Validating the Benefits of Glanceable and Context-Aware Augmented Reality for Everyday Information Access Tasks

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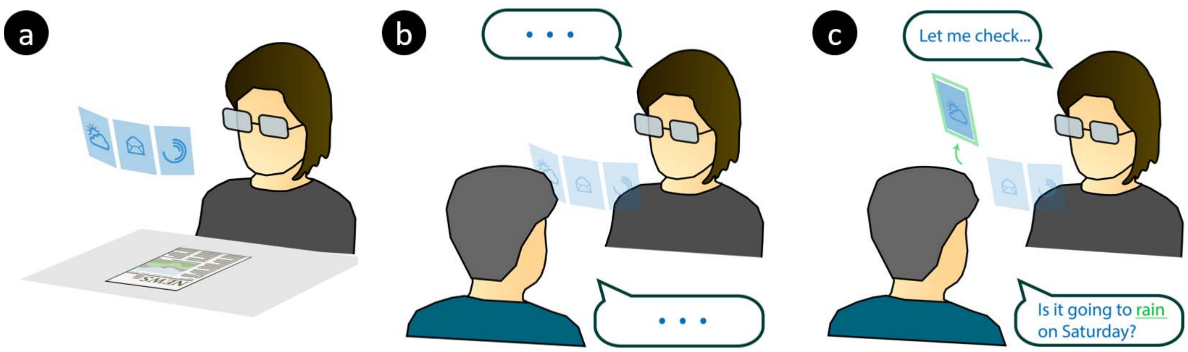

Figure 1: We propose a context-aware augmented reality interface which minimizes intrusiveness while providing fast and easy information access during both solo and social contexts: (a) In a solo context, the virtual content is glanceable and opaque when not occluding any object of importance in the real world; (b) In a social context, the real-world is prioritized, keeping the virtual content transparent when not needed, avoiding occlusion, distraction, and visual clutter; (c) In a social context, a piece of virtual content relevant to the ongoing conversation moves up and turns opaque to provide fast and easy access without blocking the conversation partner's face.

Abstract

Glanceable Augmented Reality interfaces have the potential to provide fast and efficient information access for the user. However, where to place the virtual content and how to access them depend on the user context. We designed a Context-Aware AR interface that can intelligently adapt for two different contexts: solo and social. We evaluated information access using Context-Aware AR compared to current mobile phones and non-adaptive Glanceable AR interfaces. We found that in a solo scenario, compared to a mobile phone, the Context-Aware AR interface was preferred, easier, and significantly faster; it improved the user experience; and it allowed the user to better focus on their primary task. In the social scenario, we discovered that the mobile phone was slower, more intrusive, and perceived as the most difficult. Meanwhile, Context-Aware AR was faster for responding to information needs triggered by the conversation; it was preferred and perceived as the easiest for resuming conversation after information access; and it improved the user's awareness of the other person's facial expressions.

Index Terms: Human-centered computing—Mixed / augmented reality; Human-centered computing—Interaction techniques; Human-centered computing—Empirical Studies in HCI

1 Introduction

In modern life people rely on digital information to perform a variety of daily tasks [4, 7]. This leads to near-constant information acquisition in different situations and contexts [32]. For example, digital information can be needed when you are alone reading a book and would like to check your emails, when you are walking down the street and need to check the map, or when you are planning a hike with a friend and would like to check the weather for that weekend.

Currently, mobile phones are the most pervasive personal computing devices that enable convenient information access [7, 32]. However, acquiring information via mobile phones requires physical interaction which occupies the user's hands, and it can distract the user's attention from their environment. Phones also have limited display size, so they typically only allow access to one app at a time, and thus require cognitive effort to find and open different apps when seeking multiple types of information.

For example, if someone is in a conversation about their availability to grab a coffee, they may need to: (1) pull out their phone from their pocket, (2) unlock the screen, (3) find their calendar app and open it, and then (4) check for available times. Performing all these steps takes time and induces mental workload, which can distract the user from their on-going conversation. In addition, during this process the user mainly has their eyes on the device and pays less attention to the other person involved in the conversation. Finally, the other party may be unaware of the motivation behind this information access, which can increase social awkwardness. While a wearable smartwatch can address some of these issues by providing more instant and discreet access to certain information, its display size limitations restrict the ability to perform many tasks.

Recent advances in the quality and affordability of augmented reality (AR) head-worn displays (HWDs) improve the chances that ubiquitous lightweight and powerful AR glasses may replace our smartphones as the primary tools for all-day information access. Feiner envisioned the future of AR HWDs as "much like telephones and PCs" and displaying information "that we expect to see both at work and at play" [11]. These future AR systems will have the potential to support continuous hands-free access to multiple pieces

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of information without requiring the user to close and open applications each time. These glasses are anticipated to make possible "Glanceable AR Interfaces" in which virtual content can be displayed anywhere and anytime without the need for physical displays, and information acquisition can be as effortless as a glance [6, 23, 25].

While Glanceable AR information access may be highly convenient and efficient, there is also a tradeoff between the persistent accessibility of information and the visual clutter, occlusion, and distraction that it can cause. However, the balance of concerns in this tradeoff depends on the user's context. Each context presents its own challenges and criteria for success. An interface that is desirable for one context can be completely inappropriate for another. For example, mobile contexts present challenges such as social interactions, restricted time for information access [32], where to present the virtual content and how should it follow the user [18]. Thus, the challenge for Glanceable AR is "providing the right information, at the right time, and in the right form for the current context" [32].

For example, when using an AR interface for information access, while alone in the static and familiar environment of one's own room, the constant presence of multiple glanceable virtual apps is desirable since information access convenience would be prioritized. However, when walking down a busy street, the same interface would create challenges such as occlusion and visual clutter. In this context, the user's safety and awareness of their ever-changing environment is more crucial than the ease and efficiency of information access. In social contexts, Glanceable AR interfaces should prioritize a clear view of the other person's face to avoid interrupting the social interactions and creating socially awkward situations.

In this research, we consider how Glanceable AR systems can sense the user's context and adapt to it, in order to manage the tradeoff between efficient information access and ability to view and interact with the real world. We propose Context-Aware Glanceable AR interfaces that intelligently adapt to multiple contexts and scenarios. The contributions of this work include: (1) design of a Context-Aware AR system to differentiate between solo and social contexts and adapt the virtual content display and information access technique to it; (2) evidence that both non-adaptive and Context-Aware Glanceable AR provides more efficient and less intrusive information access and a better user experience than current mobile phones in two different contexts; and (3) validation of the effectiveness of Context-Aware AR, compared to non-adaptive Glanceable AR, in a social context.

2 Related Work

2.1 Pervasive and Everyday AR

In 2016, Grubert et al. proposed that future everyday AR interfaces will be pervasive, universal, and omnipresent, enabling continuous augmentation to everyday scenarios and tasks [13]. One benefit of such an interface is to fulfill the ubiquitous information needs of users [33]. Similar to how people rely on mobile phones and wearables today, users could obtain information directly through the AR glasses without pulling out a separate display. For example, Di Verdi et al. proposed ARWin, a desktop augmented by everyday information such as weather and clock [9]. Langlotz et el. proposed ARBrowser, a mobile application that augmented the real world with relevant information anytime [20]. Lu & Bowman explored applications of AR HWDs to display personal apps in everyday scenarios [23]. Using an AR device's sensors, Morrison et al. designed an open-ended AI system to extend a blind child's capabilities in social situations [26]. Their results in a real-world deployment study shed light on the potential of AR HWDs to support the everyday general-purpose information needs of users.

However, to fulfill the pervasive and everyday AR vision, two research gaps need to be filled. First, it remains unclear how AR compares to existing devices in terms of obtaining daily information in different scenarios. Prior work has indicated that users believe AR might be more convenient than smartphones for information access [23], but we are not aware of any direct empirical comparisons. Second, most existing studies on AR information access focus on single-user scenarios. How do users perceive using AR HWDs for information access not only in situations when they are alone, but also during conversations which involve active participation of co-present others? In this research, we aimed to fill both gaps by running a systematic comparison between AR and mobile phones in both single-user and social contexts.

2.2 Context-Aware Adaptive AR

To be prepared for a pervasive AR future, as Grubert et al. suggested, it is necessary that an "AR system can adapt to the current, changing requirements and constraints of the user's context and thus allows for a continuous usage" [13]. To reach this design goal, the interface must be adaptive both spatially (e.g., layouts, and frame of reference) and visually (e.g., size, transparency, and level of detail). Existing research has extensively explored user-triggered adaptation of AR interfaces. For example, Lages & Bowman explored adaptation of the layout and frame of reference of virtual windows via button presses on a handheld controller [18, 19]. The use of gaze, hand, and head-based inputs for varying the transparency and level of detail of virtual information has been extensively explored [24, 28–30]. Ens et al. explored adaptation of size and fixation of the virtual windows in AR HWDs through a finger tap [10].

Although user-triggered adaptations could lead to good controllability and predictability [31], they also require users to determine what, when, and how to adapt, increasing the user workload. Davari et al. found that automatic adaptation of AR interfaces could lead to an increased level of efficiency in information access tasks as compared to user-triggered adaptations [6]. As such, recent research has also looked into "context-aware AR interfaces" [13], in which the interface adapts automatically based on context changes.

The term "context" refers to characteristics of people, places, or objects that are considered relevant to the interaction between the user and the interface [8]. For example, Lindlbauer et al. explored context-aware adaptation of frame of reference, level of detail, and spatial location of the AR content based on real-time estimated cognitive load and task environment [22]. Cheng et al. explored layout adaptation of AR windows based on semantic changes when users move between multiple different locations [3]. In this study, we mainly looked into the context of conversation, in which users are having interpersonal interactions while using AR interfaces.

2.3 AR UIs in Social Situations

If AR interfaces are to be used in everyday situations, social scenarios would be one of the most frequent use cases. Research has found that users are more likely to acquire certain information during social conversations, which were found to be key contextual factors in prompting information needs of the users [5, 32]. However, one major issue is the social acceptance of AR HWDs. HWDs are inherently designed for only one user and may lead to isolation of the wearer and exclusion of others [15]. Everyday AR users will be immersed in private and personalized virtual experiences, which could be invisible to collocated others due to privacy concerns [14].

Frequent uses of mobile phones during social scenarios can be considered impolite because it indicates lack of attention to the speaker [1, 16]. Similarly, during conversation, virtual content in AR HWDs might take the user's attention away from the interlocutor, yielding uncomfortable social interactions.

Twenty years ago, Höllerer et al. explored an AR interface that intelligently moved away when it occluded other people's heads in a social space [17]. Similarly, recent work by Orlosky et al. proposed a non-invasive view management AR system that changed its interface layouts automatically to avoid interfering with interpersonal interactions [27]. However, in some cases information could be needed for smooth progression of the conversation, so simply moving or removing the virtual content is not sufficient. While pulling out a mobile phone could be considered socially intrusive and rude, if designed intelligently, AR interfaces have the potential to propose an alternative that can support users' socially prompted information needs in an unobtrusive, quick, and convenient manner that can be perceived as less intrusive and more appealing in social contexts. Our proposed context-aware Glanceable AR solution aims to address these challenges in social contexts with AR HWDs.

3 Context-Aware Glanceable AR

For Glanceable AR interfaces to be accepted as a replacement for proven and familiar technologies like smartphones, it is not sufficient to simply provide more efficient and reliable information access. They must also do so in a wide variety of real-world usage contexts, without causing additional problems such as distraction, safety hazards, or obtrusiveness. At first glance, these design goals may appear to be incompatible. Increased efficiency and productivity can be achieved by using the expansive/immersive display space of AR to display more information, but this approach would inevitably lead to more obtrusiveness, clutter, and occlusion.

Intelligent AR interfaces that are aware of the user's context provide the potential to achieve both these goals. Such interfaces can automatically adapt to the user's context based on different contextual cues, of which the user may or may not be aware. Considering the context, allows the interface to display the right information at the right time in the right place, while also supporting the user's awareness of and interaction with the real world.

We have designed and prototyped a Context-Aware Glanceable AR interface that can adapt to provide a balance of efficiency and unobtrusiveness in multiple contexts. As a proof-of-concept, our interface adapts between two common usage contexts: a static, solo context and a dynamic social context. To our knowledge, our work is the first to prototype a socially aware and supportive Context-Aware AR interface that facilitates conversation between two users and evaluates it in a highly ecologically valid conversation.

In the solo context, the user is seated, stationary, alone, and focused only on a single object (e.g., a book or laptop) in the real-world. The real-world object of interest is somewhere below the user's eye level. Therefore, virtual content that is at the user's eye level will be unobtrusive and will not occlude the object of interest. The interface can also prioritize virtual content (by making it opaque) without distracting the user. This interface for the solo context (Fig. 1a) allows efficient information access (via a quick upward glance) without causing any obstruction or visual clutter.

The interface for the solo context would be completely inappropriate for a social context, however. In the social context, the user is standing and conversing with one or more others. The conversation partners may move, leave the conversation, or join the conversation in progress. Furthermore, some conversation topics may necessitate information access. Thus, the context-aware interface for this context should also be dynamic and intelligent, adapting to both the presence of conversation partners and the topics of conversation. To design a Context-Aware Glanceable AR interface for the social context, we propose three design considerations (DCs). Using the user context, DC1 and DC2 aim to address the existing challenges of AR (i.e., visual clutter and obtrusiveness), while DC3 aims at improving information access efficiency.

DC1. Real-World prioritization. Constantly visible virtual content produces visual clutter and distraction when engaged in dynamic real-world tasks [6]. Our design prioritizes the real-world by keeping the virtual content's level of transparency high (Fig. 2a). This allows the user to see the outline of the content and know where to find the information when needed, but ignore it otherwise.

DC2. Support for viewing social cues. Facial expressions play an important role in social interactions [2]. For example, ostensive gestures such as the eyebrow flash can indicate the intention to communicate and are of great importance to the receiver [12]. If virtual content is blocking the interlocutor's face, the user will miss their facial expressions, just as they would if they were looking down at their mobile phone. Similar to Höllerer et al. [17], we propose that in conversation, the AR interface should not occlude other people's faces, leaving space for sufficient attention and social awareness (Fig. 2b). However, our interface moves the virtual content away only when it occludes the faces of people who are actively engaged in a conversation with the user. This reduces over-generalization of the no-occluded-faces rule and enables the user to place their virtual content anywhere they want without undesired adaptations.

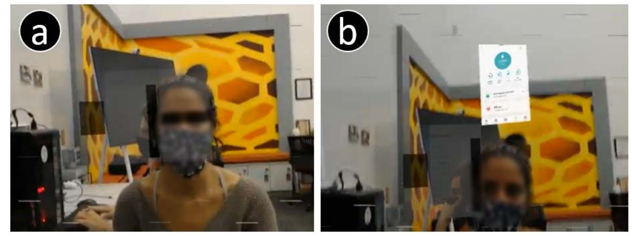

Figure 2: Screenshots of our prototype in the social context. (a) When in conversation, real-world is prioritized by keeping the virtual content's level of transparency high. (b) The desired virtual content is provided automatically based on the content of the conversation without occluding the conversation partner's faces.

DC3. Support for socially relevant information access. Since a significant number of information inquiries arise from something mentioned by others, conversation is a context that prompts many information acquisitions [32]. Based on the content of the conversation, an intelligent interface can support the conversation by automatically providing the desired information, leading to a smooth and less interrupted conversation experience (Fig. 2b). Our interface supports this by automatically making relevant apps opaque based on speech recognition during conversation, and by placing those apps near to the interlocutor's face, but without occluding it.

Fig. 1 illustrates our proof-of-concept context-aware Glanceable AR interface in a social and a solo context. Our system can adapt virtual content placement and transparency automatically to reflect both the static and dynamic aspects of the user's current context.

4 Experiment

To explore the benefits and limitations of Context-Aware Glanceable AR, we evaluated our prototype interface in both solo and social contexts. We also evaluated a naive Glanceable AR interface (without context-awareness), and a mobile phone interface was included as a baseline since it is the most pervasive tool for information access.

4.1 Research Questions

Our study aimed to address three research questions. The first two questions address the benefits of Glanceable AR over mobile phones for information access, while the third question addresses the benefits of context-awareness.

1. Do Glanceable AR interfaces improve the speed and convenience of information access in different contexts, compared to mobile phones? The transition to Glanceable AR interfaces is justifiable only if these interfaces offer more efficient and appealing information access compared to the current gold-standard of mobile phones. Therefore, we designed the study to compare the speed and convenience of information access using Glanceable AR and mobile phones, and to explore the effect of user context on these measures. Is one interface always more efficient and convenient, regardless of the user's context, or does the context influence the benefits of one interface over the other?

2. Compared to mobile phones, does information access using Glanceable AR improve the user experience and focus on the primary task in a solo context? The physical interaction requirements and time-consuming process of information access using mobile phones can distract user's focus from their primary task. We compared Glanceable AR and mobile phones in terms of user experience and distraction from the primary task when accessing information.

3. Do the automatic adaptations in Context-Aware Glanceable AR improve the user experience and reduce social intrusiveness during information access in a social context? In a dynamic social context, naive Glanceable AR may result in occlusion, distraction, and loss of social awareness, and its advantages compared to mobile phones may be lost. We designed our study to compare user experience and social awareness with three interfaces (Context-Aware Glanceable AR, naive Glanceable AR, and mobile phone) for information access during a social conversation, in order to evaluate whether Context-Aware AR can balance efficiency and awareness, retaining the advantages of Glanceable AR while mitigating its weaknesses.

4.2 Experimental Design

In this within-subjects study each participant conducted 5 different sessions. The first two sessions were in a solo context. The next three sessions were conducted in a social context:

4.2.1 Solo Context

The solo session was designed to simulate situations in which a user is doing some real-world activity alone in a static environment, and is motivated internally to access digital information. For example, the user may be reading a book when she thinks to check the current weather. We refer to such questions as Self-Triggered Questions (**STQs**). In our experiment, the user was asked to read an article. While reading, at random times they were asked to use the available interface to answer an STQ (played from a computer). The participants were asked to say the answer and immediately resume reading. Each user performed the session twice: once using the mobile phone and once using Context-Aware Glanceable AR. The order of interfaces was counterbalanced. With both interfaces, the user had access to three different applications: Email, Exercise and Weather. The answer to the STQs were different each time (i.e., the content in the apps changed throughout the session), but the question from each application was always the same ("How many VIP emails do you have?", "How many zone-minutes of exercise have you had today?", and "What is the high temperature on Sunday?"). Each question was asked twice, with a total of six questions per session.

4.2.2 Social Context

The social context was designed to represent an authentic social conversation. In each session, the experimenter would start a conversation with the participant about a specific topic ("Hiking places in the area," "Local food and restaurants," or "Weather"). Throughout, the experimenter asked them questions to keep them engaged in a two-way conversation. Each participant performed the session three times: one time with each of three different interfaces: mobile phone, non-adaptive Glanceable AR and Context-Aware AR. The order of interfaces was counterbalanced with a Latin Square design. In this context the participants were asked to perform three tasks:

Task 1: Answer self-triggered questions. During the conversation at random times the participant answered an STQ, played from a computer, just as they did in the solo context. The participants were asked to say only the answer to the question and immediately resume the conversation without interruption. Each STQ was asked twice, with a total of six STQs per session.

Task 2: Answer conversation-triggered questions. During the conversation, the experimenter would ask the participant to answer specific questions, which we call Conversation-Triggered Questions (**CTQs**), using the interface. The answer to these CTQs were different each time but the question from each application was always the same: ("How many unread messages do you have on your email?", "How many steps have you walked so far today?", and "Do you know by what percentage it is going to rain on Saturday?"). Each CTQ was asked once, for a total of three CTQs per session.

Task 3: Maintain awareness of the conversation partner's facial expression. At certain times during the conversation, the experimenter would wink at the participant. The participants were asked to raise their hand to indicate that they saw the wink. During each session, the experimenter winked at the participant seven times total, three of which were right after a question was asked. This task allowed us to evaluate how the interface affected social awareness.

4.3 Interfaces

To answer STQs and CTQs during the experiment, participants used three interfaces for information access.

Mobile Phone Interface: The participant was given a mobile phone that was placed face down on a table in front of them. To answer a question, participants had to pick up the phone and turn the screen on by swiping up on the display (Fig. 3a). Once turned on, the phone displayed the icons of three apps. Users then tapped on the appropriate app to display a screen from which they could read the answer to the question. To simulate today's most commonly used information access method for answering an unexpected question and to keep conditions similar for answering all questions, we asked participants to go back to the home screen, turn the mobile phone's screen off, and place it face down on the table after answering each question. In our experiment the user only had access to three applications, and was not required to use any password, fingerprint, or face recognition to unlock the mobile phone, making it faster than similar real-world situations.

Glanceable AR Interface: Glanceable AR interfaces are "secondary, concise and Multi-tasking AR interfaces that are user fixed and temporary" [6]. The Glanceable AR interface continuously displayed the three applications at the eye-level of the user. The apps had an identical appearance to those displayed on the mobile phone, but an AR HWD rendered the apps, and all three apps were visible at once. In the social context, since we were interested in investigating the worst-case scenario of using Glanceable AR in a social context, the scene was set so that the virtual content would block the conversation partner's face. Previous work has explored different input modalities, for example, gaze, hand, or head-based interactions to toggle content visibility in the interfaces for a glance [24, 25]. To allow users to decide whether to view the face or the content, users could use a hand-based input (i.e., "air-tap") on individual apps to toggle them between transparent and opaque modes (Fig. 3b).

Context-Aware Glanceable AR Interface: Our context-aware interface actively detects whether the user is in a social context using face and speech detection. Specifically, if our interface detects speech and one or more faces in front of the AR user, this is interpreted as a social context. In the solo context, when no social conversation is detected, the Context-Aware AR interface prioritizes the virtual content (i.e., displays it as opaque, at the user's eye-level), so it is identical to the non-adaptive Glanceable AR interface (Fig. 1 (a)). Thus, there were only two interface conditions in the solo context sessions.

When the social context is detected, the Context-Aware AR interface automatically switches to real-world prioritized mode (i.e., the apps become translucent when not needed (Fig. 1b). Based on the content of the conversation, detected by the speech recognition system, the system identifies when the user needs to access information from one of the apps (i.e., when a CTQ is asked) and automatically makes the app opaque. Since the STQs simulated questions in the user's head, the interface has no knowledge of the user's need for that information. Thus, the user must manually click on the intended

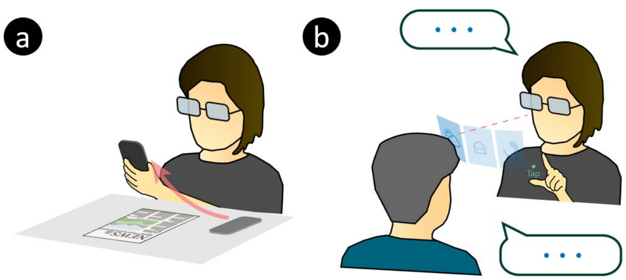

Figure 3: Conditions compared to Context-Aware Glanceable AR in the experiment. (a) Mobile phone interface. (b) Non-adaptive Glanceable AR interface, in which the user can air-tap an app to turn it opaque or transparent.

app to answer STQs. To simulate these questions in our experiment, the wording of our STQs were designed to not be recognized as associated with any of the available apps. If a piece of virtual content is opaque and blocks the conversation partner's face (the position of the face is given by the face detection algorithm), the interface automatically moves it above the face (Fig. 1c). Finally, all opaque apps automatically turn transparent seven seconds after the last time they were activated.

4.4 Metrics

For each context, we assessed the interfaces based on Information Access Efficiency, Intrusiveness to the Primary Task, and Overall User Experience & Preference.

Information Access Efficiency: We measured *information access time* and *perceived ease of information access*. We used the video-recording of the sessions to measure *information access time* (T-Answer), based on how long it took participants to answer a question (from the time the question was asked verbally). *Perceived ease of information access* was evaluated through participant responses to the post-session survey question (seven-point rating scale): "When using the current interface (while reading an article / during the conversation), how easy it was to access information from the apps?"

Intrusiveness to the Primary Task: We measured *time away from the primary task* (T-Away) and *ease of resuming the primary task* after information access in both contexts. We used the video-recording of the sessions to measure the time that the user was away from the primary task (reading or conversation) and interacting with the interface (i.e., holding the mobile device, clicking on the interface, or looking at it). After finishing all sessions for each context, the participants were interviewed and asked to "rank the interfaces from the easiest to the most difficult for resuming reading / conversation) after information access."

For the solo scenario, we measured participants' *self-reported focus on reading*, by asking them in the post-context interview if they felt that they read more of the article using a specific interface.

In the social context, we evaluated *social intrusiveness* by measuring participants' *awareness of others' facial expressions* and their *perception of the interface's social intrusiveness*. We used the video-recording of the sessions to measure the number of times the participant missed the investigator's wink during the conversation. Users' *perception of interface's social intrusiveness* was evaluated through participant responses to a post-session survey question (seven-point rating scale): "when using the current interface during the conversation, how intrusive was the interface to your awareness of the social cues happening around you?"

User Experience & Preference: To assess the user experience (*UX*), we used the standard User Experience Questionnaire (UEQ) after each session [21]. After finishing all sessions for each context, the participants were interviewed and asked to: (1) rank the interfaces based on their *preference* for that context, and (2) describe the advantages and disadvantages of each interface in that context.

Participants' *tendency to adopt AR* for their daily information access was evaluated through their responses to a five-point rating-scale question asked before and after the study: "If you had access to lightweight AR eyeglasses, how likely do you find it to use them instead of your mobile phone for your daily information access? Please explain why."

4.5 Hypotheses

We developed and tested the following hypotheses.

Information Access Efficiency:

H1. Since using the mobile phone involves physical interaction, more steps, and increased workload, the mobile phone will be the least efficient interface for information access in both contexts.

H2. In the social context, the Context-Aware AR interface will take significantly less time for answering CTQs than the other two interfaces, because it automatically makes the required content available to the user.

Intrusiveness to the Primary Task:

H3. In the solo context, Context-Aware AR will be less intrusive to the user's primary task of reading than the mobile phone, since information acquisition will be faster and less cognitively demanding.

H4. In the social context, Context-Aware AR will be the least intrusive interface to the conversation, since the virtual content automatically defaults to transparent when not needed, and the conversation partner's face is never occluded.

H5. In the social context, the non-adaptive Glanceable AR interface will be more *socially intrusive* than the mobile phone, since the virtual content in Glanceable AR can occlude the conversation partner's face.

User Experience & Preference:

H6. In both contexts, Context-Aware AR will be the best interface in terms of user experience and overall ranking.

H7. In the social context, mobile phone will be the worst interface in terms of user experience and overall ranking.

H8. Users' reported tendency to adopt AR as their primary information access tool will increase from the beginning of the study to the end of the study, due to their exposure to Context-Aware Glanceable AR.

4.6 Participants

We gathered data from 36 participants (14 female), between 18 and 45 years of age (M = 26.53, SD = 6.06), recruited from our local university community. Nearly half of the participants (17) had little to no experience with AR/VR, and only two had used AR/VR more than 10 times.

4.7 Apparatus

For the mobile phone interface, we used a Samsung Galaxy S7 device. We designed a web app for the mobile phone interface in Python 3 using the Flask package. The web app was running on a Virtual Machine (VM) Server at our university (12 Core, ARCH: x86_64, RAM 32 GB, OS: Ubuntu 20.04).

For the AR interfaces, the experiment used a Microsoft HoloLens (1st gen) AR HWD. This device is wireless and has a resolution of 1268 x 720 per eye and 30 deg x 17 deg FoV. The software was developed via Unity 2018.4.22f1 using the MRTK toolkit provided by Microsoft.

For the Context-Aware AR interface we developed a face detection system using Python 3. We used the OpenCV Deep Neural Network (DNN) Module, with caffemodel as our pre-trained neural network. We ran the face-detection on our VM Server. Using Python 3 sockets, we made a low-level network connection to the HoloLens device to receive the image from the HoloLens camera and send back the bounding-box around each detected face. On the HoloLens, we used UnityEngine.XR.WSA.WebCam to capture a photo from the HoloLens camera. The UnityEngine.Networking module was used to send the image to the server and receive the face detection results. By transforming the bounding box of the detected face from the camera space to the screen space, we detected whether any of the virtual apps was blocking a detected face. Using MRTK speech recognition and Dictation Recognizer, we detected whether someone was speaking, and if so, whether the content of the conversation contained keywords (e.g., "rain" or "exercise") related to one of the available apps. This fully implemented context-aware interface was used during the user study, without any manual intervention by the experimenter.

All the sessions were also video-recorded by a Logitech C615 HD Webcam with 1080p resolution for comprehensive observation of user behaviors.

4.8 Procedure

The experiment was divided into two parts. In the first part, participants completed two sessions, one with each interface, in the solo context. In the second part, participants completed three sessions, one with each interface, in the social context.

This study was approved by the Institutional Review Board of our university. Upon arrival we welcomed participants and asked them to read the consent form, if they had not already, and sign it. We then asked them to fill out a pre-study questionnaire to collect demographic information and prior experience with AR, and to answer to one question regarding their tendency to adopt AR for daily information access. Next, the participants were introduced to the experiment background, hardware, and the sessions and contexts involved in the study. When participants had no further questions, we introduced the first part of the study, the solo context, and the tasks involved in this part to the participant. Afterwards, the participant experienced each interface (Context-Aware AR and mobile phone) in separate sessions. After the first part, the second part of the study, the social context, and the tasks involved in this part were introduced to the participant. Afterwards, the participant experienced each interface (Context-Aware AR, non-adaptive Glanceable AR, and mobile phone) in separate sessions.

Before each of the five sessions, the participant completed training to get familiar with the tasks and interface. After each session, participants were asked to fill out a custom-designed questionnaire and the UEQ on a computer. In our post-context interview, after each part of the study, the participant was asked about the interfaces they used in that context, their preferences, and the advantages and disadvantages of each interface.

After finishing both parts (all five sessions), participants were interviewed about their overall experience in both contexts, the benefits and disadvantages of each interface in each context, and their tendency to adopt AR for daily information access. The entire experiment took about 75 minutes. Participants were allowed to take a break anytime in between sessions.

5 Results

We conducted a series of analyses to test our hypotheses and explore the trade-offs between the interfaces for each context individually. For all the analyses, therefore, we separated the data based on the context. Shapiro-Wilk tests found that our data was not normally distributed. As such, we ran non-parametric Friedman tests to test the significant effect of independent variables. Wilcoxon signed-rank tests were conducted for pairwise comparisons with Bonferroni corrections applied. We also used Wilcoxon signed-rank tests for our qualitative data collected from the questionnaire and interview. We used an α level of 0.05 in all significance tests.

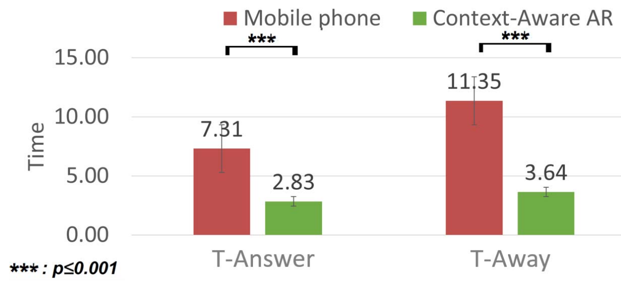

Figure 4: Time to answer questions (left) and time away from the reading task (right) in the solo context.

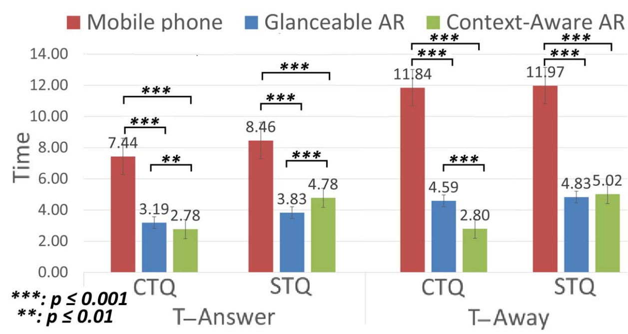

Figure 5: Time to answer questions (left) and time away from the conversation (right) for both question types in the social context.

5.1 Information Access Efficiency

We evaluated the effect of interface on *information access time* (T-Answer) in both contexts. In the solo context, a Wilcoxon signed-rank test ($Z = 17.62, p < 0.001$) revealed that Context-Aware AR ($M = 2.83$) was significantly faster than the mobile phone ($M = 7.31$) (Fig. 4, left).

In the social context, a Friedman test on T-Answer for CTQs ($\chi^2(2) = 162.66, p < 0.001$) and STQs ($\chi^2(2) = 226.8, p < 0.001$) revealed that the type of interface had a significant effect on *information access time* for both question types. Pairwise Wilcoxon signed-rank tests showed that answering both question types took significantly longer using the mobile phone. For CTQs, mobile phone ($M = 7.44$) took significantly longer than both Glanceable AR ($M = 3.19$) ($Z = 12.16, p < 0.001$) and Context-Aware AR ($M = 2.78$) ($Z = 12.09, p < 0.001$). For STQs, mobile phone ($M = 8.46$) took significantly longer than both Glanceable AR ($M = 3.83$) ($Z = 15.34, p < 0.001$) and Context-Aware AR ($M = 4.78$) ($Z = 13.07, p < 0.001$). These pair-wise tests also revealed that compared to Glanceable AR, Context-Aware AR significantly reduced T-Answer for CTQs ($Z = 2.98, p = 0.009$), but it significantly increased T-Answer for STQs ($Z = -5.33, p < 0.001$) (Fig. 5, left).

We also evaluated the effect of interface on *perceived ease of information access*. In the solo context, a Wilcoxon signed-rank test revealed that Context-Aware AR ($M = 6.11$) was perceived as significantly easier compared to mobile phones ($M = 4.69$) ($Z = -3.85, p < 0.001$).

In the social context, a Friedman test showed a significant effect of interface ($\chi^2(2) = 27.469, p < 0.001$) on *perceived ease of information access*. Pairwise Wilcoxon signed-rank tests revealed that mobile phone ($M = 3.83$) was perceived as significantly more difficult than both Glanceable AR ($M = 5.42$) ($Z = -4.14, p < 0.001$) and Context-Aware AR ($M = 5.64$) ($Z = -4.78, p < 0.001$).

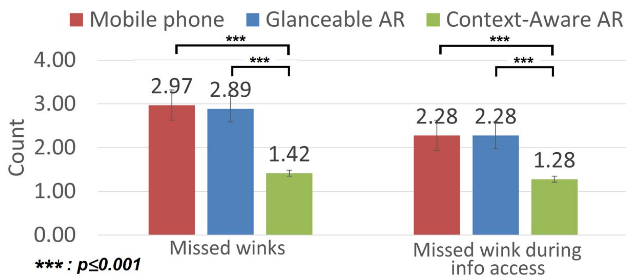

Figure 6: Missed social cues overall (left) and during information access (right) in the social context.

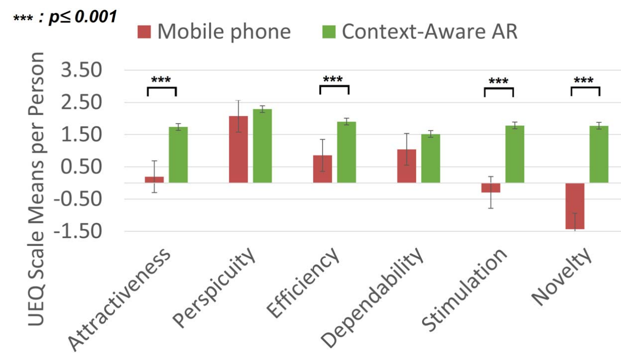

Figure 7: UEQ results in the solo context.

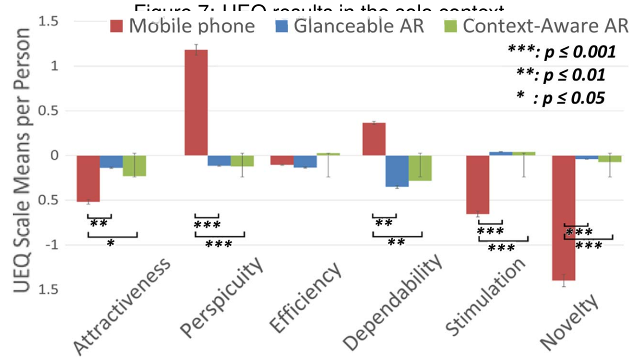

Figure 8: UEQ results in the social context.

5.2 Intrusiveness to the Primary Task

We evaluated the effect of interface on the user's *time away* from their primary task when accessing information. In the solo context, a Wilcoxon signed-rank test on T-Away revealed that Context-Aware AR ($M = 3.64$) significantly reduced *time away* from reading, compared to mobile phones ($M = 11.35$) ($Z = 17.98, p < 0.001$) (Fig. 4, right).

In the social context, a Friedman test for CTQs ($\chi^2(2) = 181.45, p < .001$) and STQs ($\chi^2(2) = 268.6, p < .001$) revealed a significant effect of interface on the user's *time away* from the conversation. For each question type, we ran Wilcoxon signed-rank tests on each interface pair. The test results showed that *time away* from the conversation was significantly longer with the mobile phone. For CTQs, T-Away for the mobile phone ($M = 11.84$) was significantly higher than for both Glanceable AR ($M = 4.59$) ($Z = 11.92, p < 0.001$) and Context-Aware AR ($M = 2.8$) ($Z = 12.39, p < 0.001$). For STQs, T-Away when using mobile phone ($M = 11.97$) was significantly higher than both Glanceable AR ($M = 4.83$) ($Z = 16.02, p < 0.001$) and Context-Aware AR ($M = 5.02$) ($Z = 16.01, p < 0.001$). We also found that, compared to Glanceable AR, Context-Aware AR significantly reduces T-Away for CTQs ($Z = 6.99, p < 0.001$) (Fig. 5, right).

We asked participants to rank the interfaces based on *ease of resuming the primary task* after information access. In both contexts, most participants (97% in the solo context and 67% in the social context) considered Context-Aware AR as the easiest to resume the primary task. In the social context, 72% ranked mobile phone as the most difficult.

In the solo context, the participants were given the same amount of time to read the article in both sessions. However, their *self-reported focus on reading* indicates that 75% read more and understood the article better when they were using Context-Aware AR.

We also evaluated the *social intrusiveness* of the interfaces. A Friedman test on the total number of missed winks during the conversation ($\chi^2(2) = 36.24, p < .001$) and the number of missed winks during information access ($\chi^2(2) = 25.35, p < .001$) revealed significant effects of interface on *awareness of others' facial expressions* (Fig. 6). Wilcoxon signed-rank tests for each interface pair showed that users missed a significantly smaller number of winks overall, and even during information access, when using Context-Aware AR. Using Context-Aware AR ($M = 1.42$) significantly reduced the total number of missed winks compared to both Glanceable AR ($M = 2.89$) ($Z = 4.36, p < 0.001$) and mobile phone ($M = 2.97$) ($Z = 4.66, p < 0.001$). During information access, Context-Aware AR ($M = 1.28$) significantly reduced the number of missed winks compared to both Glanceable AR ($M = 2.28$) ($Z = 4.4, p < 0.001$) and mobile phone ($M = 2.28$) ($Z = 4.3, p < 0.001$).

A Friedman test showed a significant effect of interface on participants' self-reported *perception of interface's social intrusiveness* ($\chi^2(2) = 19.451, p < 0.001$). Wilcoxon signed-rank tests for each pair showed that mobile phone ($M = 5.44$) was perceived as significantly more intrusive than both Glanceable AR ($M = 3.64$) ($Z = 3.64, p < 0.001$) and Context-Aware AR ($M = 4.14$) ($Z = 3.88, p < 0.001$).

5.3 User Experience & Preference

Context-Aware AR was ranked first for *preference* by the majority of participants (89% in the solo context and 64% in the social context). In the social context, 64% of our participants ranked mobile phone as their least preferred.

We performed Wilcoxon signed-rank tests for each interface pair on our UEQ results from both contexts to compare *UX aspects*. In the solo context, Context-Aware AR was significantly higher in attractiveness, efficiency, stimulation, and novelty (Fig. 7). For the social context, compared to mobile phone, both Context-Aware AR and Glanceable AR had significantly higher attractiveness, stimulation, and novelty and lower dependability and perspicuity (Fig. 8).

Finally, a Wilcoxon signed-rank test ($Z = 2.44, p < 0.01$) on the participants' *tendency to adopt AR* comparing their responses before the study with those afterwards showed that participating in the study significantly increased their tendency to adopt AR for their daily information access ($M_{pre-Study} = 3.28$, $M_{post-Study} = 3.89$).

6 Discussion

6.1 Information Access Efficiency

In **H1** we hypothesized that the mobile phone will be the least efficient interface for information access in both contexts. Our results support this hypothesis by showing that, compared to the other two interfaces, the mobile phone increased *information access time*, regardless of the context or question type, and was *perceived as more difficult* for information access in both contexts. The study also showed that Context-Aware AR took less time for answering CTQs than the other two interfaces, supporting **H2**.

Together, this constitutes strong evidence that Glanceable AR can provide rapid information access with a quick glance, and that the expansive and persistent display provided by Glanceable AR has important benefits over mobile phones. Moreover, in the social context, we showed that automatic activation of apps based on conversational content can be a powerful way to support information access in a social situation, without requiring any manual interaction.

6.2 Intrusiveness to the Primary Task

When using the Context-Aware AR interface in the solo context, our participants spent less *time away* from reading, felt it was *easier to resume reading* after information access, and reported *higher focus on reading* compared to the mobile phone. This supports **H3**, that Context-Aware AR is less intrusive to the user's primary task.

Meanwhile, **H4** was partially supported by our data. When using Context-Aware AR, participants took the least *time away* for information access, but only when answering CTQs. They also perceived the interface as the *easiest for resuming the conversation* after information access and less *socially intrusive* compared to mobile phones. Finally, they had the most *awareness of the interlocutor's facial expressions* in the Context-Aware condition.

We also noticed that participants occasionally missed the STQ, either completely ignoring the question or forgetting it. Only 20% of these missed questions occurred with Context-Aware AR, compared to 54% with the mobile phone, which indicates a greater ability to effectively multi-task with Context-Aware AR.

Together, the results from **H1-H4** demonstrate that our Context-Aware Glanceable AR prototype achieved its goals of balancing rapid information access with minimal intrusion on the primary task. In the solo context and in the case of CTQs in the social context, the Context-Aware condition automatically both ensures the visibility of needed content at a glance, and avoids occlusion of the primary task. In the worst case (STQs during a conversation), the user still has to manually interact to activate an app, but this is still significantly faster than the mobile phone and results in less time away from the conversation. We speculate that the non-adaptive Glanceable AR had less time away than the Context-Aware condition for STQs because participants waited for the app to automatically become opaque before deciding to click on it themselves.

H5 hypothesized higher *social intrusiveness* of the non-adaptive Glanceable AR compared to the mobile phone, but our results do not support this hypothesis. We found no significant difference in participants' *awareness of other person's social expressions*, or in their self-reported *perception of the interface's social intrusiveness*. We can explain this finding by observing that all participants manually made the apps translucent during the conversation, only activating them during information access. When using the mobile phone, time away from the conversation was longer due to the multiple steps of interacting with the device, and participants found it difficult to focus on the conversation or detect the social cues during this time of interaction with the device (T-Away).

6.3 User Experience & Preference

Our results partially support **H6** and **H7**. In both contexts, Context-Aware AR was ranked as the *most preferred*, and mobile phone as the *least preferred* interface. Context-Aware was also rated significantly higher than mobile phone on the UEQ factors of attractiveness, stimulation and novelty in both contexts. On the other hand, mobile phone had significantly higher ratings for perspicuity (i.e., ease of understanding) and dependability in the social context, which is reasonable since users have high familiarity and experience with mobile phone interfaces. In addition, we did not find any significant advantages of Context-Aware over non-adaptive Glanceable AR on any of the UEQ factors. We suggest that these results may be explained by general uneasiness about automatic adaptations in the Context-Aware condition. Many users expressed concerns of this sort, such as: "What if I don't need something and it keeps opening the content?" and "What if I need other applications?"

Our results on users' reported tendency to adopt AR as their primary information access tool indicated an increase from the beginning of the study to the end of the study, supporting **H8**. This suggests that experience with our Context-Aware Glanceable AR prototype helped participants envision the potential benefits of someday replacing their smartphones with intelligent AR glasses.

7 Limitations and Future Work

This study aimed to compare the most commonly used interface for daily information access against a glanceable AR interface accessible through all-day wearable eyeglasses. We assume that future lightweight AR glasses will stay unlocked as long as they are worn after being "logged in" once the user puts them on. We also assume such devices will become commonplace and socially accepted. However, these assumptions might not prove to be fully accurate, potentially limiting the validity of our results. Our prototype only supported two contexts. However, a Context-Aware Glanceable AR interface must differentiate and adapt to various daily contexts. This raises research questions regarding the definition of AR user contexts and proper adaptations to them.

Design Limitations: We limited our prototype to three Glanceable apps and used air-tap interactions for both contexts. Our interface focused on occlusion and intrusiveness challenges in AR and improving information access (**DC1, DC2, DC3**), adapting the content prioritization, virtual content's translucency and placement. Future studies should identify and address other challenges of AR and investigate Context-Aware interfaces that intelligently adapt the interaction technique and the group of available apps.

User Study Limitations: Our participants' familiarity and experience with the three interfaces was not equal, which could have biased against the AR conditions, and the Context-Aware AR condition in particular. This actually makes our positive results about AR even stronger, but it also helps to explain why Context-Aware AR did not completely live up to our expectations. Furthermore, the Context-Aware AR condition had a significant computational load, even though the computer vision and speech recognition were done on a remote server. This made performance of the Context-Aware condition less than ideal, especially when users needed to manually air tap on apps. This also helps explain some of the missed expectations. Future studies should also examine the effects of Context-Aware AR use on both sides of a social situation and on larger social situations with more than two participants, since we did not evaluate how Context-Aware AR or the other conditions affect the perceptions or social acceptance of the interlocutor.

8 Conclusions

In this work we designed a Context-Aware AR interface to intelligently adapt to changes in the user's context. The interface is designed for a static solo context and a dynamic social context. In the solo context the interface prioritizes the virtual content and places it at the user's eye-level, while in the social context, the interface prioritizes the real world, and based on the conversation's content, automatically makes the related virtual content available in a non-occluding manner. Our results largely validated our hypothesized benefits of the Context-Aware Glanceable AR approach, showing its advantages for information access efficiency, avoiding negative effects on primary tasks or social interactions, and overall user experience. We conclude that for Glanceable AR apps to be a viable replacement for smartphones to support everyday information access needs in a variety of real-world scenarios, an intelligent, adaptive, context-aware approach will be critical.

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