaces [5]). Systems that make use of technologies that can interactively alter the materiality of water are difficult to imagine, never mind develop. However, technical advances can hint at such futures. For example, research has enabled a droplet to freely float in air that users can interact with via an array of ultrasonic transducers [182]. In addition, researchers have interactively moved droplets across a 2D surface via electrowetting (electrowetting alters the water's interfacial contact angle through an externally applied electric field) [179]. These technologies move just one water droplet at a time, which means that futures in which, for example, water in a pool could be interactively moved from one end to another remain some way off. Nevertheless, stage productions such as those by Cirque de Soleil's "O", and Pinewood Studio UK, have hinted at the spectacular staging possibilities when interactively moving large bodies of water [32, 49, 62, 102, 133], while some commercial swimming pools have incorporated moving floors or bulkheads to dynamically adjust pool depth or width [2].

WaterHCI researchers interested in such futures could probably learn from five contemporary areas of research: first, investigations into shape-changing interfaces could aid with understanding what technologies might help with realizing the ability to interactively alter the materiality of water [5]; second, theory around the materiality of interaction could help with understanding how to make sense of such technologies [189]; third, research into "radical atoms" [60] could help with understanding what to learn from material science to realize such technologies; fourth, research exchange with SpaceCHI could help in understanding the impact of altered gravity environments on user experience [136]; and fifth, art research could help with envisioning state-changes in the materiality of water (i.e., steam to aerosol, water to ice, etc.) for interactivity, and conceptualizing its performativity [186].

4.4 Toolkits for prototyping WaterHCI devices

HCI research has developed many toolkits [72, 96] to enable novel interactive experiences. In keeping with this work, we contend that toolkits could encourage the embrace of WaterHCI to enable novel aquatic experiences. Although no longer available, the "Pumpspark" [39, 40] constitutes an example of a toolkit for prototyping WaterHCI devices [48], and we note that companies are emerging from the sea and space environmental monitoring industries that offer consumer-level "plug and play" marine integration toolkits, such as the "Bristlemouth", that WaterHCI researchers could benefit from [163]. A standard platform for hardware prototyping, a software layer for applications, and tools for end-user programming, could complement such toolkits nicely. Prior work suggested that such efforts could improve prototyping by a factor of 10 in time and cost [5].

5 GRAND CHALLENGES IN WATERHCI: USERS ENGAGING WITH WATER

5.1 Evaluation framework for WaterHCI experiences

Evaluating WaterHCI systems is a Grand Challenge, and we now, through the next subheadings, articulate this challenge using the "why, when, what, . . ." questions proposed in prior Grand Challenge work [44].

5.1.1 Evaluation framework for WaterHCI experiences: why and when. A survey highlighted that we have yet to answer the question of why we would want to evaluate WaterHCI experiences [30]. Is it to show that we can amplify the advantages of being in water? Or is it to demonstrate that water can enrich our experiences with interactive technology? Or are there other reasons? Therefore, we point out that we have yet to answer the question of why we would want to evaluate WaterHCI experiences.

Another challenge is that we do not yet have a sufficient understanding of when to evaluate WaterHCI experiences. Evaluating a WaterHCI experience while users are immersed in water can be challenging. While evaluating after the experience is often practical, participants miss out on being able to report on their immediate visceral response, a challenge that has been previously reported on around other embodied experiences [122].

WaterHCI is yet to understand users' long-term engagement with systems, beyond short-term novelty effects, which can fade quickly [165]. Therefore, we highlight the challenge of evaluating WaterHCI experiences after long periods of use (inspired by prior calls for long-term studies in SportsHCI [125, 146]). One of the foundational issues that long-term WaterHCI studies face is the definition of "long-term". While users of land-based systems can, for example, carry a wearable for 3 months (and be studied over that period), systems that only work by humans in water are likely to be used for merely hours at a time.

5.1.2 Evaluation framework for WaterHCI experiences: who and where. Prior land-based HCI work has highlighted that when designing user studies, researchers must take into consideration who the targeted users are and where they will use the system [161]. These considerations have been extensively discussed [25], however, when it comes to WaterHCI user studies, we note that they have mostly been conducted with participants that are easily accessible, such as students [31]. While our experience indicates that researchers are willing to involve more diverse participant groups, practical limitations often hinder doing so. For example, while adding less confident swimmers to a study might provide new and valuable insights, safety regulations that favor highly competent swimmers make it difficult to include such participants.

5.1.3 Evaluation framework for WaterHCI experiences: what and how. Researchers need to know *what* design features to consider when evaluating WaterHCI experiences and *how* these features can be measured. While evaluation can be difficult at the best of times, it can be even more challenging in WaterHCI. For example, we could ask participants during their engagement in a lake what design features of a device they appreciate and why. However, it is hard to conduct explicitation interviews [100] because they will have difficulty both talking and focusing on their breathing. Furthermore, the interviewer would either need to swim beside the participant or use an on-helmet communications system like those used by wakeboarders and water-skiers [11]. For underwater studies, researchers may need to invest in waterproof paper, hydrophones, underwater cameras, and possibly remotely operated underwater vehicles (ROV) or unmanned underwater vehicles (UUV). Even if interviews are scheduled after the water activity, they cannot always be undertaken immediately. Participants will often find it uncomfortable staying in the water or even outside because of differences in temperature and want to have a shower first. However, as most aquatic activities are rather body-centric [113] and produce immediate bodily responses, any break of context or condition before an interview could disassociate them from the water experience they just had, thus possibly diluting the richness of any immersive accounts they could provide. While there are many individual experiences, there are also shared sensory human-aquatic memory databanks, meaning that there are behaviors and perceptions that have shared cultural, evolutionary, and social traits around engagement with water [170].

5.2 Supporting human senses in aquatic environments

Better understanding perception is a general challenge for HCI, and when it comes to water, interaction designers are faced with the additional challenge of how to design for the changes to how humans perceive in aquatic environments. Sensory changes are caused by pressure-related alterations to the physiology impacting bodily gas-exchange processes called hyperbaric conditions, extending to cognitive changes impacting performance, behavior, memory, affecting spatial orientation, navigation, and timing [107]. We focus on vision, hearing and touch as interaction designers might want to start with these due to a rich history in HCI to support them, but we also highlight the need for future work to support other senses as well as multimodal interactions. We envisage that multimodal interactions may make WaterHCI more accessible. For example, prior work suggested that blind sailors benefit from vocal cues, audio feedback and tactile devices to receive spatial information during navigation [64].

5.2.1 Vision. When it comes to vision, interaction designers have a rich history of utilizing LCD displays. However, this is challenging in terrestrial-aquatic situations, as water drops on a display make any information hard to read. If the user's head is underwater, vision is initially blurry. This is because water is almost the same density as the fluid inside the eye, so underwater light barely bends as it enters the eye [154]. In addition, water causes a scattering of light between the display and the user, resulting in lower contrast. Furthermore, pollution, turbidity, viscosity and even temperature impact how people see what is shown on a display. In response, divers wear masks, and masks make objects underwater appear 33% bigger (34% in saltwater) and 25% closer than they actually are [3]. The "Oyster" helmet prototype, filled with ocean water, magnified these phenomena [141]. Pincushion distortion and lateral chromatic aberration are also noticeable. Interactively controllable lens corrections could offer ways to address such challenges, supporting vision above and under water equally [173]. Underwater head-mounted displays can therefore benefit from modified lenses [10].

5.2.2 Hearing. Another popular sense engaged with in HCI is hearing using speakers. Sound travels in water about 4 times faster and longer distances than in air. Humans can hear up to 200,000 Hz underwater, which is near ultrasonic range, and 10x greater than hearing ranges on land, yet the subjective impression is that hearing is much reduced underwater [149]. If the head is submerged, sound localization is initially more difficult, as the brain defaults to the difference in loudness and timing of the sound detected by each ear, but this is severely hindered because of the sound's faster travel time and because the sound is perceived simultaneously. Nevertheless, the user can adapt and learn to localize and hear well over time. The different hearing experience has been turned into a feature by a wellness spa that provides visitors with a soundscape only accessible if floating in a pool with ears underwater, delivered via underwater speakers [74]. There are also examples of an underwater opera [54] as well as in-water and across-water operas [147].

5.2.3 Touch. Touch as input modality has become ubiquitous thanks to the touchscreen. However, as most touchscreens use capacitance sensing, they do not work underwater. Systems have emerged that use optical sensors instead [148] or project "Moonwalk 2016" [188] used a pneumatic push-button from a small air cylinder to self-inflate and a transparent membrane pillow around the screen, thus creating an air-pocket lens for better viewing content on the screen and for differentiating the gloved user interactions from the pressure of the surrounding water [178, 180]. We point out that water affords the opportunity to provide haptic feedback through pneumatics and hydrodynamics while water pumps can result in engaging experiences as seeing water being jetted out of a nozzle can be a spectacle [66, 67] and feeling the sensation of the water hitting one's skin can make for an intriguing experience [57]. Furthermore, interaction designers can harness water turbulence, eddies, and currents to aid experiences [140] or drift light-weight participants [135]. This contrasts with using jets of air in land-based systems, where the air turbulence is often not very visible, does not reach far, nor supports full-bodied propulsion.

5.2.4 Smell. Water odor varies, ranging from appealing smells of high-end drinking water to rancid aromas of sewage canals (for examples of engagement with such smells, see [16]). When people are underwater, their epiglottis closes off to prevent getting water into the lungs and disables the olfactory sense. We could envision the use of full-face snorkeling masks as a way to control smell by releasing a scent within the mask, eliminating some of the challenges associated with smell-based interfaces with water [138, 194]. However, designers should know that breathing any substance underwater comes with associated hazards: the particulate matter of any scent transmitted via air or gas aerosols is compressed and inhaled at partial pressure. Any air mix and other substances underwater concentrate both the toxicity and absorption rates of the substance [29].

5.3 Sharing aquatic experiences

Engaging with water is very often a social activity. However, when it comes to interactive technology support, there are not many examples beyond apps, however, notable exceptions are: an AR snorkeling experience that has been enjoyed in groups [135] and a floatation experience that allows participants in different floatation tanks to sing together via internet-connected microphones [89].

5.3.1 Supporting different water exposures. One issue is how to support users with different water exposures. For example, one participant might be in the ocean, when another, connected over the internet, is in a freshwater pool, experiencing different buoyancies, smells, currents, visibilities, etc. Interesting questions arise, such as: how do we communicate a range of sensorium and sensations across participants if we want to foster a deeper understanding of each other's aquatic circumstances? What if one participant is in a large body of water, such as the ocean, while their friend only has a bathtub? Prior HCI work around "balancing" embodied activities between differently abled participants, so that all of them can engage on an even footing, through the use of dynamically adjusting the difficulty level for participants [6], might be useful here.

5.3.2 Supporting different WaterHCI systems. Another issue is how to support sharing WaterHCI experiences if participants have different WaterHCI systems. For example, what if one participant has a device that allows diving deep, whereas another participant has a different system that does not support the same depth? How do the two systems make the participants aware so that they do not "blindly" follow each other into too deep waters? This example highlights that the appeal of social support in interactive systems [117], such as demonstrated in social exertion games [112, 115-118, 123, 187], can facilitate participants entering a flow state [26, 36, 97, 174] that is so engrossing that users might forget basic safety procedures, hence WaterHCI designers should always consider safety first.

5.4 Transitions into and out of the aquatic environment

Users of WaterHCI systems must often cope with transitions into and out of the aquatic environment. Most users will be familiar with on-land interaction devices, modalities, and techniques; however, they will likely be different with WaterHCI systems; hence users will need to switch if coming from land-based interactions to the aquatic domain and back. While prior research has already investigated transitions with traditional interfaces [33] and also unconventional interfaces [14], WaterHCI systems bring about new, more complex transitions as water makes hearing, seeing, and touching "strange" [75] (as outlined in our "senses" Grand Challenge). This can affect any interaction fluidity [43], for example, when a swimmer uses a touchscreen on their phone to set up their training plan before entering the pool, but then cannot use it in the pool and therefore instead may use their augmented swimming goggles' buttons, only to switch back when exiting the pool to analyze the training results.

To aid such transitions, future WaterHCI systems may seek to lower any entry barriers. One response could be to develop WaterHCI systems that also work on land; this could be facilitated by interfaces that replace traditional mouse and keyboard interactions [113]. The use of augmented reality in pools [135] is another inspiring example that could lead to AR headsets or swim boards that support wearers both above and underwater. However, these unconventional interfaces raise the issue of discoverability [129], as it might not always be obvious what interaction possibilities they have. We agree with prior suggestions that a unified interaction vocabulary could be a step forward in reducing the learning curve for WaterHCI systems and hence make associated transitions easier [44].

6 GRAND CHALLENGES IN WATERHCI: DESIGNING WATER EXPERIENCES

6.1 Designing implicit aquatic interactions

As most aquatic activities require the user's attention and bodily engagement in submersion, such as performing swimming strokes to stay afloat, interactions with technology will often not be the primary focus. Rather, they may operate just beneath the user's conscious level. Examples are a smartwatch that monitors a swimmer's heart rate in the background or a system in a sea kayak that steers the boat subtly away from getting too close to dangerous currents. As such, interaction designers might want to focus their attention on supporting secondary interactions that make use of the subconscious [37].

Such implicit interactions have been investigated in HCI before (e.g., see [63, 111, 162]); here, we point to the fact that the bodily involvement required in many aquatic activities not only makes implicit interactions a possible alternative input modality, but frequently a necessity. As such, we confirm a prior Grand Challenge in human-computer integration that already suggested that our knowledge of how to design implicit interactions for bodily activity is still limited and holds such body-centric fields back [121].

6.2 Designing shared agency with aquatic tools

We find that many aquatic activities involve some kind of tool, for example, see the use of kickboards, surfboards, inflatable toys, pool noodles, etc. [22] We believe that there is an opportunity to utilize emerging advances around artificial intelligence and actuators to give these tools some agency, where the system can take control. For example, we can envision kickboards that autonomously change their shape to guide the user toward a particular swimming style improvement. Similarly, fins and keels could take control and guide the user towards a better wave or away from danger [19]. These examples highlight how the interaction shifts from the user exploring the aquatic environment *through* the technology to an agent-driven interaction where the system explores the world *by* itself, akin to the difference between *driving* a car and being *driven* by an autonomous car. WaterHCI systems might therefore either feel like a tool that supports the user in engaging with the aquatic domain [160], or an agent that acts on their own, with their own intent (such as an autonomous kayak [181]). "Intentional binding" is a tool from neuroscience that could help evaluate such experiences quantitatively [15], aiding the design of systems where the user will think "I did that" rather than "the tool did that" [35].

6.3 Overcoming constraints of the aquatic environment

Technologies such as VR enable to recreate aquatic experiences on land; for example, see projects that allow "swimming" and "fishing" via head-mounted displays [47, 132]. Such projects that do not use any actual water are outside the scope of this article, however, we note that augmented reality is increasingly used to augment real water activities with digital content (for example, see the use of AR to explore virtual coral reefs in the local pool [10, 18]). One issue that can arise here is that the design of the virtual environment needs to consider the constraints of the aquatic environment. For example, in a head-mounted display system that allows snorkelers to explore virtual reefs, the participant needs to be attached to a rope tied to a weight at the bottom of the pool [10]. This prevents the snorkeler from bumping into the end of the pool when traversing the endless virtual world, however, participants might feel as if they are not really moving forward as the rope holds them back. Prior non-aquatic VR work has already acknowledged the need for innovative solutions to address the constraints of reality [98]. Here, we extend this thinking to the aquatic domain. The "redirected walking" technique has used head-mounted displays to enable participants to traverse a virtual world that is considerably larger than the physical room they are in [128]. We propose that "redirected swimming" might be an approach to provide small HCI labs that do not have space for large pools with an opportunity to design larger water experiences.

7 GRAND CHALLENGES IN WATERHCI: ETHICS AROUND WATER

7.1 WaterHCI *for* and *as* sustainable practice

HCI is increasingly interested in sustainable practices [52]. WaterHCI systems not only need to address power consumption and e-waste problems as discussed in traditional HCI [144], but also water source, use, waste and pollution. The challenges are therefore: WaterHCI *for* sustainable practice and WaterHCI *as* sustainable practice.

7.1.1 WaterHCI for sustainable practice. Existing projects employ serious games to educate people about water conservation [8] and how to protect marine life [135]. These approaches are initial steps in using interactive technology to promote sustainability. In the future, we hope that WaterHCI research goes further and helps to avoid water waste, reduce pollution, protect aquatic environments and communities, and save marine and aquatic life while mitigating the effects of climate change.

7.1.2 WaterHCI as sustainable practice. The WaterHCI field also faces the challenge of becoming a sustainable research practice itself. This is particularly troubling when considering that many parts of the world face severe droughts and water saving is paramount. We note that most HCI labs are not set up to work with water, hence provisions to minimize water waste and reduce spilling are often not in place. Guidance on how to set up HCI laboratories that work with water would therefore benefit many researchers (such as exist for other sub-fields of HCI [105]). Furthermore, WaterHCI practice needs to consider the environmental impact their devices might have. For example, devices used in the ocean could easily be swept away by currents. The result could be that marine life mistakes it for food, eats toxic materials, or gets caught in it, causing the animal to die. Furthermore, the harsh environment can cause the device to fall apart, exposing any materials such as batteries to leak hazardous materials into the water. As such, interaction designers need to be careful not to contribute further to the 5 trillion pieces of garbage currently littering our oceans [130]. Current efforts around biodegradable interaction device components such as capacitance sensors [77] and logic gates [38] are interesting developments that could help towards more sustainable WaterHCI practice.

7.2 Applying WaterHCI safely

Having people interact with water raises many ethical challenges about safety that affect researchers’ practices. Addressing these is an essential part of bringing the field forward. Internal review boards for studies involving human subjects must be aware of and vigilant with respect to all safety and ethical matters involving WaterHCI. In many cases, academic institutions will have Dive Control Boards and Dive Safety Officers with the explicit mandate to review all research involving any form of aquatic activity. Furthermore, creating new forms of interactions with water poses inherent risks to the person interacting, as the technologies may have unintended consequences. For example, there is a tendency to grab when feeling vulnerable, or grasp when startled. New devices need to ensure that human reflexes do not create life-threatening situations.

Another point worth considering is that applying technology to any environment not only alters interaction in that space but also the environment itself. This might remind HCI researchers about embodied interaction [41], but it also has much simpler and practical implications: water is an asset that needs to be protected. Early expert interviews for the AReef system revealed how important the asset water and its immediate surroundings are for pool operators [135]. For example, introducing technology must not lead to potentially dangerous situations, such as broken tiles from falling gear or shards that could hurt participants or contamination of the water source.

7.3 Overcoming the divide in terms of accessibility to water

Traditional HCI is already concerned with the “digital divide” because of technology resulting in unequal access to opportunities. We see this as potentially amplified with WaterHCI systems becoming a potential double barrier to inclusion. People already have unequal access to water, not just for drinking, but also for aquatic activity [191], mostly through geographical location, but also as a result of political, financial or physical limitations. For example, many small communities simply cannot afford a public pool, resulting in their members missing opportunities to not only learn important life-saving skills and swimming but also fall short in benefiting from the associated health benefits [127]. Globally available technologies could be used to increase access to lifesaving water education, but co-design with these communities would need to be undertaken to ensure that the WaterHCI solutions are fit for purpose. Furthermore, if WaterHCI systems provide safeguarding functions, preventing people from drowning (such as suggested through life vest-dropping drones used at beaches [193]), could the operators of the drones turn this into an enterprise that only rescues people who can afford a subscription?

7.4 Addressing cultural factors

Combining interactive technology with water also requires factoring in cultural issues. For example, some cultures have different practices regarding sharing facilities and specific clothing being worn, which HCI researchers need to accommodate (such as researchers allowing participants to change first before beginning interviews). Furthermore, we point to privacy concerns as interaction with water often involves the removal of at least some clothing. A case in point is a smart shower that uses a camera-based system to reduce water wastage but raises ethical concerns about the captured vision [81, 82]. Prior work around the coming together of privacy, surveillance, and sousveillance (inverse surveillance) [93] pointed to an interesting parallel between wearable technology, where the clothing is a boundary element, and WaterHCI, where the removal of clothing could lead to the dissolution of the boundary between the human body and the world, affecting our understanding of “cyborg” technologies.

Prior research pointed out that many of today’s interactive devices are designed by developers of particular cultural backgrounds (mostly Western) that often ignore existing cultural sensitives [24, 71]. With aquatic activities being very body-centric [113], such missed opportunities to consider cultural sensitivities could increase, speaking to a prior Grand Challenge in human-computer integration that highlighted that “body bias” is a hurdle to overcome in body-centric devices [121].

8 LIMITATIONS & FUTURE WORK

Our work has limitations, as does all work that aims to identify implications for an entire sub-field of HCI through a group of experts [121]. For example, as our experts self-subscribed to the workshop, they were enthusiastic about bringing the field forward. Other, more skeptical proponents might see the coming together of aquatic experiences and technology as more doubtful. As such, we look forward to additional voices. In parallel, we also call for future work on supplementary contributions to understand the two other silent partners in WaterHCI: the body-aquatic, and the body of water, and how researchers might expand their approach towards an understanding for co-design, cooperation and synergistic performance, with fluid technocentric ambitions. To facilitate such a more critical approach, we point to “dark patterns” [51]. We encourage future work to investigate such dark patterns in WaterHCI and believe that our article might be useful in structuring such investigations.

We also acknowledge that requiring payment for the workshop might have resulted in a selective participant pool. However, being co-located with a prestigious HCI conference also ensured that the top researchers were readily available and hence resulted in expertise that might have been otherwise difficult to assemble. The number of participants was based on the conference workshop cochairs’ recommended size range. Informed by the organizers’ past experiences with workshops, we believe that the number of participants was a strategic compromise between being large enough to cover a wide range of work yet leaving enough time to discuss the work in depth. The number of participants is also in line with similar prior workshops [5, 44, 168]. However, we acknowledge that we have not (yet) validated that our number of participants was sufficient to cover all Grand Challenges, hence, we see our work as an important starting point. Additional future workshops and participants will certainly complement this work. We also point out that our approach to the Grand Challenges in WaterHCI comes from a privileged position, as we all had access to waterways and technology to experiment and tinker with [55]. As such, we are aware that our article might give the impression that some of the consequences, if the challenges are solved, are only within reach for those in similar positions. Furthermore, we point out that we see the identified challenges not necessarily as problems that require an immediate fix, but rather that they are key to WaterHCI that benefit from closer investigations and need to be developed and critiqued further.

9 CONCLUSIONS

We have described a set of WaterHCI Grand Challenges that are conceptually and technically complex. Addressing them will require a range of research communities to work together. Technical category challenges will require engineers with expertise in areas such as underwater exploration and maritime science, contributing in return to interaction design's understanding of material HCI. Challenges in the "ethics" category will depend on knowledge from wider societal areas of concern, contributing possibly in return to value-sensitive [45] and more-than-human HCI efforts [34, 185], while challenges related to the "user" category will require knowledge from social science and in return have the potential to contribute to HCI's social computing community. The field of WaterHCI offers tremendous potential and by addressing the challenges laid forth in this article will propel HCI's collective capacity to more fully realize and benefit from this potential.

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