Clairbuoyance: Improving Directional Perception for Swimmers

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Figure 1: Clairbuoyance, a system to improve a swimmer' s sense of direction.

ABSTRACT

While we usually have no trouble with orientation, our sense of direction frequently fails in the absence of a frame of reference. Open-water swimmers raise their heads to look for a reference point, since disorientation might result in exhaustion or even drowning. In this paper, we report on Clairbuoyance — a system that provides feedback about the swimmer's orientation through lights mounted on swimming goggles. We conducted an experiment with two versions of Clairbuoyance: Discrete signals relative to a chosen direction, and continuous signals providing a sense of absolute direction. Participants swam to a series of targets. Proficient swimmers preferred the discrete mode; novice users the continuous one. We determined that both versions of Clairbuoyance enabled reaching the target faster than without the help of the system, although the discrete mode increased error. Based on the results, we contribute insights for designing directional guidance feedback for swimmers.

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1 INTRODUCTION

Having a sense of orientation is important for navigation tasks. Humans have different strategies for finding their orientation and, generally, features in the environment or landmarks play an important role. In contrast to some animals, humans have no sense of magnetic fields that could provide orientation. A particularly difficult task is orientation in open waters as there are no landmarks or static features present. In this paper, we explore how to create a digital sense for orientation.

Our use case and motivation is open-water swimming, which is gaining in popularity as an amateur sport. Excitement, health benefits and the possibility to connect with nature motivate more and more physically active individuals to swim in the open waters. The largest amateur event in the UK — the Great Swim – attracts 22,000 swimmers annually and the UK Outdoor Swimming Society has grown from 300 to 23,000 members over the last ten years [11].

Yet, despite its many advantages as a sport, swimming is cognitively complex, requiring precise coordination of a large number of muscles. Technique, proprioception, rhythm and stamina all have a key impact on performance. In this environment alien to our bodies, two main challenges arise: breathing and orientation. Breathing is a vital function and all swimming styles incorporate strategies to enable inhaling air effectively, but orientation in the water remains problematic.

Novak [23] showed that humans are incapable of swimming in a straight line over longer distances. The difference in strength between arms and between legs results in a slight deviation in direction when there is no frame of reference available. This effect is typically observed in people walking in circles in the desert or unfamiliar terrains caused by the lack of an external directional reference, thus making the directional recalibration impossible [29].

Consequently, competitive sport swimming pools are divided into lanes with colourful ropes and have guide lines on the bottom to aid the swimmers. This is not the case for lakes, rivers and the sea, where competitions mostly use sparsely positioned buoys. For recreational open-water swimming, reference points need to be identified by the swimmer. For open-water swimmers, their field of view is mostly obstructed by non-transparent water and, during events, by other swimmers. Knowing where to swim depends on raising their heads above the water and trying to find visual references, affecting their swimming rhythm and performance. Depending on the situation this may result in losing a competition, excessive exhaustion, or even drowning. Currently, open-water swimmers can use dedicated devices in the form of GPS-enabled wristwatches. This improves their sense of direction, but still disrupts their swimming. Alternatively, long-distance swimming competitions use boats or kayaks to guide athletes, but these are not feasible for recreational swimming, especially given the constant increase in numbers participating in the sport. As Human-Computer Interaction (HCI) is increasingly interested in understanding interfaces for physical activity [22], the problem of providing directional feedback while swimming provides a relevant challenge and an exemplary case for creating a digital solution.

In this work, we explore the means of enhancing swimmers' sense of orientation in water. We present *Clairbuoyance*, augmented swimming goggles designed to improve the directional perception of swimmers. Our design uses peripheral light feedback to convey information about the swimmer's current direction. We contribute (1) the design and implementation of a prototype capable of providing underwater directional information visually; (2) a proof of concept of the idea and an evaluation of the device that uses two feedback modalities: absolute and relative direction; and (3) insights for designing future systems that support directional guidance, in particular, but not limited to, swimming.

2 RELATED WORK

A starting point of our inquiry was understanding the different types of feedback through which directional information could be provided to swimmers. We describe how past methods for providing directional feedback relied primarily on haptic output, then look at previously researched means of providing visual feedback in applications that convey space and direction. Finally, we present literature focused on applications for swimmers.

Feedback for navigation

Several researchers explored ways to convey navigation cues using alternatives to traditional displays. Tan and Pentland [30] investigated the use of tactile displays in wearable computing. They presented a wearable tactile directional display which used sensory saltation, a tactile illusion evoked by stimulating different regions of the skin in rapid succession. Their work pioneered the use of non-traditional approaches for conveying navigational information for implicit interaction.

Brewster and Brown [2] introduced the concept of *tactons*, or tactile icons. The authors proposed to use individually identifiable vibration patterns differentiated by their pulse intensity, duration and frequency to convey specific cues and signals to users. Later, Lin et al. [18] proposed *tactons* to provide navigation cues for pedestrians. The authors further reported on two experiments where they investigated the use of tactile feedback to present navigation information to pedestrians. Similarly, Pielot et al. [25, 26] investigated and designed a tactile compass and Kiss et al. [16] presented a wearable system to provide turn-by-turn navigational instructions for motorcycle riders. The wide use of tactile interfaces for navigational feedback shows that conveying direction through non-visual cues may be highly effective. These results inspire our work and prompt exploring the design space for directional feedback while swimming.

Visual feedback for directional cues

Another line of research explored how to design effective visual cues for conveying direction. Burke et al. [4] compared multimodal feedback in terms of error rates and reaction time in a meta-analysis of 43 studies. Their findings suggested that visual-auditory feedback resulted in better performance than visual-tactile for single tasks, while the opposite is true for participants performing multiple tasks in parallel. *Eye-q* [8] used a peripheral display embedded in glasses to provide subtle notifications, with an emphasis on the social acceptability aspect of the design.

A common application scenario for unobtrusive visual feedback for space and direction information is navigation. AmbiGlasses [27] was a system that consisted of a pair of glasses with 12 LEDs used to convey directional information, which was found to be effective. Tseng et al. [33] proposed to use peripheral light for navigation on scooters, finding a range of signals which participants could effectively recognize as commands. Similarly, Matviienko et al. investigated the use of light feedback for turn-by-turn navigation in cars [21]. Their findings suggested that ambient light-based cues are easy to use and understand. Our work builds on these past results by exploring specific considerations for feedback while swimming.

HCI for swimming

Human-Computer Interaction under water poses additional challenges for building interactive systems, both from a technical and a design point of view. Past work in HCI contibuted several systems for swimmers. Davey et al. [9, 10] built a system based on a tri-axial accelerometer and developed an algorithm to measure performance for competitive swimmers. They showed that this type of system can provide results equal to or better than manually collected data. Callaway et al. [5] compared video- and sensor-based measuring of swimming performance, showing how electronic sensors enable a more accurate analysis of swimmers' performance and provide useful tools for coaches and trainers, compared to traditional means. We were inspired by these systems as they showed that technical interventions in the swimming sport can be effective and perceived as useful.

Several past works have explored how information may be effectively presented to swimmers while considering the special perceptual conditions in water. Förster et al. [13] investigated different modalities to provide feedback to swimmers. Their findings suggest that audio feedback is not appropriate for interfaces for swimmers, whereas haptic and visual feedback are effective. The same authors later presented SwimMaster [1], a wearable assistant for swimmers. This system was able to calculate performance metrics of swimmers such as the time to swim a lane, the swimming velocity and number of strokes per lane, and provide information about other important aspects regarding style specific factors such as body-balance and rotation. Their findings confirmed the preference for visual and haptic feedback over audio in interfaces for swimmers.

Hagema et al. [14] used waterproof accelerometers to measure the rhythm of strokes from swimmers and provide LED feedback on swimming goggles. This system enabled swimmers to maintain a constant pace and train to a pre-programmed rhythm. A similar idea was presented by Marshal [20], making a smartphone waterproof and using its connectivity capabilities to enable a coach to monitor the swimmer's performance remotely. Mangin et al. [19] designed a wearable distributed system able to collect data about swimming kinematics and transmit it wirelessly to a personal computer. These works in swimming technology guided the design of *Clairbuoyance*, showing that the use of augmented swimming goggles may be effective and that swimmers are able to process a certain amount of additional information while swimming. Our work is interestingly different from these efforts as it focuses on the sense of direction and explores sensory augmentation.

More recent works explored swimming technology for social play and therapy. In SwimTrain, Choi et al. [7] explored the use of exergames for promoting fitness through group fitness activities. This work showed that additional feedback while swimming offered a playful experience. Parvis et al. [24] used waterproof inertial systems to measure the movements of swimmers and assess swimming symmetry during rehabilitation therapy. *Clairbuoyance* was inspired by the research above as it shows that technology can add additional meaningful elements to the swimming experience. In contrast, our work did not aim to create new swimming experiences. Instead, we aimed to design a device that would augment an existing activity.

3 DESIGN

The design process of *Clairbuoyance* consisted of several steps and iterations, aimed to address different aspects and problems. Technical challenges such as making our device waterproof required extensive trial-and-error attempts, sometimes even resulting in the partial or complete destruction of a prototype. Choosing our feedback modality was, at first, based on existing literature, but fine-tuning required presenting the design to users, prompting discussion and collecting observations and insights both at the lab and at a local public swimming pool. Informal interviews provided useful feedback and ideas, mostly from other swimmers at the pool.

In this paper we summarize the most relevant aspects of our design process and omit failed attempts, flawed prototypes and annoying feedback modalities. In the following subsections, we present and explain our design decisions for creating *Clairbuoyance*, a system to improve directional perception for swimmers.

Choosing a feedback modality

We chose to use visual feedback over haptic based on Burke's findings, since swimming is a single task [4]. We favored visual feedback over sound based on the findings of Förster, Bächlin and Tröster [1, 13].

Given the repeated success in providing visual feedback through augmented glasses, we chose a similar approach for our design [12, 27, 32, 33, 35]. Instead of glasses, we decided to augment swimming goggles, the most ubiquitous swimming gear besides the swimsuit. This decision also minimized the impact of our gadget on usability, portability, social acceptance and comfort. Further, light-based feedback was successfully used before in applications for interactions during physical activity [36].

Defining feedback modes

Based on the design used for ActiveBelt by Tsukada et al.[34], we identified two main types of orientation: absolute and relative. Absolute orientation describes a general awareness of directions, which is what we ideally experience in familiar environments. For example, even when we are not completely sure were the geographic North is, we can intuitively point towards particular places outside our immediate field of view.

In contrast, relative orientation depends on a given direction. This can easily be illustrated by a compass, which calculates directions respect the magnetic North. In this case, the general awareness of directions is not important, but the focus is on a given goal direction, and the important information is by how much are we diverging from it.

These two intrinsically different orientation concepts have different representations from an informational point of view. The absolute sense of orientation is a continuous signal, which can be represented as a single, uninterrupted stream of data. The relative sense of direction has a discrete nature, since there are likely only three possible states for a given observer: the observer is facing the desired direction, the observer must turn to the right to face the desired direction or the observer must turn to the left to face the desired direction (we assume here that the likelihood of being completely opposite to the desired direction is close to zero).

Given these differences between the two orientation concepts, we proposed two different representations or *modes*, matching the numerical nature of each type of signal:

Absolute continuous feedback (ACF):. we mapped all directions to the RGB color spectrum, thus each direction was represented by a single RGB colour (see Figure 2). We arbitrarily assigned red to North, and then pure green to 120° and blue to 240°. The color mapping was inspired by past work in HCI that effectively mapped hue to circular models [6]. We considered the use of a fixed color for the goal, but past work suggested that a fixed color pattern was easy to memorize [6]. Given that goals can be situated anywhere and North is not a preferred direction, a static color mapping can provide a consistent experience. Thus, a continuous spectrum without end was our choice.

This representation enabled an intuitive recognition of directions, as well as an observable variation in the signal that might indicate getting closer (or further) to a desired goal.

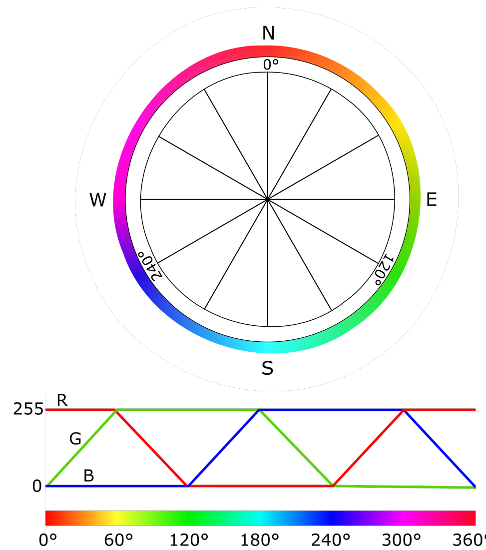

Figure 2: Mapping of cardinal directions to the RGB color spectrum.

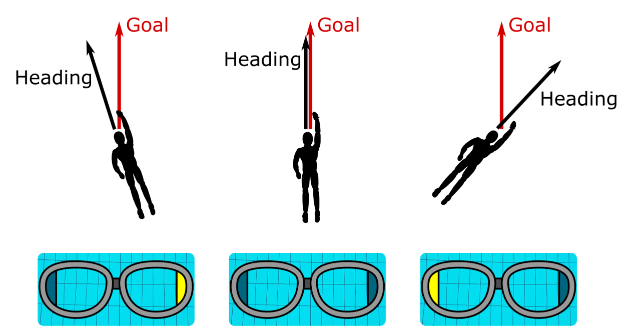

Figure 3: Relative discrete feedback mode: a light cue indicates towards which side to correct heading.

Relative discrete feedback (RDF):. since only feedback is needed when the swimmer needs to correct his/her direction, we decided to indicate which direction the swimmer must go to correct the course. When the heading is correct, no signal is displayed; when the swimmer deviates from the desired direction, a light indicates where to turn (see Figure 3).

Design requirements

A system capable of providing the described above sensory augmentations needs to fulfill multiple requirements. From a functional point of view, the device must be able to calculate directions, both absolute and relative to a desired goal direction. The system must also be able to compensate rotations respective to the X and Y axis, providing consistent feedback while the user looks forward, downwards (while swimming) or rotating the head to the sides for breathing. Additionally, it is desired that the system ignores the small, rhythmic characteristic oscillations around the current direction caused by the swimming movements.

From an interaction perspective, the system must enable the user to switch between feedback modes, as well as select the desired goal direction in the *relative discrete mode*. Additionally, the system must be capable of presenting both feedback modes to the user in the visual periphery. That means that the device is required to provide light on both sides of the field of view and present the whole RGB color spectrum.

For the technical aspects, the system must be waterproof – or at least water resistant for a few hours to a moderate depth. It also needs to be completely wireless, compact, robust and lightweight, since it would ideally be completely and exclusively attached to the goggles, without presenting any hindrance to the swimmer.

Final prototype

Based on the requirements, the definitive implementation of Clairbuoyance consists of standard swimming goggles augmented with custom made electronics. Two RGB LEDs are attached to the sides of the goggles and provide the visual cues (see Figure 4). The orientation is calculated using readings from a digital magnetometer, accelerometer and gyroscope. All these electronics, plus a microcontroller and batteries, are encased in a waterproof container fixed to the strap of the goggles. A textile band can be added to provide extra stabilization (see Figure 1). A single push-button enables the user to switch feedback modes or select the target direction.

The device provides the two feedback modes: the *absolute continuous feedback* (ACF) is conveyed to the user by both LEDs, which display the RGB color mapped to the current heading. The *relative discrete feedback* (RDF) is provided by lighting a single LED on the side towards which the swimmer must turn. When the heading is within a predefined threshold, both LEDs are off. In this mode, the visual feedback is displayed with a yellow light, since this color is easy to notice in most underwater environments.

The user can switch between feedback modes by pressing the button for at least two seconds (long-press). The effect of pressing the button for less than two seconds (short-press) depends on the feedback mode. For the *relative discrete orientation*, a short-press sets the current heading as the goal direction. In this case, both LEDs blink and briefly change colors, to provide feedback about the user's action. From this point on, the feedback will provide information based upon this acquired direction. While providing *absolute continuous* feedback, the short-press has no effect.

Figure 4: Final version of the prototype: the control button (right), the device working on the ACF mode (right) and a detail of the hardware (bottom).

4 IMPLEMENTATION

In this section, we describe our prototype to ensure the reproducibility of our study.

Hardware

Taking the same approach as Parvil et al., we based our prototype on an Arduino-compatible microcontroller board, the Teensy 2.0[1] [24]. The directional information is collected with a three axis gyroscope (L3DG20H) combined with a three axis magnetometer and accelerometer combo (LSM303DLHC). All these sensors are included in the Adafruit 9-DOF IMU breakout board, which we used for our prototype.

The devices are powered with two CR2477 3V coin cell batteries in series, ensuring a constant 5V power supply with a LT1521CST-5 voltage regulator. The visual feedback is displayed using high-brightness common-cathode RGB-LEDs (7000/8000/4000 mcd) on each side of the goggles. To improve the visibility of the light feedback, we used laser-cut acrylic light diffusors. User input was enabled with a 6mm tactile button, attached to the right LED. The button was positioned to ensure ease of use and prevent unintentional actuation.

LEDs and button were connected to the microcontroller with standard four pair and six pair cables. The LEDs and button were waterproofed with transparent heat-shrink tubing and hot-glue to enable visibility and actuation while guaranteeing the integrity of the device. The controller, sensors and batteries were encased in an IP68 ingress-protected junction

[1] https://www.pjrc.com/teensy/

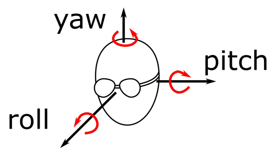

Figure 5: Aeronautical naming of the Tait-Bryan angles, in this case applied to the human head.

box, intended for outdoor installations. This method allows for easy access to the electronics for switching the device on, replacing batteries or reprogramming the board, while keeping it dry during its usage. To protect the electronics from condensation, we used silica bags.

Software

The software was written in the Arduino IDE using the Teensyduino plugin. It calculates the current heading as a unidimensional value, which is the projection of the measured magnetic vector on the horizontal plane. The horizontal plane is calculated using the accelerometer and gyroscope readings, under the assumption that the time-averaged acceleration exerted by the swimmer is negligible when compared with the gravitational pull.

Using the aeronautical angle nomenclature, where *yaw* is the heading, *pitch* the elevation and *roll* the lateral rotation (see Figure 5), the current orientation of the user with respect to the horizontal plane can be calculated with the following equations:

$$pitch = \arctan \frac{A_y}{\sqrt{A_x^2 + A_z^2}}, \quad roll = \arctan \frac{A_x}{\sqrt{A_y^2 + A_z^2}} \quad (1)$$

where A_x, A_y and A_z are the normalized values of acceleration for the three respective Cartesian axes of the sensors' local coordinate system. The calculated *pitch* and *roll* are angles in radians, with respect to the horizontal plane. The magnetic readings M_x, M_y and M_z are also normalized and projected on the calculated plane:

$$H_x = M_x \cdot \cos roll - M_z \cdot \sin roll \quad (2)$$

$$H_y = M_y \cdot \cos pitch + M_y \cdot \sin roll \cdot \sin pitch + M_z \cdot \cos roll \cdot \sin pitch \quad (3)$$

$$yaw = \arctan \frac{H_x}{H_y} \quad (4)$$

The obtained *yaw* is then the angular difference between the magnetic North and the current heading of the user. This value is converted to degrees and smoothed using an averaging filter with length 10.

The heading value are used either directly for the *absolute continuous orientation* feedback, or compared to the value stored by the user for the *relative discrete orientation* feedback.

5 EVALUATION

In order to evaluate *Clairbuoyance*, we conducted a within-subject controlled experiment in an Olympic-sized swimming pool. We wanted to evaluate how both feedback modes performed in terms of performance and usability. Participants were asked to swim to a series of targets across the pool while using *Clairbuoyance* in one of its two modes and without additional aid.

Participants

We used social media and snowball sampling to recruit participants. We distributed the experiment call both on general channels (university mailing lists) and groups specific to swimming in order to get a spectrum of novice and advanced participants. Potential participants were asked to declare that they could swim a quarter mile front crawl with interruptions as requested. Additionally, we required that participants should have had normal eyesight (or corrected to normal while swimming). We recruited 24 participants (16 male and 8 female), aged from 18 to 62 years old ($M = 26.54$, $SD = 10.93$). Participants stated that they swam an average of 7 times a month ($SD = 9.00$), with some swimming more than 5 times a week. We classified them into two groups: recreational and advanced swimmers. Advanced swimmers identified as one of the following categories: active lifeguard, active competitive swimmer, swimming coach, former competitive swimmer, club water polo player. There were 12 advanced and 12 recreational swimmers in our sample. Participants received USD 15 as remuneration for their time spent in the study. Additionally, isotonic drink and food was available for recovery after the study.

Apparatus

The participants swam towards a target on the opposite side of the pool. The target consisted of a yellow semi-circle, clearly visible on the other side of the pool (see Figure 7). To impede participants from using the lanes on the bottom of the pool as an orientation reference, we created paths for them to follow, as illustrated on Figure 6. A base path consisting of 6 straight segments, with a total length of 175 meters, was used to create three symmetric paths by inversion and rotation. This removes learning bias, since each path is perceived differently by the participant, and, still, the length and angle respective to the side of the pool of the individual segments remains equal. Counterbalancing using Latin squares was applied to the conditions and routes. To avoid confusion about the target, there was only one target on each side of the pool, which was relocated for each segment to predefined positions, marked with tape on the floor.

Through an iterative process, we produced a system robust enough to endure the study conditions. Waterproofing was the main challenge, but the effect of gyroscopic drift also required attention. Given that we expected that extensive exposure to water pressure under experimental conditions would produce enough stress on the sealing of the case to compromise the electronics, we produced three physical prototypes to be able to continue the experiment in case of damage. This proved useful, since it allowed replacing batteries preventively without interrupting participation. To eliminate possible magnetic drift effects, the prototype was restarted between trials, which kept the effect negligible. Calibration was performed in situ, to account both for geographic magnetic deviation and environmental aberrations. To calibrate each individual prototype we used MotionCal[2], a software system specifically designed for this purpose.

Hypotheses

Using this controlled experiment design, we evaluated the following hypotheses:

(1) Peripheral visual feedback will reduce completion time
(2) Peripheral visual feedback will reduce orientation errors

Conditions and measures

To evaluate *Clairbuoyance*, we asked participants to swim three times, once under each of the three conditions:

- Base condition: no feedback
- RDF: Relative Discrete Feedback
- ACF: Absolute Continuous Feedback

We collected four different metrics: Task Completion Time (TCT), error distance, task load and a score describing the usability of the system.

TCT was measured with a chronometer, and consisted of the swimming time of each participant to complete each path. Thus, TCT is the sum of the measured time to reach each target and does not include the time the participants rested.

The error distance was measured as the separation between the point where the participants first touched the side of the pool (estimated goal) and the center of the yellow target (real goal). We use the sum of the absolute value of all error distances as metric.

Task load was measured using the NASA Task-Load Index (TLX), an assessment tool to quantify and analyze the workload required to complete a task. For this, after each path was completed, participants were asked to fill a questionnaire, providing subjective feedback on six subscales [15].

[2]https://github.com/PaulStoffregen/MotionCal

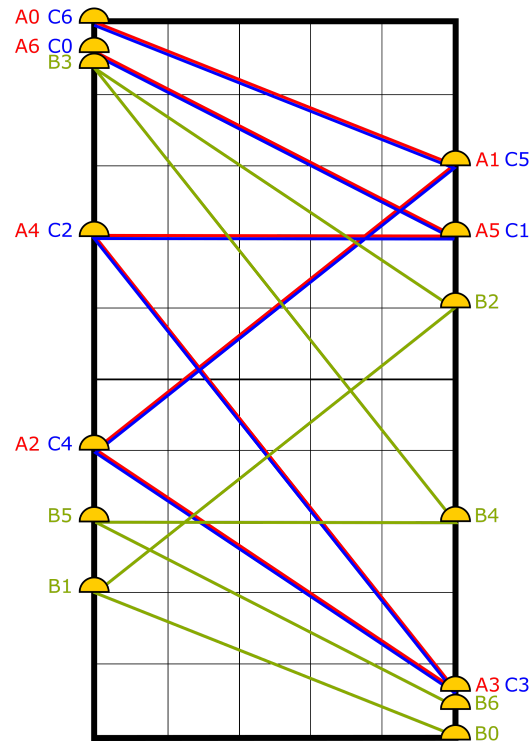

Figure 6: Path A (red), Path B (green) and Path C (blue) were assigned in a counter-balanced fashion to the three conditions (base, ACF and RDF). Path targets were ordered increasingly, starting at 0. The dimensions of an Olympic swimming pool are 25 meters by 50 meters, thus each path had a length of approximately 175 meters.

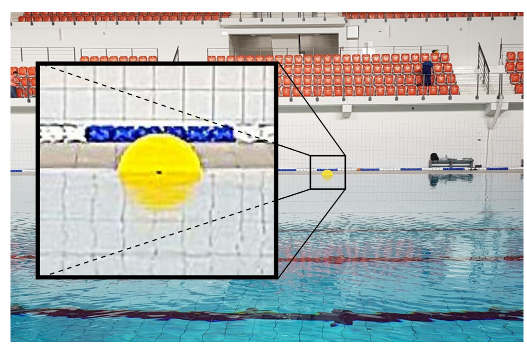

Figure 7: Target, consisting of a yellow semi-circle with a black center.

Usability of the system was measured using the System Usability Scale (SUS). For this purpose, participants were asked to fill the SUS questionnaires for each of the feedback methods [3].

Individual opinion on *Clairbuoyance* and the whole proposed interaction was collected in semi-structured interviews.

Procedure

We welcomed participants in a room adjacent to the swimming pool to brief them before the experiment. Participants were asked for their consent for participating in the experiment and processing the data gathered during the study. After explaining the experimental task in detail, we asked them to confirm in writing that they were fit to complete the task. They were specifically instructed to swim at a moderate pace and take breaks as needed in order to complete the required number of trials without perceived exhaustion. Next, we gathered demographic data and questioned them about their perceived swimming ability. We then gave them time to change to their swimming attire.

When ready to swim, each participant was assigned a starting condition and positioned at the starting point for the assigned path. An experimenter then positioned the target on the opposite side of the pool at the point specified by the target sequence (see Figure 6). We then reminded the participant to swim to the target at a moderate pace and not to look ahead, as well as use the same swimming technique for all paths. The participant was asked to raise an arm when ready, and an experimenter blew a whistle to start both the swimming and the chronometer at the target location. When the participant touched the border on the other side of the pool, the chronometer was stopped and the position respective to the target was noted. The participant was given time to rest as required, and then followed the same procedure towards the next target of the path. After completing all trials in a condition, we offered the participant an isotonic drink. After completing each path and while recovering, the participant completed a questionnaire containing the NASA TLX measures and SUS.

After completing all trials, we let the participant rest and change back to their regular clothes. Next, we debriefed the participant in a room adjacent to the pool, and conducted a semi-structured interview that focused on the experience of using *Clairbuoyance*. We asked which method the participant preferred and what strategies were employed to complete the task. We also explored usage scenarios beyond the swimming pool and possible use of the device in open waters.

6 RESULTS

We collected data about two quantitative metrics, the total error respect to the individual targets (in meters), and the total time required to complete the task excluding the rest pauses (in seconds). Additionally, participants reported the perceived load of each task using TLX, and the usability of both feedback methods using the SUS.

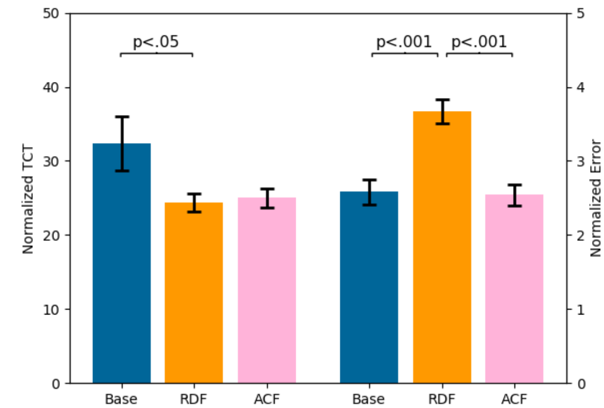

Figure 8: Mean and standard error of the normalized TCT and distance with respect to the real and estimated position of target reached by the participants, for each condition. Markings indicate post-hoc significance.

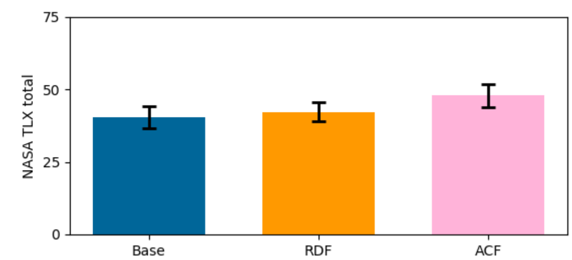

Figure 9: Mean value and standard error Total Load, according to NASA Task-Load Index, for each condition.

The normalized error, normalized TCT and TLX were analyzed using ANOVAs, with the most relevant results summarized on Table 1. We decided to standardize the TCT and Error results per participant in order to account for the differences in swimming proficiency and physical fitness between participants. The values were standardized as normality assumptions (Shapiro-Wilk test) have been fulfilled.

Post-hoc Tukey HSD tests showed that participants missed the target by a significantly higher distance when using RDF than in the other two conditions, both times at a significance level of .001. We found no significant difference between the base condition and ACF. For the TCT, post-hoc Tukey HSD revealed that the base condition took significantly longer to complete than when using RDF, with significance level at $p = .05$, while the two other comparisons were not significant.

The mean score of the SUS was calculated as 70.72 for RDF and 71.57 for ACF. A Wilcoxon test showed that the difference in SUS scores was not significant.

Condition	Error [m]		TCT [s]		NASA TLX	
	M	*SE*	*M*	*SE*	*M*	*SE*
Base	2.58	0.17	32.36	3.66	40.42	3.87
RDF	3.67	0.16	24.37	1.18	42.25	3.27
ACF	2.54	0.14	25.01	1.26	47.96	3.95
ANOVA	$F_{2,393} = 3.47, p < 0.05$		$F_{2,393} = 16.25, p < 0.001$		$F_{2,68} = 1.61, p = 0.32$	

Table 1: Mean value and standard error for the distance by which participants missed the target, TCT and NASA Task-Load Index, as well of results from respective ANOVAs. Note that the variation among conditions is significant for the distance and TCT, but not for TLX.

Interviews

All pre- and post-study interviews were recorded and transcribed verbatim. We collected a total of 3hr 24mins of recordings. First, we coded the interviews to determine their preferred feedback type (each participant was explicitly asked to make a binary choice). We then printed the statements from the interviews on post-it notes and used affinity diagramming to classify them into common thematic groups. We identified three themes in the data: Workout integration, Trusting the device and Usage scenarios.

Preferred feedback type. Fifteen out of 24 participants preferred RDF. Interestingly, advanced users had a very high preference for RDF (11 out of 12 advanced swimmers), while recreational swimmers preferred ACF (8 out of 12 participants). Advanced swimmers were focused on minimizing distractions and appreciated the fact that no feedback was produced in RDF when they were on the correct heading. One swimmer did not want to think about translating colours into directions:

> We swimmers focus on completing the distance fast and we don't want to think how far in we are or how much is left. (...) It's easy to mix up the colours and forget which colour to follow. I saw pink most of the time and I'm not used to that. It was distracting.

In contrast, amateur swimmers valued ADF as it offered stronger feedback with constant confirmation of status. One participant was concerned that light on one side may not have been visible enough at all times:

> The colours were better and I reflected that I enjoyed that the colours carried a meaning. When the sun came out, I could still see them. So, I think the colours would be nice irrespective of what kind of water you're swimming in.

Workout integration. Participants were eager to share insights on how *Clairbuoyance* could be improved to better reflect their swimming practices and fit their workout routine. One participant reflected that they would choose a different goggle model for the task.

> I wanted to make sure the light was in my field of view and I wasn't always sure of that. I constantly thought there might have been more light that I didn't see. I guess I would need different goggles.

In the ADF condition, an often-repeated remark was the need to customize the sensitivity of the device. A dynamic directional range that would change as the user was approaching the target was suggested:

> You should be able to adjust the range of the device at the starting point. And then this range should become narrower as you get closer to the target. That would make sense.

Finally, some users remarked that the device could be integrated in their regular swimming routine and produce a positive experience by alerting them when a course correction was needed. This would amount for more time to relax and thus a more enjoyable swim:

> I liked it because the diodes told you when you were off course. It's intuitive and easily visible. You have to react to it when needed, but, most of the time, you can just enjoy the swim.

Trusting the device. Another aspect often addressed by the participants which emerged from the data was how users decided (or not) to trust the device and navigate based on *Clairbuoyance*'s indications. One participant was initially doubtful about the system, but they later decided that the feedback was useful:

> There was a moment when I didn't trust the system, I thought it broke down. Had I trusted it, I would have hit the target. So, then, I decided to trust it and ended up in the right spot. Then, it started making sense to me.

Many participants reported that they needed to think less about their direction of swimming. They saw *Clairbuoyance* as an opportunity to focus more on swimming technique or relax. One swimmer remarked that the device enabled him to relax while swimming:

> You can sort of stop thinking. You don't have to focus on where you are swimming, but you can freely move and the lights give you hints. You can just relax, just swim.

Usage scenarios. Finally, users explored possible uses of *Clairbuoyance* beyond the study extensively, considering the functionality of the device in open waters. Participants would propose usage scenarios for the system. One of the advanced swimmers suggested that *Clairbuoyance* would be useful even for complex tracks often seen in open-water swimming competitions.

> The longer the distance, the more useful it is. It also depends on the conditions... in open waters, there's the sun, the colour of the water (...) when the sun blinds you, you could trust the device to navigate for you. Even for multiple buoys, this could work.

Another suggested scenario in open waters was not only making sure one was following the right heading, but also establishing the correct heading. An advanced participant commented that the system could eliminate the need to reassure oneself that one had not forgotten the swimming direction in a competition:

> I know that it will lock that point and stick to it. I would use it a lot. In open waters, the legs could be two kilometres or more, so you can't even see the target point when swimming. Sometimes, there are intermediate buoys, but it's usually not enough. It would help me keep reach the goal.

7 DISCUSSION

Having explored augmented orientation for swimmers, we observed that *Clairbuoyance* offered benefits to the users that were observed both in quantitative data and qualitative feedback. Below, we summarize our findings and outline challenges and opportunities for future systems.

An augmented sense of direction reduced TCT

Swimmers using *Clairbuoyance* needed less time to complete the path than on the base condition, confirming the *Hypothesis 1*. Given that the normalized error for ACF and the base condition is approximately the same and that we found no correlation between the Error and TCT, the reduction in TCT can be interpreted as an increment in swimming speed for participants using *Clairbuoyance*.

Psychountaki and Zervas found a correlation between trust and performance, in particular speed [28]. This, combined with the feedback collected in the interviews with participants of the study, supports the idea that *Clairbuoyance* had a positive effect on the confidence that swimmers had on their sense of direction, resulting in a increment in their performance.

Clairbuoyance did not improve accuracy

The use of *Clairbuoyance* did not result in a more accurate estimation of the direction to the target. Swimmers missed the target by approximately the same distance both on the base condition and with the ACF, and a larger distance when using RDF. This suggests *Hypothesis 2* is false.

We observed that participants swimming on the base condition did not respect the request to avoid peeking and most of them raised their heads to locate the target visually. Additionally, the tiling of the bottom of the pool and the marking of the lanes provided some reference for orientation. However, because this was present in all conditions, it is possible to exclude its effect in the performance, although acknowledging that these issues weaken the comparison among the feedback methods and base condition. Despite this, it is logical to assume that the base condition error is the minimum error to be expected, and thus the ACF shows at least good performance. This, in addition to the participants reporting no issues with the direction of color transitions or hue choice, suggests that the chosen color mapping was not a hindrance.

The difference in performance between RDF and ACF can be explained as the first method giving feedback only beyond a threshold of 5°, an effect not present for the absolute feedback. It would be interesting to determine the relationship between the threshold and the error distance.

Advanced and novice users valued different features in the prototype

We observed differences between advanced and recreational swimmers in the qualitative feedback gathered. Differences in requirements between novice and professional users in sports are a known phenomenon in HCI for sports [17]. Our work showed that advanced users preferred RDF which offered a more holistic experience, while novices opted for ACF, which made users feel more in control. As we observed that advanced users wanted to control the dynamic range of RDF, our results resonate past work that suggested that professional users require more fine-tuned controls [31]. This shows that the design requirements for swimming applications for advanced swimmers are complex as they need to combine being unobtrusive (which is often achieved by minimizing input) with a large degree of control. On the other hand, our work suggests that constant visibility of system status is an important requirement for novice swimmers.

Limitations

Conducting a proof-of-concept study, we were forced to make a series of compromises to conduct a controlled experiment. The study was conducted in a swimming pool, which even given the experiment design, possesses visual characteristics and features that facilitate orientation. We expect that a real-life open waters scenario will completely lack visual cues. We observed that large structures of steel were present in the immediate surroundings of the pool. Ferromagnetic materials in large concentrations have a disruptive effect in the behavior of magnetometers, which might also suggest that the performance of the prototype in open waters would be better.

Our choice of a study design was primarily dictated by practical, ethical and liability considerations. While we recognise that evaluating the prototype in open water would have offered more ecological validity, there was no way to ensure the safety of the participants in a lake or sea. Conducting the experiment in a swimming pool enabled us to hire a dedicated lifeguard and fulfill the ethical standards required by our institutions. A future viable alternative would be evaluating *Clairbuoyance* in a competitive swim, among its participants. However, as we did not know if and how the device affected performance, we could not request that participants jeopardize their results.

8 CONCLUSION

In this paper, we presented *Clairbuoyance*, a system that provides visual peripheral feedback about orientation, augmenting the sense of direction. We described the design considerations behind the system, its implementation and evaluation. Based on the collected data, we found that visual orientation feedback reduced TCT.

We also discovered a preference for *relative discrete feedback* among more proficient swimmers, while less experienced swimmers found *absolute continuous feedback* more useful and attractive.

In future work, we expect to refine the *relative discrete feedback* and evaluate *Clairbuoyance* in a controlled experiment in open waters.

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