Experience is not Required: Designing a Sailing Experience for Individuals with Tetraplegia

Ahmad Alsaleem, Ross Imburgia, Andrew Merryweather, Roger Altizer, Jeffery Rosenbluth, Stephen Trapp, and Jason Wiese
University of Utah, Salt Lake City, Utah, USA
{ahmad.alsaleem@, r.imburgia@, a.merryweather@, roger.altizer@, jeffrey.rosenbluth@hsc., stephen.trapp@hsc., jason.wiese@} utah.edu

ABSTRACT
Sailing has a range of positive impacts on mental and physical health-related quality of life for individuals with tetraplegia. This work describes the iterative design process of creating an adaptive sailing experience that requires minimal training and preparation for individuals with tetraplegia. The Tetra-Sail is an adaptive sailing experience that uses a Shared-Control approach to accept input from both a main user and an experienced adaptive instructor (control partner). This approach was used to create a usable experience for individuals with all types of physical abilities, including participants with high level and complete spinal cord injuries characterized by loss of sensation and function below their site of injury, with minimal preliminary training. A study of nine participants (five first-time users of Tetra-Sail and four who had used previous iterations) suggested that participants found Tetra-Sail usable and enjoyable. Participants expressed feelings of empowerment, which they attributed to the flexible adaptation to their abilities supported by the implementation of Shared-Control.

Author Keywords
Adaptive sailing; Shared-Control; tetraplegia

CCS Concepts
•**Human-centered computing** → **Accessibility systems and tools;** *Accessibility technologies;*

INTRODUCTION
Recreational activities have direct positive effects on physical and mental health-related quality of life for individuals with spinal cord injuries and disorders (SCI/D) [27]. This is broadly true for individuals with tetraplegia - paralysis resulting in some degree of sensory and motor control loss in all four limbs [8]. Unfortunately, there are a range of physical and social barriers to recreational activity associated with tetraplegia [6].

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Figure 1: sip-and-puff Tetra-Sail user with medical staff on the right and the control partner on the left. Photo courtesy of Deseret News Publishing Company

Those challenges are even more pronounced when it comes to outdoor skill-based sport activities, such as sailing.

Among other barriers, skill and experience gaps are major barriers for participation among individuals with disabilities [11]. In the general population individuals build skill and experience through frequent practice. This often requires people to travel to a particular location. However, for an individual with tetraplegia, the logistics required for this, such as having proper transportation, can be a significant challenge [19]. Simulated environments could provide a more accessible training platform [10], but face other limitations, such as being limited in number and availability and have high costs associated with installation, and may still require travel. Unfortunately, in combination with the many other barriers that limit access to these experiences for individuals with tetraplegia, requiring frequent practice puts these experiences out of reach for most.

We designed an adaptive sailing experience, Tetra-Sail, with the goal of empowering participants to pilot the craft without requiring previous sailing experience. The Tetra-Sail that employs a Shared-Control scheme between the main user and a control partner. This Shared-Control scheme was designed to enhance adaptability by creating a safe, training-in-situ experience that reduces the need for extensive pre-training.

We developed Tetra-Sail iteratively, cycling between designing, building, and deploying. We deployed the most recent prototype of Tetra-Sail in the Summer of 2019 with nine participants (five participants were first time users of Tetra-Sail and the other four were returning users). Data collected from participants indicate these prototypes are adoptable, usable, enjoyable, and offer a sense of empowerment. This paper described the design goals, outcomes, and challenges to addressing the goal of enhancing adoptability of the Tetra-Sail.

BACKGROUND AND RELATED WORK

Challenges for participating in outdoor activities

The literature on accessible outdoor recreational activities for individuals with tetraplegia is limited but growing. Many barriers to participation in outdoor adaptive sport activities have been identified [25, 28, 32], including: time constraints, lack of companionship and transportation, fatigue and difficulty resetting, social support, health condition, general lack of confidence, accessibility of exercise and recreation equipment, and lack of information about available opportunities.

Many attempts have been made to address these barriers by creating adaptive sport programs that help with providing the required logistics for accessible participation. Still, access to such programs can be limited due to financial constraints, time, and transportation. In the United States, the Americans with Disability Act (ADA), has increased access for many outdoor activities for people with disabilities, as it enforces equal access opportunities for people with and without disabilities. While this act has helped create more accessible indoor/outdoor activities, it still does not address all problems that participants can face as there are issues with use, interpretation, or enforcement of the ADA codes [25]. For instance ADA, does not specifically address change in access to lakes with a seasonal change in water levels.

Tetra-Sail is an effort to lower some of these barriers by providing a sailing experience that is operable even by first-time sailors. This affords more flexibility in terms of scheduling and accessing the experience as it does not impose any prerequisites in order to participate. Further Tetra-Sail's Shared-Control approach also provides social support, which can further encourage participation.

Adaptive sailing for individuals with tetraplegia

Although many barriers to participation in outdoor recreation are common for individuals with tetraplegia, more opportunities are developing. Accessdinghy [2] is one example of a company that has created a commercially available sailing boat that can be outfitted with sip-and-puff or joystick controls. This technology is described as functional with positive effects on the user, such as improvement in self-worth, community belonging, and level of motivation to use the system again [26]. These findings are limited to a single person case study. Also, The participant had sailing experience prior to his injury and participated in multiple introductory sailing courses before the sailing experience. Such offerings require training before participating in the sport, which can be a barrier to participation for individuals with tetraplegia.

Another example, is Hansa [15], a sailing company that produces a range of adaptive sailing boats that can be equipped with joysticks or sip-and-puff systems. This is a very exciting effort, which aligns with our goals. Currently, there is no academic literature on these systems and participants reactions. By reporting on our work using the Shared-Control scheme and reporting about our participants reactions and requests using Tetra-Sail, we aim to add to the literature reporting experiences and results for similar approaches.

A major player in the adaptive sailing field is Accessible Sailing Technology [29]. This company outfits different sailing boats and equipment with adaptive controllers (joystick and sip-and-puff) to make them accessible. One of their better-known projects is the sip-and-puff controlled Martin 16. A well-known user of their technology is Hilary Lister, a tetraplegic sailor [20]. She uses a three straw sip-and-puff interface to control the Martin 16 independently. Using this technology, she was the first woman with tetraplegia to sail solo around Britain. While clearly effective, such a system still requires considerable training and practice that is a barrier and could limit participation for individuals with tetraplegia.

Accessing the training necessary to acquire sailing skills is a must for participation, and this introduces barriers for individuals with tetraplegia. Some progress has been made towards addressing that barrier by creating a virtual sailing training simulation to provide a more convenient training platform [10]. Three participants (joystick users or users with hand power to operate the sail manually) underwent a 12-week training and validated their skills using a virtual training simulation. After training, participants successfully sailed on a real-world course. While this work promises a training platform that is more accessible, the long duration of the training remains an issue for some users. Further, the study did not include participants with high level injury (i.e., those requiring sip-and-puff) to better characterize the parameters and limitations of this approach with a diverse population of tetraplegic sailors.

Shared-Control Systems

Shared-Control has been explored in many contexts. One of the early attempts was in designing computational models for collaborative planning for multiple agents [13]. This work formalized the communication procedure and planning between multiple agents to perform a certain task or objective. A major advantage of that model, was explicit acknowledgement of each agent's capabilities that might differ from other agents. In the gaming world, Inkpen et al. [18] explored the idea of having two children playing the same game using two mice on the same computer, while collaboration to solve a puzzle together. More recently, Harris et al. [16] have explored games that are designed around the idea of asymmetric control that are carefully designed to accommodate different players' skills while ensuring close social interaction is maintained. These games were found to provide higher social presence and perceptions of connectedness in comparison to symmetric games. Other work by Harris el al. [17], presents different elements of asymmetric games that could serve as design tools for game designers in creating asymmetric games. In education, Shared-Control has been used to train surgeons to perform surgeries with the help of haptic feedback [22].

Another type of Shared-Control system is one where control is shared between an automated system and a human partner to perform a task. For instance, the work by Philips et al. [24] presented the idea of using adaptive Shared-Control for wheelchair systems. Here, a user wears brain-computer interface (BCI) that predicts a user's intentions to control the wheelchair. A laser scan with associated algorithms (i.e., obstacle detection and obstacle avoidance) further refines user controls to provide safe and efficient movement. The system allows the user to select the level of assistance from the automation system based on his/her needs.

In terms of adaptive outdoor activities, Shared-Control systems have been designed to help facilitate collaboration between two people with different physical abilities, while making it possible for a primary user to maintain a high level of independence over control [3, 4]. Baldwin et al. designed a system that supports a person who has a visual impairment to participate in outrigger canoe paddling [4]. The control system relies on two participants collaborating to control the outrigger paddling experience. The individual with visual impairment controls everything in the paddling experience except for turning, which is controlled by another person using a wireless remote controller. Shared-Control schemes have also been explored as a solution to allow individuals with tetraplegia to ski independently or semi-independently [3].

Recent work by Bennett et al. explored interdependence as a conceptual framework for approaching the design of assistive technology [7]. This work argues that independence (the long design goal of accessible technology) should not be the only design target, but that interdependence is itself also a worthy end-goal. That work highlights that in a system designed for interdependence, people with disabilities are equal participants who work with other collaborators to accomplish shared objectives. This moves away from the traditional framing of people with disabilities only being the recipients of assistance, rather than collaborative contributors.

In our design of Tetra-Sail we aimed to create an experience that can be usable by participants with or without previous experience. In addition, our solution is designed to support people with high-level injuries (sip-and-puff users), expanding access to sailing to a broader population and introducing additional design and implementation considerations. While our own past work engages applying sip-and-puff in one sporting context (skiing) [3], the context and constraints of sailing are different. However, we have been able to leverage insights about sip-and-puff control in the context of Tetra-Ski to inform our concurrent iterative design of Tetra-Sail.

TETRA-SAIL DESIGN PROCESS

Through the following sections we dive into the design process of Tetra-Sail. We started by engaging stakeholders from different fields to elicit the major factors of creating a usable sailing experience. Next we describe iterative development phases culminating with the current implementation of Tetra-Sail.

Design goals

After evaluating existing solutions for individuals with tetraplegia to sail, the team wanted to extend this offering to include a wider range of participants. Participants that have sustained complex injuries that resulted in complete paralyzation including participants who rely on electrical ventilators. These types of users require a careful design to ensure usable and safe experience. We also wanted to lower the barrier to participation (discussed above) by reducing, ideally eliminating, the need for prior training and practice in order to use our system.

We followed a user-centered design process [1], starting by collecting data from the TRAILS program at the University of Utah. The TRAILS program is an outreach program for people with spinal cord injury and is a member of the Paralympic Sport Club network. The major objectives identified by the program members for this technology to be successful were safety, an easy to learn user interface, manual overrides, and modularity. The team learned that different people in our targeted population might use a variety of input modalities in their wheelchair system, including: a joystick, head-switch, and sip-and-puff (mouth controller). There are many customizations and adaptations a wheelchair system might have, depending on the user's health condition, many of those should also exist on Tetra-Sail. Some examples include seat adaptability, straps to hold in place different body parts, padded cushions to relieve pressure, places for all of the health equipment a user might have (i.e., electrical ventilator), and holders for drinking water and other medications. The team also learned that targeted population might be fully dependant on others to perform all of their daily tasks (i.e., drinking water) and require continuous monitoring (i.e., can have sudden muscle spasms). Participants might also have cognitive conditions that affect their ability to communicate or learn. Finally, potential participants might have different health conditions that limit the duration of their participation or the specific time window that they can participate (e.g. increased risk of acquiring a pressure ucler [31]).

Based on this initial information we identified the following goals for our design:

1. The sailing system should accommodate all levels of skill in sailing. Beginners and those with more experience users should be able to use the system with little to no training.
2. The hardware should be customizable and adjustable to support all types of physical abilities.
3. The system should work with multiple input modalities that accommodate all sorts of physical abilities.
4. The system should be safe and allow for fast on-the-spot medical intervention if needed.
5. In order to maximize the number of participants we can take per sail each day, the system needs to operate all day long without recharging the battery.

We used these design goals as guiding principles as we created Tetra-Sail V1, detailed in the following section.

Tetra-Sail V1

For our first iteration, Tetra-Sail V1 [21], we modified a Hobie Mirage Island (see Figure 2) to achieve our design goals. The engineering team added a motorized rudder that could turn

Figure 2: The components of the Tetra-Sail V1 design

Tetra-Sail to the left and right directions. A major advantage of the Hobie Mirage Island is that it can accommodate up to four people on board for the sailing experience. This would allow the user's medical team to be on board with the participant during the experience. For input devices, we used an input module that is used in motorized wheelchair systems. the module has the ability to plug and play multiple input devices, including a wheelchair joystick and sip-and-puff. The team modified the signals provided by the wheelchair system controllers to control the various functions of Tetra-Sail.

The engineering team fabricated a new seating system using a similar approach to the seating supports found on motorized wheelchairs to facilitate adjustability in all aspects of the seating components to match the seating requirements for a range participants. We also provided many different types of straps and supports to comfortably secure participants in the craft.

One benefit of using the joystick and sip-and-puff controllers from a motorized wheelchair was that they can operate in rough outdoor environments and cover a broad range of abilities. The basic functions programmed were for turning left and right (i.e. this would not be a fully independent sailing experience). For sip-and-puff users, that meant soft sipping (inhaling air into the mouth controller) to turn left or soft puffing to turn right (exhaling air into the mouth controller), which is the same control scheme employed on a wheelchair. For the joystick the mapping was more intrinsic, where pushing the joystick left or right would position the rudder to steer the craft to the left or right. For joystick users only we added the ability for them to increase/decrease the motor speed.

We provided participants with an adaptive trainer on board. The goal was that this would reduce the amount of training and work required for the user to control Tetra-Sail. The adaptive instructor in V1 served as a supervisor and could control the sail, rudder and the motor. Based on the specific health conditions of the participant, they might also be accompanied by medical professional to monitor and take care of the participant. The adaptive instructor being co-located with the participant also facilitated verbal communication between the instructor and Tetra-Sail user.

We formalized the instructor's primary responsibilities based on the deployment of this initial prototype. One important responsibility was communicating any necessary information information (i.e, you need to turn left another boat is approaching from behind). Another responsibility was to observe and anticipate users' actions to maintain the safety of the experience. If a problem arose, they would stop Tetra-Sail or take control from the user if needed to avoid danger. Once the experience is safe, return control to the user. Finally, we observed that the instructor would provide goals and navigation targets to the participant to help structure the experience.

Finally, to ensure safety we added a mechanical release switch for the instructor. Flipping the mechanical switch would disconnect the control systems of the participant and give full control to instructor. This system can be used by the instructor in the event of an emergency.

Challenges with Tetra-Sail V1

After deploying V1 with participants, we faced several challenges. One such challenge was that the frequency and the duration of a user activating commands in Tetra-Sail is much higher than the one in a wheelchair context. Unfortunately, wheelchair input systems limit the speed of the outputted signal of their input device for safety reasons and to avoid sudden jerky movements. This delay was confusing for users as they lack any feedback about the performed command, and they would react by over-performing control commands. This could lead to control problems for users, and cause them to quickly become fatigued. Thus, a standard wheelchair input system was not compatible with the requirements of Tetra-Sail.

Another major hurdle the team found was that the wheelchair sip-and-puff system needed continuous calibration while sailing. The team attributes this to environmental factors (i.e., weather that could increase noise for the sensors) and having multiple participants with different abilities using the same system through the day. This is not a typical situation a wheelchair sip-and-puff system is designed to handle.

Another problem the team encountered was a diminished sip-and-puff experience if the wind wasn't blowing hard enough to power the boat. The instructor would engage the Tetra-Sail's motor (sip-and-puff users could not control the motor at that time) for the participant if there was not enough wind power, but this would break continuity of the sailing experience. We wanted to implement more control, however a major problem with the wheelchair sip-and-puff system is that it was a black box, which did not allow the team to expand the number of commands a sip-and-puff can do from the original commands.

V1 was also challenging for the instructor, who was overwhelmed by the number of tasks to perform on Tetra-Sail. Tasks bounced between instructing participants on what to do and physically overriding and controlling different aspects

Controls	Sip&Puff v1	Sip&Puff v2
Turn Left	Soft Sip	Single Short Sip
Turn Right	Soft Puff	Single Short Puff
Increase Speed	N/A	Puff Puff
Decrease Speed	N/A	Sip Sip
Unfurl Sail	N/A	SipSipSip
Furl Sail	N/A	PuffPuffPuff
Rudder to neutral	N/A	Long Puff (*PuffSip)
Turn off motor	N/A	Long Sip (*SipPuff)

Table 1: The control schemes for sip-and-puff v1 and v2. *in V2 we moved from long sips/puffs to SipPuff and PuffSip.

of Tetra-Sail (which could require them to move around the craft). In addition, the complete interruption of control by the instructor when activating the mechanical switch negatively affected the user's experience. Any need for the instructor to execute a command required taking full control from the user, which also broke the feeling of independence and control for the user.

TETRA-SAIL V2

Based on these challenges the research team went to work on another iteration of Tetra-Sail. For this iteration of Tetra-Sail, we gathered more feedback from the TRAILS program and participants from the previous summer camps. Based on these activities and the feedback and issues described in the previous section, we pursued two activities: (1) Re-design the control scheme and hardware for easier operation while providing users with more feedback about the control system and the surrounding environment, (2) Developing a simulation that a participant can use before the experience to reduce the time to adapt to doing the real-world experience of sailing. We begin by describing our changes to the control scheme and hardware from Tetra-Sail V1 to Tetra-Sail V2.

Tetra-Sail V2 Hardware Modifications

Building on the insight that the (lack of) wind affected sip-and-puff participants' enjoyment of the experience, the team decide to modify the system to allow sip-and-puff users to control the motor using the sip-and-puff system (previously only controllable by the control partner and joystick users). Having control of the motor would allow sip-and-puff participants to still navigate on the water, even in the absence of wind. Furthermore, sailing using motor power requires less experience than using wind power. This change would allow first-time sailors to to have an enjoyable experience even with minimal sailing knowledge or prior sailing experience.

Next, the development team abandoned the wheelchair-based control system in favor of developing a custom joystick and sip-and-puff input systems. This allowed the engineering team to expand the number of commands the sip-and-puff provided.Another factor contributing to this design change was the reduction in response time for both input devices to something more suitable for an active experience like Tetra-Sail. This would also hopefully reduce over-performance. The team used a joystick with a similar mechanical feel to the joysticks found on wheelchairs, and could also accept the different joystick knobs that users are familiar with on their own wheelchairs. This allowed for users to bring their own custom joystick knobs onto Tetra-Sail.

We also added a speaker system to provide feedback about the commands issued by users through the sip-and-puff controller by announcing the commands as they are issued. The goal was to reduce the likelihood of unnecessary over-performance by making the system state "visible" (audible) to the end user.

Tetra-Sail V2 Control Scheme Modifications

We expanded both joystick and sip-and-puff control schemes to accommodate more commands.

Sip-and-puff

The addition of the motor controls for sip-and-puff users and the motorized sail added more commands for our users. Having our own custom input system allowed the engineering team to expand beyond the four commands provided by the wheelchair control system (i.e. forward, back, left, and right). We also switched from an air-pressure-based sip-and-puff system (i.e. soft/hard sip/puff) to a time-sensitive one (i.e. long/short sip/puff) to reduce the number of times we would need to calibrate the system. The objective here was to reduce the likelihood the user would be concerned with how much air they were pushing into the sip-and-puff, which could in turn cause fatigue if frequently activating commands for Tetra-Sail.

After experimenting with multiple control schemes the engineering team decided on switching from continuous sipping and puffing for turning (incompatible with time-sensitive control) to discrete steps. This was also in response to a high error rate and unintentional triggering of commands by participants performing continuous sipping/puffing and having other sip-and-puff commands to perform (e.g., double puff to increase motor power). Trial and error in both simulation and real prototypes showed that having multiple distinguishable sip-and-puff commands to be performed in less than one second of time resolution was a very challenging task.

In the new control scheme (see Table 1), sip-and-puff users would perform discrete sips/puffs to turn left/right in amounts of 50% and 100% (in later iteration based on users' requests we changed these amounts to 33%, 66% and 100%). To control the motor power, we used long-duration puffs/sips to increase/decrease motor power. We found that participants would unintentionally trigger long puffs and sips, as they were confused by the amount of time they need to hold the sip or the puff as they switched back and forth between performing short sips/puffs to turn and long sips/puffs to engage the motor. To address this confusion we moved to discrete PuffPuff/SipSip to engage/disengage the motor in increments of 33%, 66% and 100% of the maximum power of the motor. We also added SipSipSip and PuffPuffPuff to completely furl/unfurl the sail.

We also created several "shortcut" commands for the sip-and-puff users: a Long Sip will set motor power at 0% from any current power level, and a Long Puff will return rudder back to neutral from any current turning position. Those commands also come from standard commands in a wheelchair sip-and-puff control system to stop forward motion or finish a turn. Because we expected these shortcut commands to be used infrequently, we extend the amount of time required to hold

Figure 3: The control partner with the wireless remote control.

the sip or the puff from 600ms to 1200ms. By extending the time to perform the Long Puff/Sip and because these will be performed less frequently, we hoped that they would be able to perform these commands more accurately than when we used those commands for controlling motor speed.

Unfortunately, we again found many sip-and-puff users unintentionally triggering these shortcut commands. This also created a problem for the instructor; Unintentionally triggering a shortcut command such as "turning off the motor" confused both parties and in some situations led them to think there were technical problems with the system requiring immediate attention by the engineering team. In other situations the accidental performance of these commands led the user to feel frustrated by not being able to control the system.

To address this issue we added two new combination commands: SipPuff and PuffSip. These are more difficult to perform than a single sip or puff, but are harder to trigger unintentionally. Though this turned out to be true, we found that none of our study participants ever chose to intentionally trigger these shortcut commands. In fact, between switching back and forth between sip-and-puff and joystick participants, the instructor even sometimes forgot that Tetra-Sail had this functionality.

Joystick

For joystick users, turning and engaging the motor was the same with the new joystick module as it had been with Tetra-Sail V1. However, we added a new command for furling/unfurling the sail. To do this, a user can push the joystick all the way back and once back then to the left/right. These changes to the control system provided our participants with a more usable experience than V1. However, deploying this new prototype control system meant that we could still encounter system failures or bugs while sailing. To address this, we added a system restart (power cycle) button that was accessible both to the participants and to the instructor. While reviewing recorded audio from during sailing sessions, we found that this button was used by the instructor to solve technical problems, rather than calling engineering team on the beach to debug in real time. This would allow debugging to happen later, after the session had concluded.

Shared-Control

After gathering feedback from the instructor about his experience using Tetra-Sail, we saw that the instructor could be overwhelmed by the number of tasks he needed to perform on board: instructing the participant, looking out for obstacles and traffic, taking control if necessary, and monitoring the physical health and comfort of the participant (including coordinating with accompanying medical/care personnel). Further, the instructor had a hard time debugging issues with the sip-and-puff system. When a problem would occur, he could not easily determine its source. For example, a re-calibration could be needed, the user might not be performing the correct command, or there could be a bug.

The instructor also had to physically move around on Tetra-Sail to perform his various jobs, including adjusting the positioning of the sip-and-puff straw for the participant, making sure the participant was hydrated, getting to the mechanical override switch if he had to take control. Finally, if the instructor overrode the controls, it resulted in a complete interruption of control for the participant. This was disruptive, and the instructor balanced between the negative impacts of disruption and general safety and piloting.

We wanted to address these challenges, and in particular to help the instructor keep most of his/her focus on instructing the participant and supporting them to have a usable and enjoyable experience. We especially wanted to resolve the disruptive nature of switching control back and forth between instructor and participant. We focused on Shared-Control as a potential solution for this challenge, drawing on our past work exploring Shared-Control in adaptive skiing [3], we defined a control scheme utilizes the idea of Shared-Control for Tetra-Sail. Shared-Control is a control scheme that relies on idea of two parties working collaboratively to control an activity.

Tetra-Sail's Shared-Control system works by having an experienced human (adaptive instructor) as the control partner use a handheld wireless controller, similar to a Wiimote (see Figure 3) to issue commands. This helps the control partner be able to focus on user performance and training, rather than moving around for manual override. Another major benefit of the remote control is that control partner has complete control of Tetra-Sail from any location. This helps the control partner move to other places (i.e., shift weight for better sailing performance), be able to get a better view to give the main user more information, or to assist the participant (e.g., by adjusting the sip-and-puff system to reach the user's mouth) without losing access to controls or the emergency break system.

Shared-Control also supported a more fluid, less disruptive collaborative control process between the control partner and the main user. With Shared-Control, the control partner has the option to refine users' actions rather than taking full control. For instance, a control partner can engage the motor to be a certain speed while having the user in control of the turning. For safety reasons, the remote control always has the highest priority in control. Thus, if both the main user and the control partner issued a command to control the same aspect of the sailing experience the main user's command will overridden. This introduces an imbalance. Instructors are sensitive to the potential for this to negatively impact the experience and they take steps to minimize this. For example, the control partner informs the user verbally when taking control or performing certain actions. We avoided announcing control partner commands through the speaker system to avoid confusion for both parties and reduce the amount of disturbance that could be caused by frequently announcing actions through the speaker.

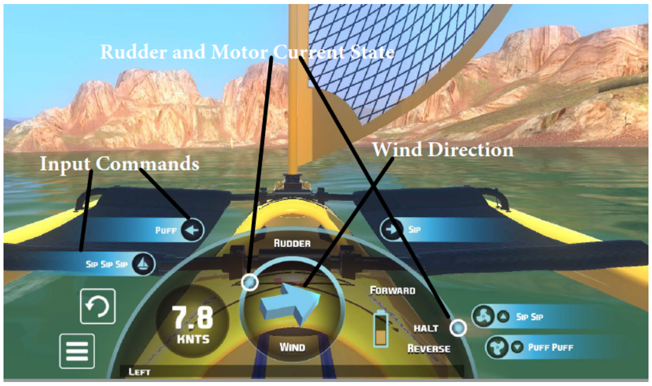

Figure 4: A level from the Tetra-Sail simulation

Another major advantage of Shared-Control is having all control options enabled for the main user at all times. A control partner can handle the controls that require more experience (e.g., best position for the sail) for the beginners users at the beginning of the experience. Once a user is more experienced with the system, the control partner can seamlessly cede control to the main user immediately. Since the control partner and main user are co-located, this process of switching between a full control scheme (full control of all aspect of Tetra-Sail) and a more basic scheme (i.e., only turning left or right) can happen seamlessly as many times and as is needed based on the main user's request or as suggested by the control partner. This leads to adaptive performance, where the system through the control partner can adapt to the user performance and provide the most appropriate control level that ensures usability and minimizes frustration by our main users.

Shared-Control also facilitates effective communication. Regardless of physical abilities, beginning users are unlikely to be familiar with sailing terminology and concepts. Having a human control partner can help to facilitate learning in this context. A control partner using Shared-Control can act as a translator between Tetra-Sail and the main user. For example if the main user wants more speed (depending on wind conditions this can be accomplished in different ways, such as changing the angle of the boat relative to the direction of the wind), the control partner can work with the main user to define what "more speed" means, and can make adjustments in collaboration with the main user to realize this goal to scaffold their learning. The team kept the manual overrides in place as a fail safe in case of system malfunction. This is especially important as the system continues to see changes as an iterative prototype. The research team had been concerned that implementing Shared-Control could negatively impact the main users' feelings of independence and autonomy. The extent to which the control partner automates task for the main user could affect his/her complacency, situational awareness and skill levels [23]. We aimed to provide a high level automation for information acquisition (verbal communication by the control partner), as a model by Parasuraman, et al. suggests [23], and to have a lower level of automation for decision selection and action implementation for the main user. Admittedly, there is a training process before novice users had more direct control over all aspects of Tetra-Sail (lower level of automation by the control partner). However, this approach showed a positive effect on users' feelings of autonomy and independence as we report in our user study.

Tetra-Sail simulation

Starting with Tetra-Sail V2 we also developed a training simulation to explore opportunities for participants to become familiar with Tetra-Sail before the real-world experience. Part of the goal was to maximize their time on the water, which was limited both by health constraints and by the availability of the craft for other participants. We developed the simulation terrain based on the environment at the lake destination where the Tetra-Sail experience takes place. The participant can use the same model of joystick and/or sip-and-puff as the ones used on the Tetra-Sail, and can even use them simultaneously.

While it was not necessary to use the simulation before piloting Tetra-Sail, the simulation helps accomplish the following goals: (1) Participants can practice using the input device and the control scheme of Tetra-Sail before trying Tetra-Sail in the real-world, (2) Participants can try both the joystick and the sip-and-puff controller so that they can decide which one they prefer and gives them better control, (3) Training users on the basics of sailing using wind power.

The simulation evolved over iterative development cycles. Initially we created the simulation with the sole purpose of training participants on how to use Tetra-Sail controls. Later the simulation became a useful tool for testing new ideas and control schemes. This was especially valuable since modifying the simulation and having participants try the new version is not constrained by the season or logistics of getting to a location. Furthermore, making software changes to the simulation was simpler than modifying the Tetra-Sail firmware or hardware.

The Tetra-Sail simulation impacted the of design for the real-world Tetra-Sail experience in two ways. First, participants using Tetra-Sail in a summer camp 2017 and informal testing sessions with multiple participants that have tetraplegia told us that the visual representation of different control aspects in the simulation (UI) was confusing to them when it came time to control the real-world experience. Participants were confused by having the visual feedback of the UI in the simulation, but not a similar visual representation in the real-world experience. While we realized that a visual interface was infeasible for the real-world experience, we determined that we could switch to audio feedback in the simulation and that if this worked we could also provide it in the real-world experience. Based on positive feedback from simulation participants, the engineering team implemented the audio feedback system in the real-world experience. Participants found this feedback helpful, and the consistent experience meant that there was less confusion going between the simulation and the real-world.

Second, the simulation has enabled us to test different input devices for Tetra-Sail. For example, we have implemented and tested Electromyography (EMG) switches in the simulation environment. Users were not able to consistently trigger the EMG switches at the right time in the simulation. We also implemented "sip-and-puff with a button," which added a mouth-triggered button as an additional input in conjunction with sip-and-puff (e.g. a sip while holding the button for turning). While this did enhance the accuracy of triggering commands, users had difficulty simultaneously biting on a button and closing their mouth around sip-and-puff to provide adequate air-pressure. Finally, in a small study (N=11) we asked participants with limited hand motion if they were interested in combining both the sip-and-puff and the joystick controller to control Tetra-Sail for more accessible control. None of the participants were interested in this option.

The Tetra-Sail simulation enabled us to test new ideas and design decisions on a platform that is accessible year round and does not come with the logistical constraints of the real-world system. By implementing and testing these solutions in the simulator, we saved the time and effort of modifying Tetra-Sail to test these control options, and also the precious time on the water that it would have taken to test them.

Finally, we designed the simulation to help users become familiar with Tetra-Sail prior to the real-world experience. Similar to the issues raised in past work, logistics like transportation, scheduling, and unexpected health conditions prevented them from having a simulation session. For example, despite our best efforts, in our last study six of the participants did not have the chance to use the simulation in any capacity. Two participants had 30 minutes of training on the simulation before participating. One participants had the chance to train at home for two days on the simulation after her Tetra-Sail experience. These challenges motivated our work to have a usable experience for our users even without any simulation sessions. In the future we hope to figure out a way to distribute the simulation in a more accessible way for our participants.

USER STUDY

After multiple iterations of development, we wanted to understand user perspectives on the Tetra-Sail experience. The aims of these studies were to understand: (1) the usability of Tetra-Sail, especially in the context of the Shared-Control system; and (2) users' reactions and feedback.

Participants

Our study included nine participants (two female) during the summer of 2019. In this study we refer to participants with pseudononymous labels S1-S9. S1, S5, S6, S7, S8 and S9 were all first time users of Tetra-Sail. S1-S5 were sip-and-puff users, and S6-S9 used the joystick. We added the following attributes to participants labels: -N for new Tetra-Sail participants, -R for returning participants, -sip for sip-and-puff users and -joy for joystick users to increase readability. For example a first time sip-and-puff user will be denoted as S1-sip-N. Participants were recruited through TRAILS, an adaptive recreation program associated with The University of Utah's Division of Physical Medicine and Rehabilitation. All except S6 and S7 were individuals with tetraplegia. S6 and S7 were individuals with paraplegia, paralysis primarily limiting use of the legs. S6 and S7 were included because they had health conditions (e.g., fatigue, limited hand motion, pain) that prevented them from using other adaptive equipment designed for individuals with paraplegia, which made our experience more suitable for their physical abilities. A single control partner accompanied each participant for this study. As a part of this study we also asked the control partner for feedback and observations after each sailing experience. This study was reviewed and approved by the IRB at the University of Utah.

Study procedure

The research team met each participant at the sailing camp before they engaged in the activity. We first conducted qualitative interviews to query for expectations and concerns related to using Tetra-Sail. After the session, we administered questionnaires and conducted a second qualitative interview with each participant to gather additional data about their experience. At the end of each session, the research team also asked the trainer for observation and feedback about the user's sailing performance and other information about the session. When participants agreed and weather permitted, we installed an audio recording device on Tetra-Sail to record participants' reactions and interactions with the control partner.

We used a mixed-methods approach to capture as rich of a view as possible. We used semi-structured interviews to query for the participants' lived-experience before and after the sailing activities. Interviews were relatively short(5-14 minutes) in order to accommodate the health and care needs of the participants. The recorded interviews were transcribed. We read and listened through the raw data multiple times to increase the familiarity with data. We then generated nine categories (themes) using a general inductive approach [30]. To enhance reliability, two researchers reviewed the generated codes and themes, resulting in the seven themes we present here.

We also administered the System Usability Scale (SUS) [9] to measure the usability of the technology, and to facilitate comparison with data we might collect in the future.

RESULTS

Each participant used Tetra-Sail for at least 30 minutes. All Tetra-Sail participants used both motor power and wind power during their experiences. All participants except for S1 used Tetra-Sail for the entire time available to them. Both quantitative and qualitative results indicate that the experience was an overall positive one for these participants. SUS scores indicated that Tetra-Sail was above average in usability, Participants' SUS results were within the "good" and "excellent" ranges of the SUS rating scale [5], ranging from 72.5 to 90.

Participants enjoyed their Tetra-Sail experiences

Participants reported that they enjoyed sailing using Tetra-Sail: *"I enjoyed it"* [S1-sip-N], *"Excellent [sailing experience]"* [S2-sip-R], *"It was fun, I enjoyed it."* [S3-sip-R], *"it's fun."* [S4-sip-R], *"Excellent [sailing experience]"* [S4-sip-N]. We had been concerned that Shared-Control might detract from the experience because it may lead to less of a feeling of independence, however participants' overall reactions indicated that even if Shared-Control did detract in some ways, that it did not tip the overall experience in a negative direction.

Participants felt that the experience matched their ability well

Participants felt the experience provided an adequate challenge: *"Several times, we [participant and control partner] felt we had the rudder where we want and motor at the right position made it feel like sailing like able bodies."* [S2-sip-R], *"It's [Tetra-Sail and sip and puff] so unique, I say that [because it] helps me, being paralyzed to cruise around and have fun"* [S3-sip-R], *"enjoyed it. easy to do, as far as as far as ability wise, it's super peaceful"* [S6-joy-N].

Control system was usable, but sip-and-puff still challenging
Participants felt the control system (input system and control scheme) was usable: *"The controller i think is spot on."* [S2-sip-R], *"It was easy to do the controls", "they worked on it for years so today [it worked] smoothly"* [S4-sip-R], *"it is pretty good, kinda move like a regular wheelchair. once you get the hang of it"* [S7-joy-N], *"is just like my chair so I had no trouble"* [S9-joy-N].

However, some sip-and-puff users felt they still needed some level of training to participate, or that they were not proficient at the controls: *"I wasn't very good at sip and puff."* [S1-sip-N]. We provided S1-sip-N with the simulation and sip-and-puff controller at home for three days before she returned for another round with Tetra-Sail. After the second sailing experience S1-sip-N reported that she was able to better understand how to use the sip-and-puff: *"[I] felt like the simulator helped me and I was not as frustrated as I was last week. I realized after using the simulator how long the delay time was between my blowing and the boat's reaction. I also realized that if I was not patient and tried to blow again that the command would not be recognized at all."*

S4-sip-N shared similar feedback, but was able to better understand how sip-and-puff worked after a few minutes of using Tetra-Sail: *"takes a minute to get used to"*. Both S1-sip-N and S4-sip-N reported some difficulties using the sip-and-puff system, but also reported overall enjoyment using Tetra-Sail.

Participants felt Shared-Control was important
Participants appreciated the role of the control partner and Shared-Control in supporting their sailing experience: *"He told me where to go how to straight it out. He took over when it was too hard and he did a good job."* [S1-sip-N], *[Sailing] With [Control partner] being able to process much more quickly what I was doing particularly well, or what changes the attendant perceived that my needing to make to make the function work correctly and I would not have been able to, to quickly come to those conclusions and understandings and very quickly I had a much clearer understanding of why things were happening the way they were and why things weren't happening the way they weren't* [S2-sip-R].

Shared-Control did not affect their feeling of independence
Participants did not express that Share-Control affected their feeling of independence while controlling Tetra-Sail and they felt that times when the control partner took control were important for a successful sailing experience: *"[the control partner would] leave me to my own commands and direction until he could see that we would be better suited to bringing the boat or the rudder or the motor to a different position, but only chimed in when he clearly had a better understanding than I did."* [S2-sip-R], *"Yeah, it was fun. I enjoyed. I really enjoyed it hanging out with the [control partner], [he] just gave me a lot of control."* [S6-joy-N], *" "[the control partner] just let me drive [the way] I wanted"* [S9-joy-N].

It is, of course, difficult to decouple these aspects from the overall enjoyment of the experience. It is also hard to know if participants are regulating their responses because they would not want the control partner to hear that they were critical. We are also sensitive to the phrase "he gave me a lot of control," because it suggests that participants still perceive themselves as not making decisions about who is in control.

Sip-and-Puff users felt the speaker was essential
In previous Tetra-Sail experiences sip-and-puff participants reported the need for better feedback for what commands were received by Tetra-Sail. Participants found our installed speaker system provided helpful feedback: *"The voice on the boat was very helpful as last week I was not sure if I got the command right and sometimes did it again. Also, hearing command repeated out loud helps me to make sure I had chosen the command I wanted."* [S1-sip-N], *"that audible is huge not to have it." ... "It's a game changer"* [S2-sip-R]. During early attempts with the speaker, some technical issues left the speaker system nonfunctional. This happened during S1-sip-N's session, and she indicated that she felt less competent not having the speaker system: *"I notice when the voice confirmation went out about halfway through our sail, I was much less competent"* [S1-sip-N].

Having a family member on board increased enjoyment
Three of our participants had family members accompanying onboard the Tetra-Sail. Participants enjoyed having family members to share the experience with: *"so, I love being on the water with my family again. I haven't done that for a while. And it was just a nice and pleasant day I enjoyed being outside"* [S1-sip-N], *"I like [to sail] with my sister and mom"* [S9-joy-N]. Some participants also reported that they would prefer to sail with a family member as their control partner.

DISCUSSION AND DESIGN RECOMMENDATIONS

Shared-Control and the human control partner enabled us to deploy a usable adaptive sailing experience. In this section we reflect on the results from the iterative design, development, and deployment of Tetra-Sail, and provide some design directions to consider for future adaptive sailing experiences.

Shared visibility between control partner and main user

We believe that key to the success of Tetra-Sail was having an effective communication channel between the control partner and the main user. We capitalize on the idea of having a human control partner on-board Tetra-Sail with the main user, which facilitated verbal communication between the two.

However, it was difficult to communicate verbally about potential technical problems to the control partner. We encountered this problem in particular with sip-and-puff users when they were not able to perform a certain action. In these cases, it was usually not clear to the control partner what the problem was. With a joystick user there are visible directional physical movements that the control partner can use as a visual clue for what the user it trying to accomplish. However, this is much more subtle for the sip-and-puff user. This caused the control partner to go through multiple steps of diagnosing the problem with the sip-and-puff system to identifying the problem.

For Tetra-Sail V2, the speaker system announced what action was being performed by the sip-and-puff user as a training aid to help the user understand what action they have triggered. However, we were pleased to find that the audio speaker system also helped the control partner have better visibility on the actions of the sip-and-puff users, mirroring literature on workplace awareness [14]. This made it much easier to diagnose a situation as relating to user versus system performance (e.g. commands were announced but system was not responding).

The format of the information communicated through the speaker is also important here. Rather than repeating what command is being performed ("sip"), the audio system announces the effect of the command that is currently performed ("motor at X speed"). We found this information to be helpful both for the main user and for the control partner to understand the current state of the system. Another major advantage of the audio system we found was that the control partner can focus his attention on the environment around the boat, rather than frequently looking back at the user to monitor performance.

There is the potential to present additional information through the audio interface. However, caution is necessary because of the possible negative impact that these broadcasts can have on the experience.Long or frequent messages could easily become a source of annoyance and detract from overall enjoyment. We limited these announcements to only a few words, and only in response to an action by the main user. Before adding more information to the audio system, we would consider the frequency and duration of the messages and the potential benefit of making this information available.

Prototyping using Shared-Control and simulation

It's already difficult for individuals with tetraplegia to participate in outdoor activities with all of the social and logistical barriers. For an individual with tetraplegia, leaving the comfort of his/her daily routine to participate in an outdoor activity is a burden that comes with many physical challenges. From this perspective, even if we are working with early prototypes, we need to provide participants with an enjoyable experience. At the same time, improving these prototypes and making them accessible and enjoyable to the target population means that we need to test it out with those individuals. Furthermore, deploying Tetra-Sail prototypes is limited by season, weather and financial resources to pay for access to the lake destination and the time of the staff to run that experience.

Both the simulation and Shared-Control helped us to address those concerns. The simulation was a very useful tool for us to prototype and evaluate new ideas for input systems. While we know that additional factors of being out on the water may also come into play, implementing and testing new input ideas on the simulation was a valuable way of getting initial feedback and gaining some insight into whether or not the idea is a plausibly good one. It also provides us with a simple way of testing those solutions with members of our target population, since we can bring the simulation to them, which is much easier logistically than getting them out to the lake.

However, there are also many contextual factors and other variables in real life that are impossible to replicate in the simulation or anticipate with the simulator. Shared-Control provided us with a reliable solution to being able to deploy and test our prototypes with the target population and to be confident that we can provide them with a safe, fun, and engaging experience, even when the hardware is still in earlier phases of development. Designing for outdoor activities is an iterative process that comes with many logistical and resource limitations. Streamlining the process of prototyping by having a simulation test session, then deploying the most successful prototypes with the help of Shared-Control is one potential solution to reduce these limitations.

Computer-mediated support Vs Human-mediated support

The control partner was valuable for the research team when deploying early prototypes to ensure the safety of our users. Although valuable, the primary cost to involving a control partner is scalability of the systems. Experienced control partners are limited in numbers and availability, and paying a professional for this task also increases the cost. A solution is to use a computer system to replace some of the functionality performed by a control partner. A challenge, however, is whether computer-mediated support really could remove the need for the human control partner for our experiences. When we proposed the idea of computer-mediated support to fully replace the control partner, both control partners and participants were concerned. Participants in particular were concerned about safety without a human partner sharing control.

While we believe automation could support parts of our system more effectively (i.e, provide feedback on user performance with input devices), we also believe that Shared-Control should perhaps be the long-term plan for Tetra-Sail, rather than just a convenient tool for developing prototypes. An end goal for our development, however, is to reduce the need for someone with specialization to share control. Moving forward, it is interesting to consider designing Shared-Control systems to explicitly support control partners with fewer qualifications or less experience (e.g. friends or family who can perform basic sailing). Given participants' experiences in our study, we believe that facilitating a shared experience (through Shared-Control) might even be preferable to a functionally equivalent computer-mediated experience. This is in line with motivation theory [12] that describes value in having a familiar, safe other, to fulfill a person's need for relatedness. This might improve upon use of automation or sharing control with a control partner who is not known as well to the individual.

CONCLUSION

Individuals with tetraplegia have many barriers to participate in recreational activities. We designed Tetra-Sail to reduce these barriers. Tetra-Sail is an adaptive sailing experience that relies on the idea of Shared-Control. With the help of Shared-Control, which enabled us to engage in an iterative design, development, and deployment process in the real world, we were able to design a sailing experience that required no previous knowledge of sailing from our participants, while supporting control and independence for our users. Results showed that participants enjoyed their experience and appreciated the presence of the control partner, indicating that Shared-Control is a valuable part of Tetra-Sail for all stakeholders.

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