HoloCPR: Designing and Evaluating a Mixed Reality Interface for Time-Critical Emergencies

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ABSTRACT

Performing time-critical procedures such as Cardiopulmonary Resuscitation (CPR) usually requires trained individuals on the scene. Even when step by step instructions are available, most bystanders do not attempt resuscitation due to panic or fear of failing, often at the cost of the victim's life. We propose Mixed Reality (MR) as a compelling medium to support time-critical emergencies, and study its use in this context through an iterative user-centered design process. Our research outlines a number of key considerations for the design of time-critical emergency interfaces that led to the creation of HoloCPR, an MR application providing real-time instructions for resuscitation through a combination of visual and spatial cues. HoloCPR's comparative evaluation during a realistic resuscitation scenario indicates how the use of MR can result in decreased reaction time and increased procedural accuracy. With this work, we hope to bootstrap a new wave of MR applications for time-critical emergencies that can be included in first aid kits in the future.

ACM Classification Keywords

H.5.m Information interfaces and presentation (e.g., HCI)

Author Keywords

Mixed Reality, Augmented Reality, HoloLens, CPR, Checklists, User-Centered Design

INTRODUCTION

With the advent of novel technology for head-mounted displays, both researchers and the industry demonstrated growing interest in understanding the potential of Augmented Reality (AR) and Mixed Reality (MR). Microsoft HoloLens[1] is a good example, which supports immersive holographic experiences and an easy way to create MR applications.

[1] http://www.microsoft.com/hololens

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We are interested in the use of MR to assist people during time-sensitive activities when users might be under high pressure or particular stress. Our research focuses on non-expert users who are confronted with a time-sensitive task and have to react quickly to solve a critical problem.

To study the use of MR in these challenging situations, the first step is confirming that the technology is indeed appropriate to help fulfill the demanding requirements of a real-time resuscitation aid for novices. In this paper we approach this problem by using a user-centered design process, aimed at outlining both opportunities and challenges for MR in time-critical emergencies. By engaging a group of 16 users in an iterative design process we were able to uncover key problems and propose solutions to help design better MR interfaces in this domain. We distilled the results of our design work into an application, *HoloCPR*, targeted at helping bystanders that are not trained in Cardiopulmonary Resuscitation (CPR) to intervene and follow a correct procedure to resuscitate a person. We evaluated the effectiveness of HoloCPR against a standard paper-like checklist interface in a comparative study with 42 participants that shows how MR has the potential to help bystanders during time-critical situations. We believe that the outcomes of this paper will help research in MR progress towards application and use in the real world. In particular, we envision HoloCPR to be the first of a series of applications that can be part of first aid kits in the future, and help non-experts to effectively respond to time-critical emergencies using MR.

In the remainder of this paper we outline how our work contributes two critical elements to the current state-of-the-art:

1. Our in-depth design process clearly outlines a number of challenges in terms of designing MR interfaces in the current technology environment, and proposes practical strategies to overcome obstacles, and design for time-critical situations in MR.
2. With the HoloCPR application and its comparative evaluation we demonstrate that MR can be used by novices to respond to time-critical emergencies and that its use significantly reduces reaction time and increases accuracy.

BACKGROUND AND MOTIVATION

Each year, approximately 350,000 people in the United States experience an out-of-hospital cardiac arrest, but only 12% survive the event, making it one of the top killers in the US [13, 15]. Responding to a cardiac arrest requires a wide range of people to be prepared to act. Basic Life Support (BLS) is CPR combined with the use of an Automated External Defibrillator (AED). Performing BLS immediately after a victim collapses plays a major role in the increase of survival rates in the event of a sudden cardiac arrest. It has been shown that chances of survival fall by 7-10% for every minute without resuscitation and if not provided within 10 minutes, the survival rate is close to zero [11].

However, it usually takes 8 minutes or longer for medical personnel to arrive. Therefore, initial care in the first minutes after a sudden cardiac arrest critically relies on the action of bystanders. Bystanders are people, not part of the organized emergency response system, and often without a professional healthcare education, who happen to be near the victim. Bystander-initiated CPR in the US was found to double or triple chances of survival, with survival rate increasing to 49-75% when an AED is used [14].[2] Despite evidence that bystander-CPR is crucial for both survival and health improvements, administration rates remain very low, reaching only an average of 30-40% [15].

Studies show that CPR provision increases in bystanders that have CPR training, and that carefully designed interventions can help increase CPR training [7]. For instance, a national program in Denmark that included widespread CPR training, dissemination of CPR education kits, and improvement in dispatch-assisted bystander-CPR, resulted in a significant increase in post-CPR survival over 10 years (1-year survival increased from 2.9% in 2001 to 10.2% in 2010) [26]. However, it has been observed that bystanders hesitate to perform CPR even when trained, and a significant increase in providing CPR is only observed in bystanders with an active CPR training, one that has occurred within the past five years [7].

Unfortunately, the complexity of resuscitation guidelines and the cost of CPR training decreases the likelihood that the general public is able to maintain an active CPR training. More importantly, it has also been shown that panic may influence readiness to act in an emergency situation irrespective of prior CPR training [7]. The most commonly cited barriers are fear of harming the victim or performing CPR improperly. Given the importance of bystander-CPR and its potential to save lives, having additional aids on site is an important step towards improving CPR delivery. In particular, we believe that providing real-time resuscitation aids could increase the confidence of the bystanders, overcoming the barriers created by panic and the ability to initiate CPR.

The typical response to improve guidance for bystanders during CPR is to increase availability of checklists and alike to guide the provisioning of CPR step-by-step. These checklists and step-by-step guides are sometimes included in first-aid kits, or are made available in public spaces (e.g. installed on the walls where AED devices are also located). While increased availability is good, these guides tend to be text-based, and following them is hard, especially in emergency situations. The use of mobile phones has been strongly encouraged for bystanders responding to a cardiovascular emergency [9]; while this makes instructions more readily accessible than checklists, bystanders still have to read and interpret the instructions, potentially increasing their cognitive load in an already stressful environment. Traditional media like paper and two-dimensional screens also require the user to switch focus between the medium and the victim, reducing the promptness with which they can respond. There is therefore a need for real-time contextual assistance systems to guide high-quality resuscitation.

[2] Note that this varies markedly across US counties

Mixed Reality as a Viable Medium for CPR Assistance

Mixed Reality (MR), referred to as the merging of real and virtual worlds, allows digital content to co-exist in the same environment as the user [12]. This medium naturally lends itself to spatially localized instructions – enabling users to view and interact with their environment in ways that traditional media cannot afford. In integrating information directly into the user's environment and translating information found in traditional instructions (like text and pictures) into visual cues, MR could potentially lower cognitive load.

We posit that these additional visual and spatial affordances could lead to a decrease in the time it takes to translate instructions to action, especially for non-skilled users, enhancing the promptness with which bystanders can respond to the victim. With its additional affordances, Mixed Reality could prove particularly suited to encourage bystander CPR, and overcome the barriers caused by the lack of an active resuscitation training and panic. In the event of a sudden cardiac arrest, spatially localized instructions can offload the burden of interpreting location specific instructions to the system itself (e.g.: correct placement of hands for CPR or retrieving and attaching AED on the victim's chest). The increasing availability of AR and MR devices creates a possible future where providing real-time guidance for critical procedures such as resuscitation might be available as specific applications. Bystanders could access these applications on their personal MR devices, or on a publicly available first aid kits equipped with MR glasses. Using such a system during an emergency could potentially be more effective than traditional media in providing expert guidance.

However, the design of such an interface raises several questions: Are spatially localized instructions truly better than those on a two-dimensional screen? Should the system automatically track user actions? Is providing feedback useful? If so, how much feedback should the system provide? Should visual instructions be complemented with voice commands?

These questions only scratch the surface of truly understanding the use of MR in time-critical situations. The goal of this paper is to start investigating the use of MR for time-critical emergency guidance in order to answer some of them. More specifically, we want to understand the effects of the additional visual and spatial affordances that MR provides over traditional media. In the future, we plan to assess the integration of automatic recognition and tracking of users' actions.

In order to effectively explore and demonstrate the utility and feasibility of MR in such time-critical emergencies we present a study of its application for CPR. We engaged novice users in an iterative multi-step design process that led to the creation of HoloCPR, an MR interface that provides a real-time resuscitation aid for CPR. To truly understand the effects of the additional affordances that Mixed Reality provides over traditional media, we evaluated HoloCPR in a between-subjects study, comparing it with traditional CPR instructions.

Hypotheses

We hypothesize that users guided by HoloCPR will have multiple benefits from being able to view spatially localized instructions during their CPR delivery. More specifically:

H1 In comparison to traditional media, MR will reduce the response time needed to begin resuscitation in the event of a sudden cardiac arrest.

H2 In comparison to traditional media, MR will reduce the time it takes to read, interpret, and act upon an instruction.

H3 In comparison to traditional media, MR will improve procedural adherence.

RELATED WORK

Augmented Reality and Mixed Reality have been long seen as an attractive medium to aid procedural task execution. Visualizing information in the space around the user has seen many applications in fields like manufacturing, assembly, entertainment, education, military, and even medicine, for both training and real-time guidance [23, 19, 27]. However, over the years there has been very little research focusing on user-based interface design approaches. Until 2004, out of all the publications in primary venues for AR, only 14% of articles were HCI-related and only 8% of those contained any user-based experiments [20]. A more recent review of publications reporting on AR assembly tasks applications found that while 39% of the articles deal with assembly guidance, only 8% focused on effectiveness evaluation and only 4% conducted usability evaluations [24].

Despite an overall lack of user testing, pioneering work since the 1990s has enabled AR and MR to advance to today's standards. In 1993, Feiner and colleagues [4] described an augmented reality system that "provides explanations of, and assistance with, complex 3D tasks". In the same period, Caudell et al. [2] devised a system to aid assembly of complex aircraft parts at Boeing, digitizing vast amounts of instructions on a personal screen. A few years later, Whitaker and colleagues [25] developed a method to track and register information on real objects, allowing virtual annotations to describe different pieces of complex systems.

Following up on these initial AR prototypes, more recent studies focused on comparing and evaluating different approaches targeting AR for procedural tasks execution. Sarupuri et al. [18] explored the use of AR to assist pallet racking and pick up tasks, and observed a significant increase in task performance. Uva et al. created a system, the SAR Workbench [23], intended for maintenance procedures, and Funk et al. [6] used in-situ projected instructions for manual assembly and evaluated its long term usage in the industry. Results suggest that AR was useful in helping untrained workers learn, but decreased performance for experts. Tang et al. performed a more extensive study comparing the relative effectiveness of providing instructions on paper, a 2D laptop interface, static images on Head-Mounted Displays, and full AR on assembly operations [21]. When used for an assembly task based on Duplo blocks, they found significant reduction in error rate with the use of full AR. Their results also indicate decreased mental effort, showing that AR could complement and help reduce the user's overall cognitive load. Henderson et al. [8] focused on using AR during the psychomotor phase of a procedural task and conducted user studies comparing the AR system to one based on a standard LCD screen. They found that participants were faster and more accurate with the LCD screen, but preferred using the AR system. Very recently, Blattgerste et al. [1] compared in-situ instructions on Epson Moverio (a wearable AR system based on a glass-like support), Microsoft HoloLens, a smartphone, and paper. Participants were given an assembly task and took less time when using instructions on paper, but committed less errors using HoloLens.

Despite increased attention to user studies that compare AR (and HoloLens) with standard interfaces, to the best of our knowledge no work has investigated the use of AR or MR to support novices during time-critical emergencies. The rare applications focusing on CPR tend to be designed for training purposes and also tend to lack user testing. Park et al. [17] created a system for CPR training that provides interactive feedback using projections. Like many other CPR training programs, this AR system is dependent on sensors embedded within a mannequin that cannot be directly translated into a system to be used in real events. HeartiSense [10] is also an AR system for CPR training; the authors conducted user tests using the system to validate its accuracy. However, their participants were expert emergency responders with prior CPR training, and as such the results cannot be translated to similar interfaces for novices.

DESIGNING MIXED REALITY INTERFACES

Successfully guiding bystanders, especially if untrained in CPR, through the time-critical and stressful task of resuscitation, requires an interface that allows for the intuitive comprehension of the information presented to them. To understand how users would interpret and piece together the information that their augmented environment would now offer, we employed an iterative user-centered design approach [16]. This approach proved crucial in outlining the design elements of our prototype MR application. In this section we detail our design process, and the elements that emerged from it, while the next section introduces the resulting application, HoloCPR.

Design Process

The goal of the first phase of our research was to design a MR prototype that would effectively exploit the visual and spatial representation of instructions enabled by MR, as well as the cues that would prompt the transitions between instructions (Fig.1, Left). Our iterative design methodology continuously involved users who contributed to the implementation of intermediate prototypes. To implement our MR prototype we used Microsoft HoloLens (Fig. 1, Right), a standalone head-mounted display that renders virtual objects (which Microsoft

Figure 1. Envisioned MR prototype for expert-guided CPR. Left: chest compression instructions, and correct positioning of the hands displayed on top of a resuscitation mannequin. Right: Microsoft HoloLens head-mounted display; note the clicker taped to the head-mounted display as it was used for our experiment.

calls ‘holograms’)[3] into the user’s environment. We chose this device because of its self-contained nature, the Unity-based SDK, and the availability of many development libraries which supports rapid prototyping, allowing us to focus on the user experience and design.

We recruited 16 participants (7 females), with an average age of 23 years. Participants’ background were in Computer Science (4), Cognitive Science (4), Public Health (1), Biology (1), and Other/Undeclared (6). All of them had no or limited experience with MR or HoloLens, and 5 of them had been trained in CPR. We engaged the participants in a four-phase iterative design process based on (1) user testing, (2) participant interviews, (3) rapid prototyping, and (4) prototype development.

1. **User Testing**: In each iteration participants used the latest prototype on the HoloLens to try and resuscitate a simulation mannequin. They were instructed to wear the HoloLens and follow the steps indicated by the application. Each session lasted between 10 and 15 minutes.
2. **Participants’ Interviews**: After testing the prototype each participant was interviewed to shed light on the obstacles they faced. We employed semi-structured interviews [3] to balance eliciting specific feedback on our prototype, and encouraging the participant’s own view on MR. Topics and ideas that emerged during the interview were analyzed by our team and discussed prior to proceeding to prototyping.[4]
3. **Rapid Prototyping**: A rapid prototyping session supported by sketches, low-fidelity paper prototypes, and a whiteboard representation of the different entities of the envisioned system (Fig.2) helped design the next iteration based on the observed user challenges.
4. **Prototype Development**: The resulting prototype was finally implemented using Unity 3D and deployed onto the HoloLens to be tested with the new iteration. Development continued until we reached saturation and no new or missing design element emerged.

Design Challenges and Proposed Solutions

We hypothesize that mixed reality interfaces will overcome some of the problems of providing real-time guidance on traditional media. Through our design phase we were able to uncover a number of challenges that we did not anticipate, but resulted in key design elements that we eventually integrated in our application, including a particular attention to current technical limitations of MR systems, as well as users’ unfamiliarity with the medium.

[3]http://www.microsoft.com/hololens/developers

[4]When feedback from one participant did not result in enough material to warrant a prototyping phase, feedback from up to 3 participants was analyzed before moving onto the prototype phase.

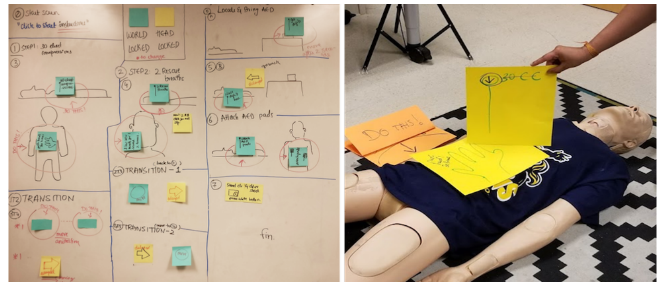

Figure 2. Prototyping with HoloLens and our HoloCPR mannequin. Left: Our iterative prototyping environment on a whiteboard. Right: Physical projection of the 3D representation using paper prototyping.

In the remainder of this section, we describe the design elements that resulted from our iterative prototypes and discuss how they contribute to the more general development of MR interfaces for time-critical situations.

Lack of familiar design patterns for information guidance

Over the years two-dimensional interfaces have benefited from design patterns that emerged from common usability research –e.g. users expect interfaces to follow a sequential direction (usually top-down, left-right) to scan for and read instructions [22]. On the other hand, MR does not inherently offer users a way to intuitively scan the interface for information. Besides some basic guidelines,[5] designers are left with a mostly unknown interaction space. This lack of familiarity with design patterns was particularly challenging in our scenario where users had to interact with and consume information rapidly, in a stressful situation, and with information that did not necessarily appear in the same position all the time. In the case of time-critical emergency situations, MR instructions are spread in space (rather than on a specific 2D interface), and their position depends on the user’s relative location with respect to the victim and the environment.

In order to support this situation, we needed to explicitly guide user attention to the task at hand and help users establish patterns in the interface so that they could easily find the information they needed without prior training. To guide users in the MR space, we introduced a composite visual element that we called the *Circle of Attention*. The Circle of Attention is composed of a white *circle* with an *arrow* on its perimeter, textual prompts, and any number of additional images. Figure 4 shows its representation applied to rescue breaths.

In addition to the circle of attention, often it was important to guide users away from their current gaze position (e.g. while focusing and looking at the victim’s chest), in case they needed to attend to a different instruction. We used a *Red Arrow* that followed the users’ gaze to direct them towards the instruction they needed to attend to. Figure 3 illustrates how the red arrow helps users find the AED pads elsewhere in the room and apply them correctly to the victim.

[5]http://developer.microsoft.com/windows/mixed-reality/design

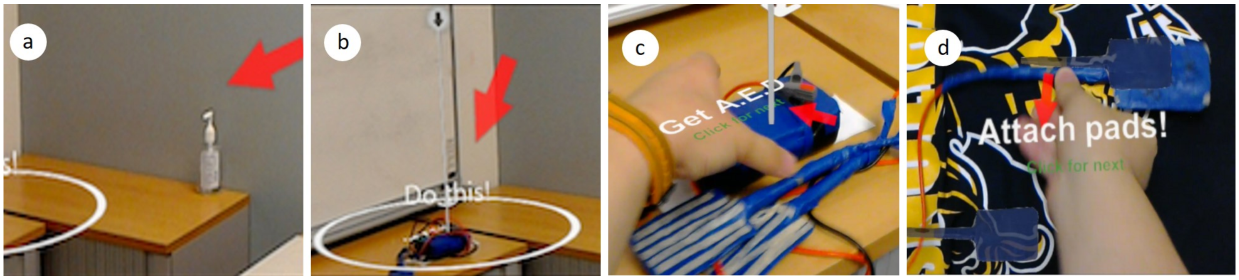

Figure 3. The "Red Arrow" guides the users indicating them where the important things are located and where they should act. From left to right, the prototype shows how to locate first the AED (a, b) and then how to grab it and position the AED's pad correctly on the victim's chest (c, d).

Narrow Field of View

A narrow Field of View (FoV) on the HoloLens causes holographic content to frequently be cut off. [P8] noted how "*the frame cut off weirdly at some parts, which made it difficult to know whether or not there is something supposed to be projected into a certain surface*" and [P4] pointed out how "*it was a little hard to see all of the instructions, so I had to look around to actually see them all.*". Because of the limited FoV, digital content could be invisible even if it is in the user's natural FoV (see example in Fig. 5).

Although this is mostly a limitation of the current technology, we wanted to mitigate the limited FoV and compensate it by encouraging users to use less eye movement and more head movements when they needed to change their gaze attention. To accomplish this and allow stationary users to be aware of information outside of their FoV, we integrated a *Vertical Pole* at the center of the Circle of Attention (see Fig. 4) that stretches upwards vertically. When the area of instructions is in the user's natural FoV, but vertically outside the HoloLen's FoV, the vertical pole helps users direct their gaze to the center of the circle, towards the needed information.

In addition to the Vertical Pole, we designed the *arrow* on the perimeter of the Circle of Attention to move around and always be diagonally opposite to the user. It always points to the center of the circle, prompting them to look towards the center to find more instructions.

Close Ranges and Erratic Movement

Current technical limitations inherent to many MR devices cause visual aids to disappear when users gets too close to objects or people in front of them. Extensive movement also causes those visual aids to shift and makes focusing on instructions more difficult. [P15] mentioned that "*moving around with the HoloLens made it a little harder to read the instructions*". Since performing CPR means that users would both be very close to the victim and move erratically, we needed to be able to help users hold their attention and minimize discomfort during extensive rapid movements.

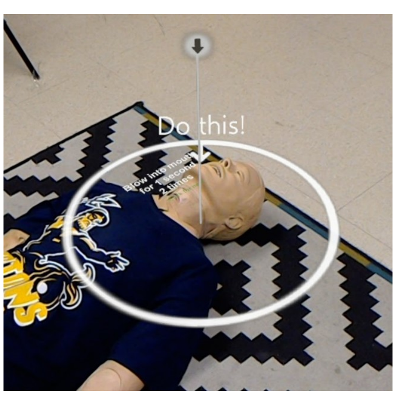

Figure 4. Instructions for rescue breaths, as seen by the wearer. Visible are also the Circle of Attention and the Vertical Pole in the middle of it.

The circle of attention described above also served to help users retain their focus on the instructions, even when in close range to the digital content and when moving extensively. In addition, the constant presence of the circle of attention helped mitigate the effect of *disappearing* holograms.[6] The appearance of the circle of attention and the arrow on its perimeter, as soon as users move far enough from the objects or people in front of them, helps users to immediately *recapture context* and proceed with their intended interaction.

Finally, interaction during erratic movements (e.g. during chest compressions) proved to be problematic. While textual information always looks jittery, we found that adding enough thickness to the border of our circle of attention helped users to keep the focus and their attention in the correct place, and move back to that particular position if their body or gaze moved during the erratic movements.

Managing High User Expectations for Intelligent Systems

One thing that was extremely clear from our interactions with all the participants was that they had very high (and often wrong) expectations from the MR experience. Expectations were especially focused on the *smartness* of the device, and how it would automatically assess the situation. In particular the majority of our participants expected the device to automatically recognize their actions and guide them accordingly.

While somewhat natural for an emerging and mostly unknown technology, we were surprised by how this expectation recurred in many of our design sessions. In order to mitigate these expectations, we added a *clicker* taped on the side of the

[6]E.g., when users lean in to breathe into the victim's mouth, the head moves very close to the instructions, and digital content disappears.

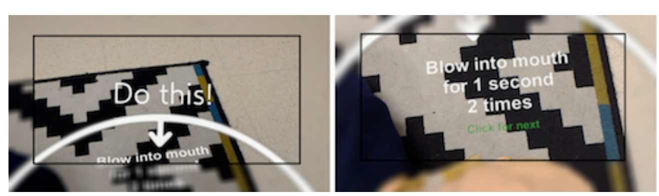

Figure 5. In this image, we can see how the "Circle-of-attention" points the user to where the important information is (users move their gaze from what they would see in the left picture to the right one). The figure also shows how the holograms in the area outside the black rectangle are not visible for the user, given HoloLens' narrow field-of-view.

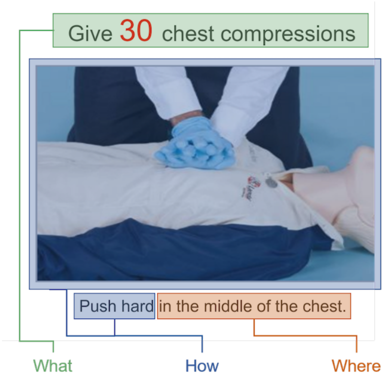

Figure 6. Dividing instructions into "What", "How" and "Where"

head-mounted display (see Fig. 1, Right) and asked participants to explicitly click to move to the next stage of the CPR. However, their expectation was so severe that even after explicitly telling participants that their actions were not recognized and to use the clicker, we received feedback like "*I waited for it to move by itself*" [P3] and "*I did expect a little for the headset to tell me what to do, even though I was warned not to*" [P10]. The only way to avoid these misunderstanding, was to add a textual instruction "Click for next" in green in front of the users to remind/prompt them to do so. We selected green because while clearly visible, its appearance is less salient than the white texts and images used for task-related instructions.

HOLOCPR

Our iterative design process yielded key observations in terms of design, interactions, and visual components. We integrated these observations from partial prototypes into a complete MR application to support the real-time delivery of CPR. HoloCPR was built as a HoloLens application using Unity 3D[7] and exploited the prototypes developed in our design phase. In this section we describe the overall goal of the application, as well as its envisioned use. In the next section we then describe how we evaluated its effectiveness.

HoloCPR has two main components, the first one is focused around the physical resuscitation, and the second one assists with the placement of an AED. In the event of a cardiac arrest, users place the HoloLens on their head and activate the HoloCPR application. When users look at the victim, the system indicates the correct placement of the two hands in the center of the victim's chest and instructs the user to perform 30 chest compressions (see Fig 1, Left). When they are done, the system guides the users to the correct placement of their hands around the mouth of the victim, and instructs them to blow into the victim's mouth 2 times (see Fig. 4).

If an AED is available nearby, HoloCPR instructs the users to stop CPR and guides them to the location of the AED and back to the victim using a red arrow in the center of their visual field (see Fig. 3). It then instructs them to place the AED pads in the correct position on the victim's body to provide defibrillation.

Participants' feedback and expectations outlined how automatic recognition of chest compressions (including rhythm and force applied), mouth positioning (including blow frequency and length), as well as automatic AED localization are key elements needed for an effective deployment of HoloCPR in the real world. While this paper focuses on the current implementation of HoloCPR and investigates visual and spatial cues in Mixed Reality, advanced recognition features are part of our immediate future work.

As a result current interactions between different steps in the resuscitation are performed through direct interaction by the user (e.g. "click to go to the next step"), using a HoloLens clicker taped on the side of the device (see Fig. 1, Right).

Based on the needs we observed during our design phase,we decided to divide the standard instruction in each step into three groups: *what*, *where* and *how*. We then used the *where* to provide positional context for the instructions, and used text and images to convey the *what* and *how*. For example, to help users perform chest compressions (see Fig. 6), they needed to know what to do (chest compressions, 30 times), how to do it (push hard, use this hand form) and where to do it (in the middle of the victim's chest). HoloCPR represents this particular interaction using two sets of text and an image depicting the hand form as well as the position (see Fig. 1, Left). A similar approach was taken for all other HoloCPR instructions.

HoloCPR in action

In order to better illustrate how HoloCPR works, in the remainder of this section we focus on a scenario, based on Avi, a 28 year old graduate student who uses HoloCPR to resuscitate a victim. The goal is to direct Avi towards the instructional point of interest where she would find textual prompts and images that guide her through her actions. The scenario outlines both the use of HoloCPR and how the visual aids that resulted from our user-centered design helps her to proceed through the CPR experience. Figure 7 shows a schematic representation of the central elements of the scenario we illustrate below.

> *Avi enters her office and sees a person on the floor who is not breathing. After rapidly assessing the situation she decides to perform CPR, but she does not remember all the steps. She decides therefore to make use of the HoloLens and the new HoloCPR application from the first-aid kit that has just been deployed in the building. When Avi initiates resuscitation guidance, the victim's chest is not in her natural field of view, but she immediately notices a red arrow that points towards the upper body of the victim (Fig 7, Left). She also registers a white circle, big enough for her to stand in that moves away from her almost as soon as she sees it. The slight delay in movement serves as the first cue in understanding its purpose. Avi instinctively looks towards the direction it moved to and notices that the red arrow is also pointing in the same direction, waiting for her to follow it. Now she can see that she needs to rapidly approach the victim's chest to start resuscitation. Just as she feels like there aren't any instructions (because it is outside the HoloLen's FoV), she notices a vertical pole in the middle of the white circle in front of her, and she immediately traces its length vertically (Fig 7, Center). Avi sees the*

[7]https://unity3d.com

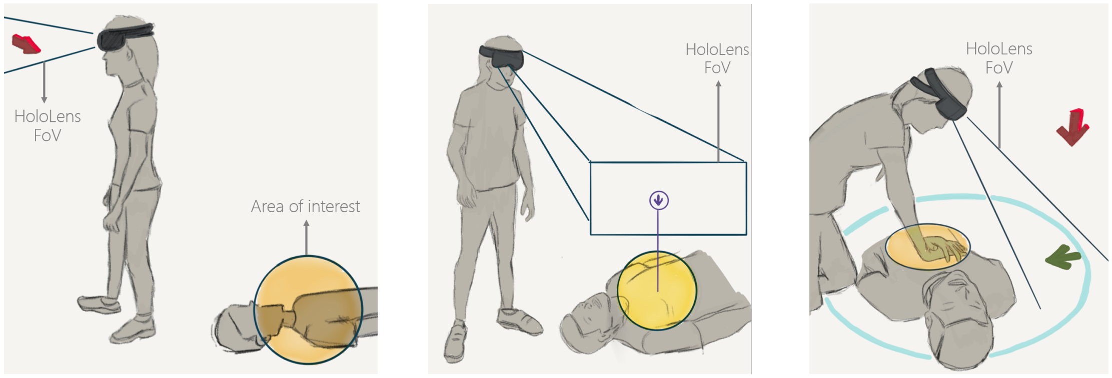

Figure 7. HoloCPR Scenario. Left: User faces away from the area of interest; Center: Area of interest in the user's natural FoV but not in HoloLens' vertical FoV; Right: Area of interest at close range and in the user's natural FoV but not in HoloLens' FoV

white circle again, now with additional information that instructs her to do 30 chest compressions by placing her hands on a digital representation of two hands projected onto the victim's chest.

She immediately kneels down beside the victim, places her hands on the victim's chest, making sure to interlock her fingers as shown (see Fig. 1, Left) and begins chest compressions. As she performs chest compressions, Avi can no longer see the instructions (Fig 7, Right). She moves her eyes to look down at where she just saw the digital representation of a hand, but she doesn't see it anymore. Avi however remembers registering an arrow on the perimeter of the white circle that seems to move around and always face her. It also seems to always point to the center of the circle, encouraging her to look towards it. When she does, she finds the instructions again. Although the rapid movement due to the chest compressions makes the HoloLens feel heavier on her head, she is able to focus on the only thing that isn't jittery, the white circle. She continues counting through her compressions. When she is done with 30, she presses the clicker to move to the next step...

EVALUATION

To assess the effectiveness of HoloCPR we conducted a between-subjects experiment in a realistic lab setting. Participants were asked to perform CPR on a simulation mannequin by following the steps shown by HoloCPR. We measured the time it took for them to go through the simulation, as well as the accuracy with which they performed the procedure. We compared HoloCPR with a control condition that simulated the traditional CPR experience using standard 2D instructions for guidance on a separate support. The instructional medium used for guidance was the only independent variable.

We based HoloCPR's resuscitation guidance on published and recognized guidelines taken from the Adult First CPR/AED Reference from the American Red Cross.[8] For the sake of our evaluation we chose to prompt participants to perform only 2 rounds of chest compressions and rescue breaths before they moved on to 1 round of simulated defibrillation. This amounted to a total of 7 instructions:

1. Give 30 chest compressions
2. Perform two rescue breaths
3. Give 30 chest compressions
4. Perform two rescue breaths
5. Locate the AED
6. Attach the AED pads to the mannequin's chest
7. Defibrillate the mannequin

[8]http://www.redcross.org/cpr

Experimental Constraints

To allow us to measure reaction time and the time it took for participants to transition between instructions, the interface presented one instruction at a time and was designed to include a "startup page" that prompted users to click to initiate resuscitation guidance. In addition, to simulate traditional CPR guidance and measure time-to-task, in our *control condition* we used a tablet interface that showed a 2D representation of the CPR/AED guidance on an Apple iPad Pro. We carefully designed the tablet interface for the control condition to mimic as much as possible a paper-based checklist. The only difference for participants was the *start* button to begin resuscitation guidance and the *next* button to go to the next page. Instructions consisted of title, two lines of text and a picture, all from the CPR guidelines. At the bottom was the title of the next step along with the *next* button.

Participants

We recruited a total of 42 participants (12 female), graduate and undergraduate students at the University of California San Diego, across multiple departments (i.e.: 23 from Computer Science and Engineering, 6 from Cognitive Science, 4 from Biology/Medical School, 2 from Electrical and Computer Engineering, 2 from Mechanical and Structural Engineering, 2 from Bioinformatics, 1 from Nanoengineering, 1 from Chemistry, 1 from Economics), with ages spanning from 18 to 27 years (average 22.7 years). None of the participants had been exposed to HoloCPR and only 10 had been trained in CPR. All but 6 participants had never used a HoloLens or any mixed reality device before. All participants were familiar with the general use of a tablet and touch screens. Participant assignment to the two conditions balanced gender, background, and CPR experience. All participants were unaware of the task and the instructional media they would use.

Experiment Design

Setup — The experiment was conducted in a room equipped with a simulation mannequin, a mock heart rate monitor showing on a large screen, a mock AED device, and a computer where participants would fill out the quick pre and post-task questionnaires (see below). The mock heart rate monitor was remotely controlled and could be set to flatline and trigger an alarm to indicate a "crash" (cardiac arrest). We instructed participants to start resuscitation of the mannequin (either with HoloCPR or with the 2D checklist, depending on the assigned condition) when the alarm would start. A video camera recorded the activity in the room for further analysis.

Introduction to the HoloLens — To introduce participants to the HoloLens and acquire basic familiarity with its weight, the concept of holograms, and the clicker, we asked them to play RoboRaid[9] (a mixed reality 3D first-person shooting game) for 12-15 minutes. This also served to familiarize the users with the position of the clicker. Participants were kept unaware of any HoloCPR specific interface details. To account for the possible fatigue introduced by this procedure, and ensure that any variables introduced by playing the game remained constant across conditions, all participants in both conditions were required to complete it.

Experimental Procedure — Once the participants completed the necessary training, they were taken into the experiment room where they were asked to fill out a pre-study questionnaire asking for basic demographic information. For both conditions, a researcher took up the role of a caretaker and introduced the simulation mannequin (henceforth called the victim). Participants were told the victim was recently moved back home from an ICU and that they would be alone with him for a short period of time while the researcher stepped out to "run an errand". They were alerted of the heart rate monitor and the instructional medium available to them (HoloLens or iPad) and were instructed to attend to the victim should anything go wrong. No additional instructions were given.

Participants in both conditions were ready to initiate resuscitation aid before the researcher left the room. HoloCPR participants kept the HoloLens on and saw the prompt "Click to start". Control participants were given the iPad with the start page already opened and ready to go. They were, however, instructed to not initiate resuscitation aid unless they needed to (i.e. when the victim was in need of their help). Once they were left alone in the room the heart rate monitor was set to indicate a cardiac arrest at a random time within the first two minutes. The alarms from the heart rate monitor were kept going until participants reached the very last step of the resuscitation to help build and sustain a sense of urgency.

After all steps were accomplished we asked participants from both groups to fill out a post-study questionnaire about their experience. Participants reported their subjective opinion on the importance of the aids used with respect to performing CPR (step-by-step guide using a tablet, or HoloCPR using MR). We also inquired about difficulties or confusion they experienced during resuscitation, and performed a semi-structured interview that elicited more in-depth feedback on the interface, as well as specific feedback on their performance.

[9]https://www.microsoft.com/en-us/hololens/apps/roboraid

Data Analysis

All the sessions were recorded using an external camera and basic logs were collected on the HoloLens and the iPad. Videos were coded using the ChronoViz analysis tool [5]. We then used a Python script to extract and analyze the data from the videos. Of the 42 participants we excluded 9 from quantitative data analysis (4 in the HoloCPR, 3 females, and 5 in the control condition, 1 female) who did not complete the whole experiment due to technical issues (5) or because they misunderstood the task (4). In the next section we report and discuss the results of our experiment and the answers collected through the post-study interview and questionnaire.

RESULTS

Data extracted from the videos of the experiment was coded for response time, performance, and procedural adherence, with the goal to compare the control (i.e.: paper-like step-by-step on tablet) and treatment (i.e.: mixed-reality with HoloCPR). To assess the statistical significance of our results we used a 2-sample t-test ($\alpha = 0.05$). In this section we report on the outcomes of our analysis and discuss results with respect to our original hypotheses. Figure 8 summarizes our results.

Response Time

HoloCPR users react faster – We compared the time it took for participants to attend to the victim, more specifically, the time it took them to start resuscitation once a cardiac arrest on the mannequin was triggered. HoloCPR was significantly faster than the control condition ($p < 0.01$). On average, HoloCPR allowed participants to respond to the victim in 7.04 seconds while tablet users took 11.96 seconds.

To better understand what contributed to this difference, we broke this response time into two phases.

1. **Guidance Initiation Time** was defined as the time it took for participants to initiate resuscitation guidance on their respective devices ("click *start*") once a cardiac arrest was triggered. HoloCPR users clicked *start* within 2.96 seconds on average while tablet users used 3.7 seconds on average. While HoloCPR did show a trend towards shorter initiation times, our comparisons showed no statistical significance between the two conditions ($p = 0.175$).
2. **Initial Reaction Time** was defined as the time it took for participants to start CPR once they initiated resuscitation guidance. This time the difference was statistically significant ($p < 0.01$) with HoloCPR users taking an average of 4.08 seconds vs. control users taking 7.25 seconds.

Performance and Transition Time

HoloCPR users spend more time searching for AED – While the difference is not statistically significant ($p = 0.12$), we observed that the control participants generally spent less time searching for the AED (5.77 seconds on average) compared to HoloCPR users (8.61 seconds on average).

HoloCPR users are faster while attaching AED pads – On the other side, HoloCPR users were faster ($p < 0.01$) in attaching the AED pads on the victim's chest. On average HoloCPR resulted two times faster than the control condition (8.98 seconds vs. 19.41 seconds on average).

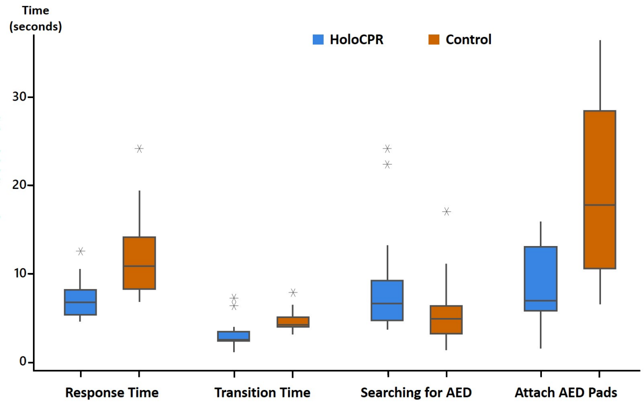

Figure 8. Response time, transition time, time spent searching for the AED, and time taken to attach AED pads across both conditions.

HoloCPR users transition faster to next steps – Transition time was measured as the time it took participants from the end of one step to the beginning of another. This generally included clicking *next* as well as interpreting the instructions before moving on to the next step. HoloCPR users were significantly faster ($p < 0.01$) than the control condition, and took an average of 3.17 seconds to transition to the next step (vs. 4.65 seconds).

Procedural Adherence

HoloCPR helps stay on track with the procedure – While all users were instructed to follow the 7 steps indicated in our simplified procedure, 3 of the control participants performed additional rounds of chest compressions or rescue breaths, with a total of 12, 10, and 8 steps instead of 7. For HoloCPR only 1 participant deviated, performing 2 additional steps.

Hand position is often correct with HoloCPR – Both the control condition (using a picture) and HoloCPR (using a representation of digital hands) instructed participants to perform chest compressions with one hand on top of another and their fingers intertwined. However, we observed that only 12.5% of the control participant started CPR with the correct form. For HoloCPR this number tripled with 41% of the HoloCPR users performing the chest compressions correctly. Out of the participants that started with the wrong form, none of the participants in the control condition corrected their form whereas 30% of the HoloCPR users did.

HoloCPR does not help with correct AED Pad Placement – We observed that 18.75% of the control participants and 17.65% of the HoloCPR users placed the AED pads in the wrong position. A correct position was one where users places one pad on the upper right side of the victim's chest and the other pad on the left side of the chest.

Subjective Feedback

Besides the quantitative measures outlined above, we also report on subjective feedback from our users. The vast majority of the HoloLens participants (82%) reported that the technological aid was important (score of '5' or '4' on a 5-point Likert scale), while only half of the control participants (56%) reported that the technology was important (score of '5' or '4'). When asked about ease of use of the interface (with '1' being easy to use and '5' being hard/confusing), HoloLens participants were mostly neutral (37.5% selected '3', 25% selected '1', easy, and 25% selected '4', difficult). The majority of the control participants, in contrast, reported the interface to be easy to use (54% selected '2').

Participants using the tablet interface commented on its simple and intuitive use – "*All of the buttons were big so it was easy to know what to do on the tablet*" [P58], "*The directions were simple and easy to follow, the pictures helped a lot!*"[P52]. However, non-CPR trained tablet users recalled feeling uncertain about how to put in practice the steps indicated: [P20], for instance, reflected "*I felt like I was losing time because I had to keep reading the tablet for the next step. The instructions were easy to follow though because of the pictures and diagrams but I wasn't sure if I was doing it correctly*". A CPR-trained tablet user [P25] also mentioned "*I felt I wanted more instructions regarding how to perform chest compressions or the rescue breaths – technique is important in these maneuvers*".

On the other hand, users expressed positive feedback for HoloCPR's interface – [P48] commented "*Showing the positioning of where to press for CPR and where to position the AED was helpful because I didn't have to spend extra time figuring that out myself*" – non-CPR trained users like [P32] and [P41] noted how *"the system told me what to do - otherwise, I would have no idea"* and how "*the spatial awareness was key. Telling me *where* and *how* I had to hold my hands and telling me where the CPR device was, made it super intuitive*". HoloCPR Participants were however also critical, for instance [P38] commented on how *"to put on the HoloLens in such an emergency situation could take some time"*, and [P46] noted that *"when the arrows would try to guide me to do something, it would've been nice to know ahead of time what I was being guided to"*.

DISCUSSION

Overall we have been able to observe a trend towards better response times, accuracy, and performance when HoloCPR was used for resuscitation guidance. In particular this is true for all of our hypotheses (H1: reduced reaction time; H2: reduced interpretation and faster action; H3: improved accuracy).

Our analysis suggests that mixed reality reduces the reaction time needed to respond to a cardiac arrest (faster reaction and reduced initiation time), and confirms H1. Performance and transition time are mostly reduced as well, so in general, hypothesis H2 is also supported. Although we saw a tendency to spend more time looking for AED, our results suggest that mixed reality reduces the time it takes to read, interpret, and act upon an instruction. Finally, we can say that H3 is partially supported as well: HoloCPR helps positioning hands and improves accuracy of the steps to follow, but does not help with AED more than the traditional guidance does. In general, however, HoloCPR did not decrease accuracy with respect to the control condition.

All in all, the results of our study support our initial intuition that the additional visual and spatial affordances of mixed reality decrease the time it takes to translate instructions into action, especially in a time-constrained environment. In overlaying information directly onto the area of interest, HoloCPR reduces the need to switch focus between the instructional medium and the victim. Spatially distributing information (especially in a non-textual manner, like showing a digital representation of hands with interlocked fingers on the victim's chest) also reduces burden of reading and interpreting instructions, instilling a higher sense of confidence in users.

We also observed a higher degree of procedural adherence from participants using HoloCPR. However, our observations could be the result of attention bias – a phenomenon that occurs when users focus on highlighted areas at the cost of other areas [28]. More extensive studies are needed to understand exactly how much procedural adherence is due to this phenomenon and discuss how the extreme reliability on cues in augmented reality displays influence its use in emergency time-critical scenarios. In our study we observed interesting episodes of extreme reliance on the mixed reality interface, especially during our iterative design session. For example, a participant performed chest compressions when directed, even though the indicated location was not on the victim, but under a table, due to a calibration issue. Others followed and waited for the *red arrow* even when the AED was in their field of view. Our experiences confirm existing literature [28] which points to a need to design mixed reality interfaces to sustain users attentional focus, without encouraging unwarranted reliability on the technology. This, in concert with a number of new and exciting possibilities, will be the focus of our future work.

CONCLUSION AND OUTLOOK

In this paper we introduced HoloCPR, a Mixed Reality application targeted at supporting novices in performing time-critical emergency procedures. We presented and discussed our user-centered, iterative design process, outlining the challenges of developing for MR in the setting of time-critical emergencies, as well as the strategies that we were able to propose to overcome the current hurdles. We believe that many of the implications from our work can be applied broadly to the emergent landscape of AR and MR experiences that will be developed in the coming years. Finally, we were able to demonstrate the potential for MR to improve response time, accuracy, and performance when used in time-critical situations. With Mixed Reality becoming part of our life and our devices, we envision HoloCPR to be a first instance of a larger ecology of MR applications that could be integrated to empower non-skilled individuals to perform critical procedures and help people in need in more effective ways.

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