Player-Computer Interaction Features for Designing Digital Play Experiences across Six Degrees of Water Contact

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ABSTRACT
Physical games involving the use of water or that are played in a water environment can be found in many cultures throughout history. However, these experiences have yet to see much benefit from advancements in digital technology. With advances in interactive technology that is waterproof, we see a great potential for digital water play. This paper provides a guide for commencing projects that aim to design and develop digital water-play experiences. A series of interaction features are provided as a result of reflecting on prior work as well as our own practice in designing playful experiences for water environments. These features are examined in terms of the effect that water has on them in relation to a taxonomy of six degrees of water contact, ranging from the player being in the vicinity of water to them being completely underwater. The intent of this paper is to prompt forward thinking in the prototype design phase of digital water-play experiences, allowing designers to learn and gain inspiration from similar past projects before development begins.

Author Keywords
Digital water-play experiences; degrees of water contact; player-computer interaction; swimming; water

ACM Classification Keywords
H.5.m Information interfaces and presentation: Miscellaneous.

INTRODUCTION
Water is a prominent environmental factor in everyday life and has often been used as a medium for playful experiences. Water can either be the object of play or the arena in which play occurs; whether its children creating their own games with nearby water, aquatic sports, or water theme parks. Notably, technological innovations appear to have mostly ignored this facet of entertainment. While play on land has experienced a transformation in the last half-century with the development and adoption of digital games, most play in or around water has remained the same due to obvious concerns of integrating electrical components in a water environment. However, recent advancements in ubiquitous computing have led to improved sensing and acting technologies that are either water-proof or operate from a distance, allowing for new forms of player-computer interaction when the player is in a water environment.

In this paper we examine a series of interaction design features; thirteen relating to the *player* and fourteen relating to the *computer* in the interaction, separated into the four categories of *State*, *Sensing*, *Acting*, and *Networking*. We propose these features are beneficial to consider when designing and developing player-computer interaction around water, henceforth referred to as *digital water-play experiences*. We evaluate these features at six degrees of water contact that a player may experience, as each degree of water contact can affect a feature differently. These degrees of water contact are when the player is in the *Vicinity* of water, experiences *Sporadic Contact* with water, is *On Top of Water*, is *Partially Submerged* in water, is *Floating* in water, and is completely *Underwater*.

As this is an initial investigation into player-computer interaction in water, we focus on the affordances of players in water and computing technology in water separately. That is, at this stage we do not directly reference existing player-computer interaction theory but rather take a first step toward such a joint analysis by establishing an understanding of how water affects both sides individually. We hope that by discussing these features and the existing work within this space this paper will not only act as a guide for prototypical investigations that are currently in the design phase but also to motivate future work into player-computer interaction in and around water.

RELATED WORK
The report by von Lukas et al. [49] refers to underwater environments as "unconventional" and highlights the small amount of existing HCI work in such an environment and some of the opportunities regarding virtual reality and augmented reality. They define a conventional environment, such as a lab or office, as one where air is surrounding the user and

CHI PLAY 2015, October 03 - 07, 2015, London, United Kingdom

DOI: http://dx.doi.org/10.1145/2793107.2793134

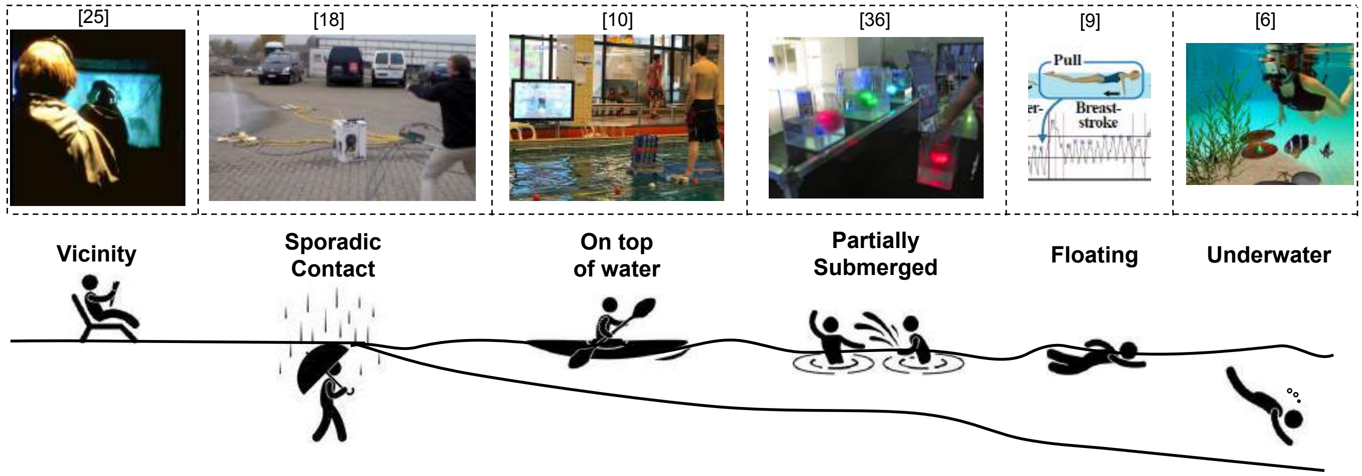

Figure 1. The six degrees of water contact with images from sample projects that have studied digital water-play at the associated degree of water contact. All images originate from the corresponding reference and are used here with the permission of the original authors and publishers.

the technology. Similarly, we recognize the uniqueness of designing digital play experiences for water environments and thus examine how various player-computer interaction design features are affected by being in contact with water. However, we analyze six degrees of water contact rather than the dichotomy of 'air' and 'underwater', as each design feature may be minimally or greatly affected depending on the degree of water contact that the player is experiencing.

The design features that are examined in this paper are categorized into four groups depending on their function for the user or the computer. These are State, Sensing, Acting, and Networking. Mueller et al. [28] examine similar categories to produce a design framework for exertion games. However, the exertion framework focuses on interaction design features that relate primarily to a player during an exertion game, while the current terminology was adopted to relate to both features of the players and of the computing technology in use, assuming the player is at a specific degree of water contact.

Prior work has also examined numerous properties of underwater environments and their effect on user and technology design features. The Underwater Handbook by Shilling et al. [44] provides an extensive list of such properties and was written to provide a central knowledge repository and common language for diving engineers. Antonelli et al. [2] also provide in depth model descriptions that accommodate for the physical effects of water on robotic sensing and actuating. While these works and others discuss the intersection of water and technology in mostly work environments and engineering applications, to the best of our knowledge there is no similar central knowledge reference for designing more casual water-based digital experiences for consumers.

As there are limited examples of digital water-play for us to draw knowledge from, throughout this paper we include references to alternative but similar experiences. These include the combination of HCI and water in the study of novel information displays [24], system control [50], music creation [27], immersive theater [25], aquatic performances [35], and activity motivation [23]. Likewise, many of the insights within this paper can be applied to all manner casual, ambient, or artistic HCI experiences in water. However, in this paper the language is specifically focused on player-computer interaction and digital water-play experiences as we perceive this to be a significant gap in existing literature and, by discussing it, there is the potential to inspire innovative future works in interactive entertainment.

DEGREES OF WATER CONTACT

We believe one of the primary influencing factors while designing a digital water-play experience is how much water the player is expected to be in contact with, which we refer to as degrees of water contact. The degree of water contact can influence the capabilities and performance of both the player and the digital technology. It is for this reason that we introduce a taxonomy of six degrees of water contact to shape the discussion of the player-computer interaction features in later sections. These degrees, shown in Figure 1 and described below, are on a linear spectrum from being in the vicinity of water to being underwater, with the addition of being on top of the water on a flotation device.

Vicinity

At this level there is no physical contact between the player and the water. However, this does not mean water cannot be used to influence an experience. The sight and sound of water can be both relaxing and invigorating. The sight and sound of waves at a beach can be mesmerizing, the sound of rushing water at a water park can immerse visitors in the overall water experience, and the sight of others getting unexpectedly wet or playing a game in water while staying dry can be entertaining.

Sporadic Contact

Here, no part of the body can be considered to be completely underwater but water is nevertheless in contact with the player's skin. This may come from rain, a shower, running through garden sprinklers, playing with water guns and balloons, or riding down a water slide. A defining characteristic of many of these experiences is that water is typically dispersed and in motion, colliding with a player rather than requiring them to enter into a body of water.

On Top of Water
Being On Top of Water is somewhat of a blend of the Vicinity and Floating categories. It is at the Vicinity level as there is no direct physical contact between the player and the water. The player is also on the surface of the water and not touching solid ground, similar to the Floating degree of contact. However, the defining feature here is the indirect contact between the player and the water through a flotation device interface, such as a surfboard or boat.

Partially Submerged
This category ranges from having a single extremity, such as a hand or foot, submerged to having the entire body up to the neck submerged. However, the unifying element of all of these experiences is that a portion of the player's body is submerged in water but the player's head is above water and they are standing on a solid ground, regardless of whether this ground contact is inside or outside the body of water. This distinguishes Partially Submerged from Sporadic Contact as the player is now entering a body of water. Also, unlike in the Floating state below, the player will have similar (though not exactly the same) limb movements, vestibular senses, and oxygen availability as the previous degrees of water contact.

Partially Submerged is a broad category, encompassing both minimal hands-only submersion as well as deeper bodily submersion. We acknowledge that a more extended version of this framework could have these as two separate categories. However, we combine them here as the effect that water has on the player and computer features tend to be similar.

Floating
Here, most of the player's body is underwater with only a small portion above water, which must include the face for at least re-occurring periods of time to aid in breathing. It is similar to the upper bound of the Partially Submerged category except that the player is no longer in contact with a solid ground. Thus, the Floating category includes all situations in which the player is treading water or swimming on the surface of the water.

Underwater
At this level, the player is completely submerged, is holding his or her breath or using a breathing aid, and is typically using different swimming skills to those that are used when floating on the surface.

SUMMARY OF INTERACTION DESIGN FEATURES
The graph in Figure 2 shows a variety of features that can be affected by water and that should be considered when designing a digital water-play experience, divided into those that concern primarily the *player* and those that concern primarily the *computer* being utilized. These are henceforth referred to simply as *design features* and have either been mentioned in previous studies into digital water experiences (either for play or work) or are those that we have needed to address in our own design sessions aimed at investigating aquatic play with robotics [36, 37], underwater performance [35, 39], and cyber-physical innovations in water theme-parks [40]. Of note, Pell and Mueller [36] correlated data on human-aquatic interactions and narcosis with a range of game design principles to produce a design pallet for digital water-play from a Partially Submerged degree to an Underwater degree of thirty meters. The next two sections describe each of the design features in this figure.

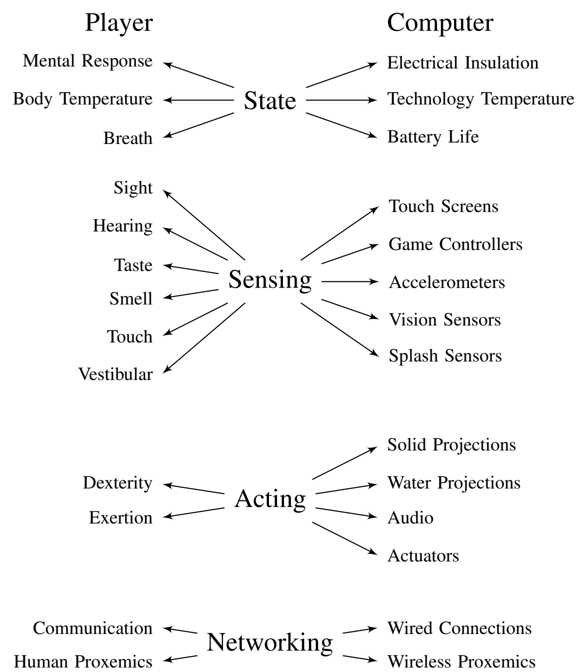

Figure 2. The player and computer design features that are affected by water and that are examined in this paper. These features are categorized as either a State feature, Sensing feature, Acting feature, or a Networking feature.

In Figure 2, the design features are further grouped into State, Sensing, Acting, and Networking. These categories are similar to the lenses of the exertion framework described by Mueller et al. [28]: the responding body, the sensing body, the moving body, and the relating body. However, the state, sensing, acting, and networking terminology was adopted here in order to unify the features of players and computing technology.

The *State* category refers to those features that describe the internal state of the player's body and mind or the hardware of the digital system. *Sensing* indicates various biological and technological mechanisms used to allow the player or computer to sense the environment around them and collect feedback from each other. *Acting* features are then those relating to how the player or digital system can act in the environment around them and convey messages to each other. Finally, *Networking* features pertain to how a player may interact with another other player or how a component of a digital system may communicate with other components.

PLAYER FEATURES IN WATER

In this section we describe the player interaction design features that are found in Figure 2. These are repeated in Figure 3 and combined with the six degrees of water contact. Each cell of the table indicates the extent to which a given degree of water contact may affect each feature. That is, when designing a digital water-play experience with a given degree of water contact, what are the important features as opposed to if the experience were designed away from water?

The cell values are on a three point scale to draw attention to the design features that are most likely to be affected by the respective degree of water contact and that should be considered early in the design process. A light cell indicates that we do not perceive much of a difference between designing for water and designing for conventional land and air environments. A medium shaded cell indicates that the water will have a minor effect on the feature and a dark cell indicates a strong effect. For example, the player's sense of hearing could be greatly affected by being Underwater but is unlikely to be any different to other land environments when they are in the Vicinity of water.

The extent of effect here is neither inherently negative nor inherently positive. This is because we believe that regardless of whether a design feature at a given degree of water contact is initially perceived as a constraint (negative), it can potentially be turned into an opportunity (positive) with creative thinking.

Additionally, the last row of this table shows the references in this section that address some form of HCI in a water environment. References in bold are those that directly relate to digital water-play experiences. These are plotted against the degree of water contact that is targeted in the referenced work. Worth noting is that Deen et al. [10] is found in multiple columns of the table; this is because this single reference encompasses numerous prototypes target a variety of degrees of water contact and thus is a valuable source of inspiration for future digital water-play experiences.

Internal State

Mental Response

Even when in the Vicinity of water, the mind and body can be relaxed similar to how a person is relaxed when exposed to other natural sights and sounds [1]. This effect also occurs in the other degrees of water contact; warm and cold showers, placing ones hands in a stream of slow moving water, sitting on a bobbing boat, and floating on ones back can all be used to calm the mind [7]. However, in both the Vicinity and Sporadic Contact degrees of contact, water can also cause frustration such as the slow rhythmic drip of a leaking tap. Pell and Mueller [36] additionally suggest that the altered sense of gravity, increased pressure, and disorientation while Underwater can affect a player's emotions and cognition.

Water can also be a source of enjoyable surprise. The shock of jumping into cold water, the awkwardness of having clothing become wet, or the surprise of unexpectedly being squirted by a jet of water can all provide momentary discomfort followed by joy. This is even more prevalent in social settings where a larger audience is entertained by witnessing these things happening to others. Benford et al. [5] elaborate on using uncomfortable experiences, such as surprise, as valid forms of entertainment. Finally, both the altered mental states experienced in water and the increase in exertion needed to move through water can cause exhaustion, which may also affect cognitive abilities during long play sessions.

Body Temperature

Hot and cold water can be used to raise and lower the body temperature of a player. This may be due to the wind-chill coming off of the beach while in the Vicinity of and On Top of Water, shower temperature in the Sporadic Contact category, or a naturally or artificially heated body of water in the more submerged degrees of water contact. Different water temperatures can also be used to convey messages, such as using a splash of icy water as a form of penalty for failing a task in a game. However, in bodies of water with unregulated temperatures, the player's body temperature may also drop to uncomfortable levels during increased exposure to the water.

Breath

It is important to take into account variation in players' lung capacity or additional breathing apparatus. Underwater experiences are constrained by varying time limits resulting from these differences in lung capacity. However, in traditional games set around pools, such as diving for items, the challenge of overcoming the lack of breath is often a key factor in the entertainment of the experience.

Sensing

Sight and Hearing

Water can often hamper a player's sight and hearing. When there is Sporadic Contact, the player may experience involuntary flinching and loss of eye contact if the water moves towards the face. The sound of moving water hitting nearby objects can also add noise to any audio signals entering the ear. With the eyes and ears underwater, the light bending qualities of water distort sight [22] and hearing sensitivity is reduced [34]. Additionally, devices such as glasses and hearing aids that some players rely on may not be usable around water. Finally, Lee et al. [9] identify that one's sense of direction of sound is affected by splashing sounds while swimming on the surface of water.

On the other hand, the mental affect that the sight and sound of water can have on people, as mentioned earlier in the description of the Vicinity degree of water contact, can be used to enhance a player experience or convey meaning, as is discussed further in the Actuation computer design feature. For example, Mann et al. [27] use moving water in various ways to produce a novel musical instrument while interactive art installation company Random International produce the sensation of being surrounded by torrential rain while keeping the user dry [51].

Taste and Smell

Taste will rarely change at any degree of water contact because the mouth is an enclosed environment where water from the surrounding environment does not usually enter unless the player is actively seeking to drink it. However, the

Extent of Water Effect (Minimal / Low / High)		Vicinity	Sporadic Contact	On Top of Water	Partially Submerged	Floating	Underwater
State	Mental Response	High	High	High	High	High	High
	Body Temperature	Low	High	Low	High	High	High
	Breath	Minimal	Low	Minimal	Minimal	Low	High
Sensing	Sight	Minimal	Low	Low	Low	High	High
	Hearing	Minimal	Low	Low	Low	Low	High
	Taste	Minimal	Minimal	Minimal	Minimal	Minimal	Low
	Smell	Low	Low	Low	Low	Low	High
	Touch	Minimal	High	Minimal	High	High	High
	Vestibular	Minimal	Low	Low	Low	High	High
Acting	Dexterity	Minimal	Low	Minimal	Low	High	High
	Exertion	Minimal	Minimal	High	Low	High	High
Net-work	Communication	Minimal	Low	Low	Minimal	High	High
	Human Proxemics	Minimal	Low	Minimal	Minimal	High	High
References		[23, 51]	[27, 47]	[10]	[10, 36]	[9, 10]	[10, 37]

Figure 3. The player features and the extent to which they are affected by water when the player is experiencing the specified degree of water contact.

flavor of any object in the mouth may be affected as this flavor is influenced by both senses of taste and smell [45]. The sense of smell is often affected by water. There may be scents emanating from the water such as those arising from aquatic life or chlorine; Sporadic Contact of water may prevent the player from taking a deep breath through the nose for fear of choking; and having the head submerged completely prevents the sense of smell from being utilized normally unless a breathing apparatus is used. However, the taste, flavor, and smell of water based substances can also be refreshing for a player in most of the degrees of water contact. For example, Khot et al. [23] use drinkable water not only as a reward for physical activity but also as a means of conveying activity performance through the sight and flavor of a combination of water-like liquids.

Touch

A player's sense of touch can be affected in all degrees of water contact involving direct interaction with water. Water can be used as a means of providing simple and risk-free haptic feedback such as splashing a player as a penalty or reward in a game. This may be due to the contrast between skin that is touching water and skin that is not, such as in the Sporadic Contact and Partially Submerged categories, or by the movement of a large volume of water in the Floating and Underwater cases. The sensation of the player touching water can even be used as novel input, as Sylvester et al. [47] show by making use of a user's acute sense of touch on delicate soap and smoke bubbles on a water surface to give a unique input mechanism and tactile feedback to room lighting controls.

In addition to using water for tactile feedback, water also affects our skin in other ways, such as increasing grip of wet objects [21], which may allow for better control while interacting with computer interfaces. Additionally, the presence of water in and around the skin can greatly affect the conductivity of electricity through the skin, which, as we show later, may prevent certain existing sensing technologies from being used.

Vestibular Sense

The buoyancy and pressure of water affects how players experience gravity, both on individual limbs that are Partially Submerged and on the entire body in Floating and Underwater situations. This affect is heightened when the player is deep Underwater, where altered sight, hearing, and vestibular senses combine with added pressures on the body, resulting in disorientation, changes to balance, and altered cognitive abilities. This property is examined by Pell and Mueller [36] who craft playful robotic interactions in deep water to investigate the effects of water on a player's vestibular sense during underwater play. Additionally, when On Top of Water, players will often require extra effort to balance as the interface that is in contact with the water reacts to both the movements of the player and the water itself. This lack of balance can be used as a source of challenge in gameplay, such as in the PirateRaft game [10] that requires players to complete movement activities while standing on a floating raft.

Acting

Dexterity

How we move through deep water is often quite different to how we move on land. Unless a flotation aid is used, in Floating and Underwater scenarios when the player is swimming or treading water, both their arms and legs are constantly in use for maneuverability and stabilization, preventing them from being used for other activities such as interacting with a digital controller. For this reason, many studies have investigated novel ways of allowing a player to interact with a digital system while Floating or Underwater, which is discussed later with regards to the computer sensing features. To a lesser extent, this may occur when the player is Partially Submerged or On Top of Water, where the latter may require activities such as rowing that will occupy the hands and prevent the use of traditional interfaces. These restrictions on limbs encourage novel forms of player-computer interaction such as the diverse prototypes by Deen et al. [10] that often use as input the player's body itself, small or floating objects, or simple button presses, all of which can be easily manipulated while swimming.

Exertion
The increased friction and drag of water compared to air means that movement through shallow and deep water can be more difficult. Additionally, water activities such as swimming and rowing typically require a lot more upper body strength than land-based activities such as running and cycling. Both of these result in either increased effort for typical movements such as running or an emphasis on muscle groups that are less often utilized. This may be desirable in the case of exertion games [30] but also may be dangerous in Floating and Underwater scenarios where over exertion without nearby refuge could result in drowning. The games SwimMix and SwimJumpRoll by Deen et al. [10] make use of the friction and altered gravity of water to encourage high energy movements that are only possible in water.

Networking

Communication
Normal verbal communication between players may be disrupted due to the altered sense of hearing caused by either Sporadic Water colliding with nearby surfaces, splashing while Floating, or blocked ears while Underwater. Additionally, other forms of communication such as typical body language or facial expressions may be difficult to perform due to altered gravity, balance, and limb availability or may be difficult to observe with reduced sight. Meanwhile, other forms of physical communication such as basic arm gestures, sign language, or movements that are unique to water environments [39] are logical forms of communication in water that may often be overlooked when designing a game for a land environment.

Player Proxemics
The interpersonal distance between people can be broken up into four proxemic zones: intimate, personal, social, and public. Hall [16] originally defined these zones and their distances while Greenberg et al. [15] have recently indicated how they may be applied to ubiquitous computing. We believe that when considering these proxemic zones in a water environment, the affective responses of being in each of these zones may differ to when the players are on land. For example, while in most environments the breach of the intimate and personal zones by a stranger can be uncomfortable, in Floating and Underwater situations where drowning is a possible concern, unregulated interaction within these inner proxemic zones may be seen as more dangerous. Likewise, a player can feel the effect of another player's movement indirectly through water displacement and spray, even at the interpersonal distances of the social and public proxemic zone. There are opportunities to explore how these various interpersonal distances can alter a player's affective state while in water, just as Huggard et al. [19] did in land-based play by creating a game that encourages intimate and personal distances between players.

COMPUTER FEATURES IN WATER
This section discusses the design features relating to computing technology. Similar to the player features of the previous section, Figure 4 plots these design features against the six degrees of water contact and provides an indication of the extent that water can affect them. Some of example references in this table are found in both the Vicinity and the Partially Submerged (or Sporadic Contact) columns; this is because the water in the example is used both as an information display and an input interface.

We note that the degrees of water contact define the contact between the water and the player. Therefore the digital technology must accommodate the player being in the given state but the technology itself may or may not be experiencing the same degree of water contact. For example, a game controller held by a player in a Floating position may be likely to come into contact with the water. Meanwhile, a camera sensor may be positioned outside of a body of water but detects the player who is within it.

Internal State

Electrical Insulation
Insulating electrical components, or water-proofing, is typically the primary initial design concern of a digital waterplay experience where computer components may come into contact with water. At a minimum, water will disrupt an uninsulated electrical system and at the worst it could lead to the destruction of devices or the electrocution of the player.

Technology Temperature
Similar to the temperature of a human body, the temperature of technology in contact with the water may also be affected. This can be a benefit as a system that is operating in cold water may be less likely to overheat, offering a natural cooling solution. This allows for the utilization of much more powerful computer hardware that requires cooling.

Battery Life
If a device such as a wireless controller or a portable propulsion system is operating on battery power then there will need to be convenient strategies for charging or swapping batteries or switching to a cabled alternative. While this is similar to being on land, the player may need to exit a body of water before swapping batteries or charging, resulting in a longer break in gameplay. Wired alternatives may also not be practical in larger bodies of water. For self-propelled devices, the player should also be given early and clear warnings of power failure to prevent the device from being stranded in the water. These restrictions can be woven into the game design though, making the act of recharging a battery part of the game itself.

Sensing

Touch Screens and GSR Measurements
Water can interfere with sensors that detect electrical signals from the body. For example, most modern touchscreens operate by recognizing the unique conductive properties of skin

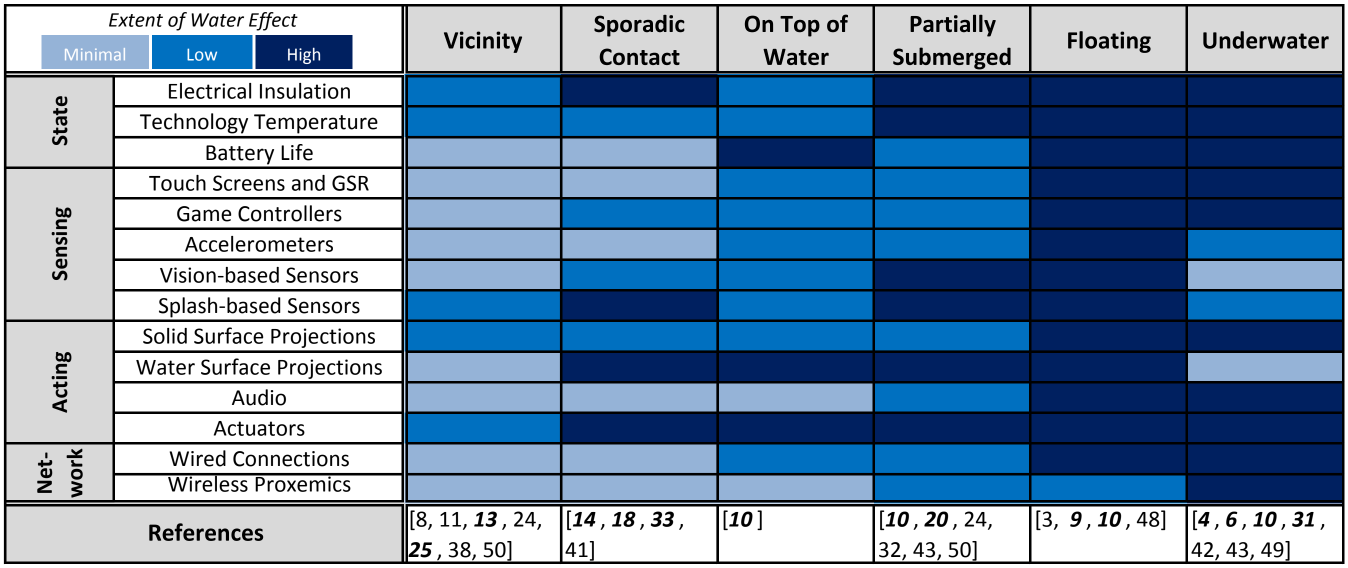

Figure 4. The computer features and the extent to which they are affected by water when the player is experiencing the specified degree of water contact.

within a weak electric field in order to differentiate between finger movement and other objects that may be touching the screen. This means that in the presence of water, a touch screen will not be usable as the surrounding water will change the electrical signature of a finger. Schuster et al. [43] explore a few research projects and commercial patents that aim to remedy this with waterproof tablet holders and unique touch interfaces. Alternatively, Matoba et al. [24] make the surface of the water itself a touchscreen by using a projector and a Microsoft Kinect. The disruption of electrical fields also means that the use of GSR, EEG, ECG, or similar sensors may be unreliable or otherwise require careful planning to prevent water from coming between the sensor and the skin.

Game Controllers

The lack of limb availability and a solid surface in the Floating and Underwater degrees of water contact mean that traditional input interfaces such as keyboards, mice, and game-controllers are difficult or impossible to use. Even with Sporadic Contact, a traditional controller can become slippery to hold if the player's hands become wet. In deeper water, as with audio and visuals, one solution may be to simplify controls to just a few buttons that can either be mounted on a wristband or to some solid surface in or around the body of water. In these cases, one hand can input simple commands while the other maintains balance.

Accelerometers

Another popular means of sensing player input is to use accelerometer devices to capture arm, leg, or torso movement. This is already a well investigated method of capturing and reporting on a swimmer's form [3]. In some applications, the accelerometers built into most smart-phones have been used as a convenient means of recognizing land-based activity [52]. However, as many player's may be cautious about having their phone near water, it is likely that such an accelerometer-based interface will need to be custom-made, being water proofed and provided with a non-intrusive means of carrying it, such as a wristband. Alternatively, Lee et al. [9] demonstrate how a common smart-phone can be waterproofed and attached to a swimmer's back in order to recognize swimming strokes for use into a digital game.

Vision-based Sensors

Vision-based sensors provide a means of capturing player input without requiring the player to directly interact with a physical controller. Such devices may include standard cameras, infrared depth sensors, and marker-based motion trackers. A few of the SwimGames presented by Deen et al. [10] utilize this type of approach to allow for interactive digital entertainment in public pools. For example, the game WaterPong uses a Microsoft Kinect to convert swimmers' bodies into a game object that a virtual ball can collide with.

However, many of these technologies are also inhibited by water. Many of the games by Deen et al. [10] that use vision sensors are played on the surface of the water and inspection of gameplay videos shows that the sensors are having difficulty detecting a player's body at depth. This is tested by Ozsvald [32] who shows that the refractive properties of water only allow the infrared depth sensors of the Microsoft Kinect to detect players in shallow water and even then with added noise. There are however marker-based motion trackers that are tailored for Underwater use, such as the Qualisys Oqus Underwater used by Sydney et al. [46]. Alternatively, Sattar and Dudek [42] present computer vision solutions to track key items such as a scuba diver's flippers.

Some vision-based sensing approaches that detect a certain body part, such as eye tracking or facial recognition, may not be able to see that body part at all times. In the example of an eye tracker, a player that is underwater may struggle to keep their eyes open and focused without goggles but such goggles may reflect camera or infrared eye tracking technology.

However, as oppose to dry environments, here vision systems can uniquely detect the movement of water, rather than the motion of the player or a physical game object. Campbell et al. [8] use a camera to sense the movement of water on a flat plain as a way of prototyping touch gestures on an abnormally shaped interface, all while keeping the user in the Vicinity of water rather than in direct contact with it.

Splash-based Sensors

The movement of water to sensors can act as input by detecting small displacements of a body of water, the collision of water on a sensor caused by splashing activities, or the filling of a container. Many of these activities have the benefit of either passively resulting from a player's interaction with the water or requiring movements that are easy to achieve from a Partially Submerged or Floating scenario. In this vein, Geurts and Abeele [14] demonstrate how displacing water in a bowl can be sensed and used to encourage rough interaction with an input interface, showing the benefit of water being both a traversable and indestructible input interface.

Acting

Solid Surface Projections

A typical gameplay interface may consist of a monitor or a projection onto a solid surface. However, the typically detailed imagery used in digital games may be difficult to see in a water environment. This may be because of the distortion effect that water has on the player's eyes, because the player has intermittent visibility due to splashes or swimming position, because the monitor is outside of a large body of water that defines the boundaries of play, or because the player is not using glasses as they usually would.

Some of these issues may be solved by using bigger monitor sizes or projections, lower resolutions, more discrete color ranges, and displaying fewer details or slower movements in videos. Ukai and Rekimoto [48] show an example of this by converting a video image of a swimmer's body into binary colors for easier viewing so that the swimmer can analyze and modify their form in real-time. They also place the monitor underwater on a robot that follows the swimmer, which demonstrates how strategic positioning of a monitor can make information more easily accessible.

An alternative is to embed the monitor into a pair of diving goggles or a hand-held device that can either remove the water between the player and the monitor or at least be held closer to the player's eyes. Blum et al. [6], Bellarbi et al. [4], and Oppermann [31] all use this type of technique to create augmented reality games underwater by respectively using a head-mounted display, hand-held submarine with a monitor, and a conventional tablet. Von Lukas et al. [49] provide a report on these and other techniques used for either producing augmented reality while the user is Underwater or for producing a virtual reality simulation of an underwater environment while the user is on dry land.

Water Surface Projections

Images and video can also be projected onto water to provide visual feedback to the player. Whether such a water interface is for just output or for input as well, a player can pass through it in a way that is not possible with more solid interfaces. Watanabe [50] shows how a bathroom sink full of water can be used for both input and output, allowing the water to retain its original function in the bathroom but also to be used as a digital interface. Koleva et al. [25] similarly show how such a traversable interface can be used to blend the barrier between the virtual and physical worlds by using a water curtain during an interactive theatrical experience that allows participants to traverse through the screen.

Audio

Due to the sounds of splashing water or because the player's ears are underwater, the ability to convey complex information through audio is reduced, similar to visual projections. When the player's ears are out of the water and the audio is contending with ambient water noises, simply raising the volume of audio may make it more audible. However, when the player's ears are underwater, increasing the volume may not make the signal clearer. Additionally, some audio frequencies are easy to hear in air can cause discomfort or ear damage in water [12]. One solution to this may be to use simplified sounds such as individual beeps or low fidelity audio formats such as MIDI, operating within appropriate frequencies. The other alternative, as shown by Lee et al. [9], is to provide the player with headphones. However, this has the added challenge of requiring a nearby computing device, such as one that is worn by the player, to relay audio data to the headphones.

Actuators

Actuation of mechanical systems that are Floating or Underwater must account for the altered gravity, pressure, and drag of the water environment. This means that robotic systems for land can be substantially different to those in water. Antonelli et al. [2] provide a substantial list of such considerations, producing models of underwater physics that can be used when simulating and engineering underwater robotics. There is also a recent push toward fish-like locomotion [26] to propel robots in underwater environments in a bioinspired manner.

Actuators such as water pumps can also be used to move the water itself, rather than to move a computing device through the water. The sight of moving water can be used to convey messages to a player in the Vicinity of water through visual fountains [33], falling water displays [38], or the filling of containers [13]. The PumpSpark [11] has been designed with this type of interaction in mind, making water pump actuation simpler in HCI applications and giving further examples of how these pumps can be used.

The movement of water against a player's skin can also be used to convey the state of the game to the player. General examples include being splashed by water from a fountain or shower, the feeling of bubbles rushing past the body, waves on the surface of the water, or currents in deep water. Hoste and Signer [18] use water as a projectile in order to hit other players in a fighting game while Richter et al. [41] use fine water jets as tactile feedback for touch interfaces.

Water can also be used to surprise the player in a gentle manner, with surprise being one means of eliciting enjoyment [5] as we mentioned earlier with regards to the Mental Response player feature. The use of this property can be seen in water attractions created as far back as 1612 in Hellbrunn Palace (Austria) [17] in which palace guests in the gardens could be soaked by jets of water. These types of water activities still exist today, such as running through sprinklers, carnival dunking games, and fountains that are embedded in the ground of pedestrian public spaces, all of which are enjoyed due to the risk of getting wet and the unpredictability of when it will happen. While not conveying a message through water contact, the sight of moving water can also be used to convey a message when the player is in the Vicinity of water

Networking

Wired Connections

Separate components of a computer may be required to communicate with each other, with each component potentially experiencing a different degree of water contact. For example, a game controller being used by a player within a body of water may need to communicate with a game system outside of the water or a computer may need to send commands to an actuator located underwater. If the player or a segregated computer component is within a large body of water, the cabling will need to extend over a long distance. Also, there may be concerns of a player becoming entangled in the cabling or the insulation surrounding the wiring deteriorating and passing an electrical current into the body water. However, wired connections may provide a quick means of prototyping and have a distinct advantage regarding signal strength and clarity over wireless communication in water, as discussed next. Cable management can also be a part of play, requiring the player to anchor a cable at regular intervals, which not only would keep the cable out of the way but would also provide a visible path of where the player has been.

Wireless Proxemics

An alternative to the above is to use a wireless connection that can easily reach over a longer distance without obstructing the player. However, Mueller et al. [29] discuss the proxemics of wireless technologies and how the signal strength of such technology can be affected by water. As with visible light and audio, water can distort and absorb radio waves, especially in salt water. Though, as with many of the features in this paper, this can be a positive design element. For example, the Jelly-Stomp game [20] exploits the limitations in Bluetooth radio communication by encouraging players to push other players' controllers underwater to break the connection to the computer, triggering game events.

CONCLUSION

The amount of research that investigates digital water-play experiences is relatively small but recently growing faster due to emerging sensing and acting technologies that allow for player-computer interaction in water environments. We see water as a powerful and mostly unexplored means of digital interaction, with unique properties that are not found in other physical environments and multiple degrees of water contact that provide differing context to similar experiences.

In this paper we proposed a taxonomy of six degrees of water contact and four categories of player and computer design features to be considered during the design and development of digital water-play experiences. By combining these, we gave an indication to the types of features that may be affected when the player is in or around water. We also indicated the extent that the water may affect each feature at the given degrees of water contact. From this analysis, it is clear that many of these features are greatly affect by the Floating and Underwater degrees of water contact, reinforcing the intuition that designing for these scenarios is a substantially different practice to designing for conventional land and air environments. This further motivates the need for future studies into establishing a cohesive set of design principles for digital water-play experiences.

It is important to note that the features, categories, degrees of water contact, and the interactions between all of them that are described here are based upon our own experiences and those that we have perceived in the work of other authors and practitioners. There may very well be other taxonomies for the degrees of water contact, other design features that we have not identified, or disagreements in the level of effect that water has on each of these design features. Furthermore, we have yet to thoroughly evaluate the features that were described in this paper through implementation and experimentation. However, we believe this to be a useful starting point for designers creating digital experiences in water. It collates a breadth of experiences from numerous past projects and identifies some of the key features that ought to be considered early in the design process and that we feel may otherwise be overlooked or encountered too late in the prototype development stage.

ACKNOWLEDGMENT

We acknowledge the support from our industry partner Village Roadshow Limited and the Australian Research Council (ARC) Linkage Grant LP130100743.

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