Push2AR: Enhancing Mobile List Interactions Using Augmented Reality

Jonathan Wieland*
HCI Group, University of Konstanz, Germany
HCII, Carnegie Mellon University, United States

Hyunsung Cho†
HCII, Carnegie Mellon University, United States

Sebastian Hubenschmid‡
HCI Group, University of Konstanz, Germany

Akihiro Kiuchi§
The University of Tokyo, Japan
HCII, Carnegie Mellon University, United States

Harald Reiterer¶
HCI Group, University of Konstanz, Germany

David Lindlbauer‖
HCII, Carnegie Mellon University, United States

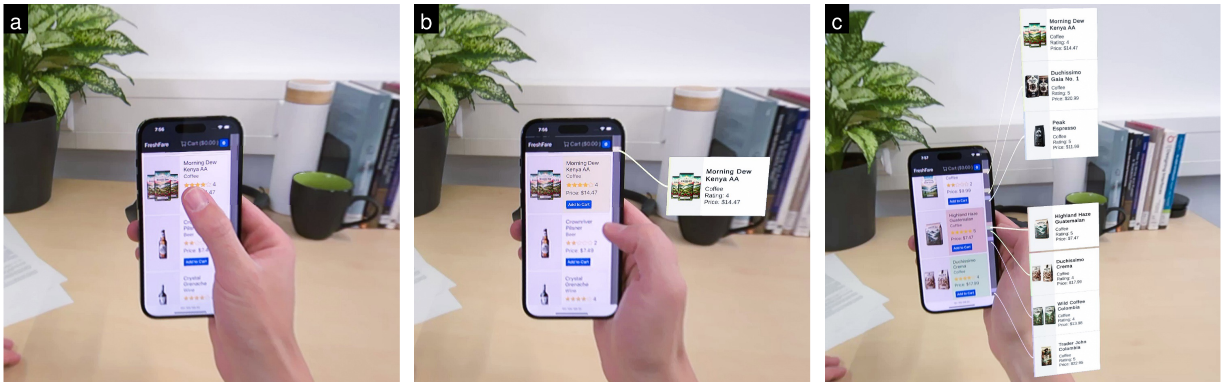

Figure 1: We present *Push2AR*, a novel interaction concept that enhances scroll list interaction on phones by pushing list items to the AR space. (a+b) The user bookmarks an item by swiping right on it to slide it into the AR space. (c) The position of bookmarked items in AR are synchronized with their respective position on the smartphone. Items outside the smartphone's screen space are gradually stacked at the top and bottom. *All photos are live recordings from the head-mounted display.*

ABSTRACT

Smartphones provide convenient access to vast data collections (e.g., online shops, social media) within a compact, portable form factor. While the prevalent infinite scroll lists address the inherently restricted screen space, they also introduce navigation and orientation challenges. Users often lose track of their position within these lists and find it difficult to efficiently access, compare, and filter items of interest. To address this challenge, we introduce *Push2AR*, a novel interaction concept that extends the phone's high-resolution display and familiar touch interaction with the virtual display space offered by Augmented Reality (AR) headsets. *Push2AR* enables users to transfer individual list items from their phone to its surrounding AR space, facilitating bookmarking, filtering, and side-by-side comparisons while maintaining orientation through visual links to the original scroll position. Our evaluation shows that our approach enhances user experience and reduces subjective workload involved in locating and comparing list items in contrast to conventional phone-only lists.

Index Terms: Augmented reality, mobile devices, cross-device interaction.

1 INTRODUCTION

Users frequently navigate large amounts of digital information, with activities such as browsing through news articles, comparing products while online shopping, or scrolling through social media feeds. This typically involves list-based web browsing interfaces that are designed for the limited confines of mobile device screens. Such interfaces, while functional, are constrained by the dimensions of the screen, often requiring excessive scrolling and switching between tabs to access and compare information. This traditional method can introduce visual clutter and increase users' cognitive load as they attempt to comprehend and interact with large amounts of data on a small display [18].

To overcome these challenges, we explore the complementary use [59] of Augmented Reality (AR) using head-mounted displays (HMDs) to expand the potential of mobile interfaces for list-based interactions, aiming to improve user engagement and efficiency in data interaction. With ongoing technological advances, AR HMDs may soon become as ubiquitous as smartphones and are already worn by enthusiast on a daily basis, showcasing their rapidly improving versatility and wearability. We thus argue that operating a phone while wearing an HMD will soon be commonplace. Prior work has already shown that, for example, offloading menus to the phone's surrounding AR space (e.g., [6, 32, 50, 60]) can be used to increase the available screen real-estate [6, 24].

Building on this work, we propose *Push2AR*, a novel hybrid interaction concept that leverages the complementary combination of mobile and AR technologies by projecting user interface (UI) elements from mobile web browsers into the AR space surrounding the smartphone. We address navigation and orientation challenges in ubiquitous list interactions by using the large AR screen real estate to expand users' information and interaction space while maintaining the familiarity and precise touch interaction of smartphones.

Our approach is illustrated in Figure 1. A user is scrolling

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*e-mail: jonathan.wieland@uni-konstanz.de
†e-mail: hyunsung@cs.cmu.edu
‡e-mail: sebastian.hubenschmid@uni-konstanz.de
§e-mail: aki8704927483@g.ecc.u-tokyo.ac.jp
¶e-mail: harald.reiterer@uni-konstanz.de
‖e-mail: davidlindlbauer@cmu.edu

through a list of items while online shopping (Fig. 1a). Once they find an item to bookmark, they simply "push" the item to the AR space by sliding the finger from the item on the phone to the right (Fig. 1b). Positions of these AR items are synchronized with scroll positions of respective items on screen. Using *Push2AR*, users extract and bookmark items of interest to make comparisons among large amounts of data (Fig 1c). *Push2AR* further provides interactive *scroll bar indicators* that map the pushed items to their location on the phone. They serve as a bridge between the mobile and AR interaction spaces, allowing users to quickly jump to an item on the phone by tapping on its scroll bar indicator. By allowing users to interact with large data sets through familiar gestures, our concept leverages the strengths of both AR and smartphone usability.

We evaluated our approach in a user study with 16 participants and compared it against a smartphone-only web-browsing baseline to answer the research question on how *Push2AR* affects interaction efficiency, task load, and satisfaction. Users reported lower task load and higher levels of satisfaction when navigating through dense information using the AR space, but exhibited higher task completion times. Based on the user study feedback, we highlight advantages of cross-device [7] and cross-reality [2, 14] interaction and discuss future work to further utilize the expansive AR interaction space combined with familiar and efficient tactile mobile interaction.

In summary, we contribute the novel interaction concept *Push2AR* for pushing list items into a phone's surrounding AR space, together with a detailed description of our design and open-source implementation. We furthermore contribute insights from a user study ($n = 16$) and demonstrate the applicability of our prototype with different scenarios.

2 RELATED WORK

We review prior work on *list navigation* methods and discuss the potential of *screen extensions* in AR. While there is a large body of work exploring content transformations between 2D and 3D spaces (e.g., [33, 53]) or content extraction from websites (e.g., [35]), they do not align with our primary focus and are thus not discussed here.

2.1 List Navigation

Despite being *"irritatingly slow"* [43] compared to paper documents, scrolling through information landscapes is a pervasive navigation method on both desktop and mobile devices. We discuss list navigation in terms of *scrolling behavior* and *scroll indicators*.

Scrolling behavior describes how the user navigates through a list (e.g., inertial scrolling on a smartphone). On the desktop, prior work has improved scrolling behavior by automatically changing the zoom level based on scroll speed [10, 25], using fisheye distortion [54], or keeping important information (e.g., headings) briefly on screen [34]. By utilizing reality-based interaction paradigms [26] on smartphones, prior research has also improved scrolling methods by introducing pinching gestures [17], applying artificial friction to items of interest [29], or using tilt-based scrolling instead of touch input [13, 42].

In contrast, interactive *scroll indicators* (e.g., scroll bars) help to visualize the user's current position relative to the document, allowing users to *"frequently return to previously-visited regions"* [1]. To further support revisitations and navigation, prior work has explored different augmentations of these scroll indicators on the desktop, for example by adding artificial landmarks [39], semantic segments [27], histograms [20], search results [9], or even the entire document [37] to the scroll bar. Specific to this work, prior research has investigated the addition of visual indicators (e.g., bookmarks) to the scroll bar [1, 31, 44], resulting in decreased navigation time for revisitations [1]. In addition to visual indicators, Alexander et al. [1] studied the use of thumbnails, thus providing a visual preview of these indicators to further improve navigation. Although desktops provide enough space for thumbnails, we argue that such thumbnails might be either too small or take up too much screen space on a smartphone to be useful. Prior work has also demonstrated that visual links can direct a user's attention between distinct areas of interest [55, 56], potentially strengthening the connection between thumbnails and scroll indicators.

2.2 Screen Extensions

Since the constraints of smartphones limit the available screen space, research in the field of cross-device interaction [7] has explored different methods for screen extensions. For example, Rädle et al. [52] proposed a system to dynamically track and combine mobile devices, thus distributing parts of one device's UI to other devices. However, such approaches are still restricted to the screen space and layout afforded by available physical devices.

Instead, cross-reality approaches [2, 14] with HMDs may be used to dynamically increase the available screen space while preserving the advantages of interacting with a familiar device (e.g., smartphone) and allowing users to work within any environment [16] comfortably. By combining *"heterogeneous display and interaction device technologies"* [12], these hybrid user interfaces can be used to extend devices such as display walls [51], desktops [12, 45, 48], tabletops [8, 46], tablets [23, 32, 58], smartphones [24, 30, 49], and smartwatches [15] through AR HMDs. The concept of "pushing" and "pulling" content between realities has also been explored in the context of projector-based AR [19], allowing for intuitive interaction between smartphone and AR environment. Similarly, Wu et al. [58] proposed "MergeReality", allowing users to "pull" sticky notes from a phone into AR.

Building on the screen extension metaphor, Normand & McGuffin [41] proposed to use hybrid user interfaces to create virtually extended screen-aligned displays (VESADs), potentially improving spatial memory and user experience for spatial navigation [24, 28] and task performance [15, 41]. Here, prior research has proposed and explored different use cases, such as offloading menus into AR [6,32,50,60]. For example, Brasier et al. [6] found that offloading UI elements to AR can free up valuable screen space with little impact on performance. Recent research also shows that this concept can be extended to virtual reality by replicating the smartphone screen [61], or using a tablet for mobile scenarios [4]. However, the concrete benefits of VESADs for list navigation purposes and their interplay with content on the phone have yet to be explored.

3 PUSH2AR

We introduce the novel interaction concept *Push2AR*, illustrated in Figure 2. It addresses the following challenges in list interactions on phones resulting from limited screen space.

Offloading. The small screen space can only show a limited amount of information at a time. Users need to *memorize* items of interest, or *offload* them to individual tabs or separate lists (e.g., *favorites* or *cart*). This introduces additional switching cost between the original list and the additional tabs or lists of bookmarked items. Furthermore, this offloading can lead to the creation of additional lists, which themselves can become too long for efficient navigation. *Push2AR* aims to reduce this switching cost by leveraging the AR space for always-available side-by-side comparison. We explore an efficient design to prevent such information overload of the user's space while providing in-situ information.

Limited Awareness of Item Location. List interactions on phones, such as offloading, limit users' awareness of where items are located in the list. Even if an item is saved for later in the bookmarks list, the information of where the item was originally located in the list is often lost. This information, however, might be useful for comparisons and sensemaking. To overcome this, *Push2AR* creates spatial links between the offloaded information and its original position on the list (see [55, 56]).

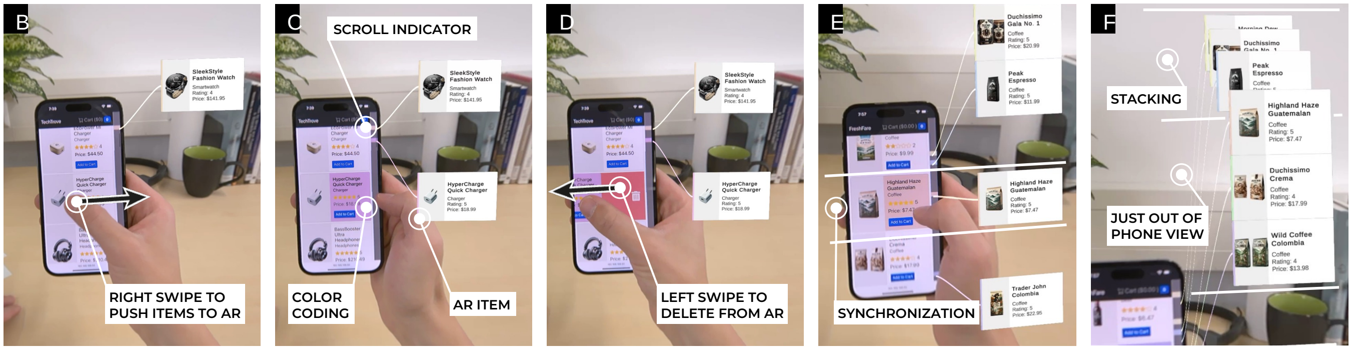

Figure 2: Interaction concept of *Push2AR*. (a) Users can swipe right on a list item on the smartphone to initiate the push gesture. (b) Once the swipe gesture crosses a predefined threshold, the list item is pushed to AR and appears as a brief summary on the right side of the smartphone as well as a colored indicator on the smartphone's scroll bar. (c) AR items can be removed from AR by swiping left on the corresponding smartphone list item. (d) AR items are synchronized to their corresponding item's position on the smartphone screen. (e) AR items that are no longer within the smartphone's viewport are stacked and gradually moved behind each other to keep them in the field of view of the AR HMD.

3.1 Interaction Concept

To address aforementioned challenges, our *Push2AR* approach allows users to *push items to AR*, which are then affixed to the right side of the smartphone and move in sync with the device. *Push2AR* further provides an interactive *scroll indicator*, and enables *synchronization and stacking* for AR items. All interactions with the AR items are performed on the touchscreen of the smartphone to leverage its tactile feedback and precise input.

Push Items to AR. Users can *push* list items into AR by swiping right on a list item on supported websites on the smartphone (Fig. 2a). During the swipe gesture, the item is moved right matching the user's touch position. If the swipe gesture crosses a predefined threshold, a matching AR item using the item's metadata (i.e., image, title, and description) is created to the right of the smartphone, indicating that the item has been "pushed" to AR (Fig. 2b). After the swipe gesture, the list item on the smartphone is reset to its original position. To further strengthen the connection between smartphone and AR item, a random pastel color is assigned to the background color of the smartphone item, the left border of the AR item, connecting line, and scroll indicator. Bookmarked items can be removed again by swiping left on the bookmarked item on the smartphone, which shows a red indicator with a 'delete' icon as the item is moved left (Fig. 2c).

Scroll Indicator. Once an item is pushed to AR, *Push2AR* adds a custom scroll bar (see [1, 31, 44]) on the right screen border with colored indicators for each bookmarked item (Fig. 2b). Each indicator shows the position and height of bookmarked items relative to the entire height of the list and is updated whenever the scrolling list is adjusted (e.g., in case of infinite scrolling). In addition, each indicator serves as an anchor point, connecting the bookmarked items on the phone to the AR items through a Bézier curve. Users can use the scroll indicators to quickly jump between bookmarks by touching the relevant indicator. We argue that keeping the input space on the phone, rather than expanding to AR, is beneficial since it is familiar to users and provides highly accurate tracking.

Synchronization and Stacking. Once bookmarked, the AR item's vertical position is synchronized with its position on the smartphone (e.g., when scrolling, see Fig. 2d). If the item is no longer within the smartphone's viewport, the AR items are stacked at the top or bottom of the AR space, depending on the list item's position on the smartphone (Fig. 2e). We differentiate between three zones to best utilize the surrounding space [24], support comparisons, and reduce clutter: (1) AR items that are currently visible on the smartphone screen appear directly to the right of their smartphone counterpart; (2) Up to three of the closest items that are no longer visible on the smartphone's screen are lined up at either the top right or bottom right of the smartphone (Fig. 2e *Just Out of Phone View*); (3) All other items are gradually stacked behind each other to keep them within the HMD's field of view, reduce clutter, and still provide a rough estimate of how many items were bookmarked (Fig. 2e *Stacking*).

3.2 Scenarios

Push2AR can be used in a variety of usage scenarios for list interactions. Figure 3 shows a set of scenarios, which can be largely categorized into information *comparison* and *collection* by the individual activities.

Examples of list interactions for comparison include finding an item in the list that best fits the user's needs and queries, such as finding a restaurant (Fig. 3a), shopping for an item, booking a hotel, and finding a movie to watch (Fig. 3b). Finding the best option among a list of items involves a series of comparisons between different properties or attributes (e.g., price, duration, and quality) of each item, given the user's constraints (e.g., budget, time, and preference). *Push2AR* supports comparisons among list items by providing a side-by-side view of items, utilizing the AR space.

Information collection has a different goal of foraging multiple, diverse information, such as literature search (Fig. 3c), web search (Fig. 3d), creating a watch list of videos, and creating music playlists. The process may still involve comparison, for example checking if an item has been already added, but may also involve substantial subjective factors that cannot be captured by objective filtering (e.g., selecting songs for a playlist). However, the main goal of the activity is to form a curated list among a myriad of information. *Push2AR* facilitates information collection by offering to create a curated list by pushing items to AR space, reviewing previously added items through easy navigation using scroll indicators, and deleting the items with a swipe.

3.3 Implementation

We divide the implementation into a *web extension* for the smartphone and an *AR application* for the HMD. A Colibri [21] server handles communication between the smartphone and AR HMD, while study data was logged using ReLive [22].

The *web extension* is written in TypeScript and works with all compatible browsers (e.g., Chrome, Firefox, Safari) via Manifest V3. This allows us to inject our own code (e.g., event handlers and websockets) into any website. When swiping on a list element, we identify list items by looking through parent elements until we find

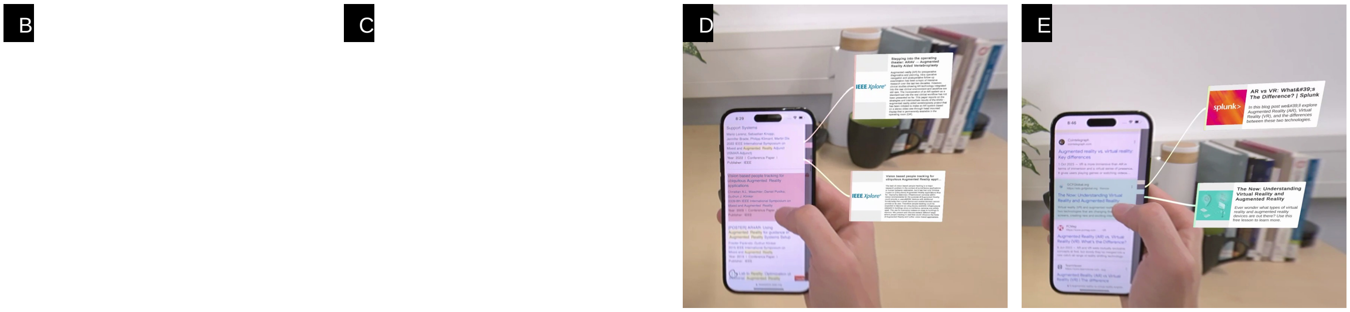

Figure 3: As a proof of concept, we demonstrate how different application scenarios can benefit from our novel interaction concept. Users can use *Push2AR*, e.g., to (a) decide on a restaurant, (b) find a movie to watch, (c) collect related work, (d) or search for interesting web pages.

either a commonly-used list element (i.e., `<li>` or `<article>`), or a significant amount of siblings with matching CSS classes. Once identified, we use the browser's API to extract the element's height, look for a valid link within the list element, and send both to the AR application. We also listen to relevant events (e.g., scroll events) and use the browser's API to determine item and viewport position. This is then continuously sent to the AR HMD and transformed into the appropriate position (e.g., to synchronize scroll positions).

Once a link is received from the smartphone, the *AR application* retrieves and extracts relevant Open Graph[1] data (e.g., image, title, description) from the website's metadata. This information is formatted using a generic template to reconstruct the item with the same height as the item on-screen. The *AR application* is implemented in Unity 2022.3 and can thus be deployed to most current AR HMDs. Our prototype is available as open source project.[2]

4 USER STUDY

We evaluated *Push2AR* in a controlled lab study. We compared our interaction concept with the traditional *Phone* interface for scroll lists while participants perform a shopping task in terms of performance, workload, and user experience.

4.1 Participants

We recruited 16 participants (4 female, 12 male, all right-handed) between 18 and 38 years ($M = 25.13$, $SD = 4.73$). Participants were students ($n = 14$) from a local university or employees ($n = 2$) with different backgrounds (e.g., audio research, industrial design, computer science, robotics, medicine, bio-engineering, accounting, music, and electrical engineering). On a scale from 1 ("very inexperienced") to 5 ("very experienced"), participants rated their smartphone experience as very high ($M = 4.81$, $SD = 0.39$) and reported moderate AR experience ($M = 2.69$, $SD = 1.10$).

4.2 Task

Participants solved a shopping task in a simulated online store (see Figs. 1 and 2), completing a total of four item sets – two sets using a phone only and two sets using *Push2AR*. Each set featured 36 items of three categories, each with 12 items. Each item had a price and a rating from 1 to 5 stars. Participants had to identify the three cheapest items of each category with at least a 3-star rating and add these nine items to the shopping cart. The task was completed by tapping on the checkout button in the shopping cart. As a tutorial task, we used two item sets with the categories headphones, smartwatches, and chargers (Fig. 2a-c). For the main task, we generated another four item sets featuring the categories beer, wine, and coffee (Fig. 1). For each item set, we pseudo-randomly generated different prices and shuffled the item order. We defined a reasonable price range for each category (i.e., \$8–35 for wine, \$5–25 for coffee, and \$5–15 for beer) and ensured that prices within each category were unique. Further, we generated prices with common endings (e.g., .99, .49). To maintain similar task difficulty across item sets, we used the same ratings within the tutorial task and also within the main task.

4.3 Dependent Variables and Operationalization

For performance, we measured task completion time and accuracy (i.e., the proportion of wrong items in the final checkout). Further, we counted how often participants opened the cart, as well as the number of times they added or removed items from the cart or pushed and deleted the items from AR (with *Push2AR*). For workload, participants completed the NASA Task Load Index (TLX). User experience was collected using the User Experience Questionnaire (UEQ) and a semi-structured interview. In the interview, we asked participants which condition they preferred and to list advantages and disadvantages of both techniques, ideas for improvements, and possible use cases. All interviews were transcribed, and the authors clustered participants' answers thematically using an affinity diagramming approach.

4.4 Procedure

We welcomed participants to our lab and provided them with an introductory document explaining the study's procedure and goal along with a verbal explanation. They signed a consent form and filled out a demographic questionnaire. We counterbalanced the order of conditions (i.e., half of the participants started with *Phone*, the other half with *Push2AR*). In an initial training phase, the experimenter introduced both conditions according to their counterbalance order (e.g., *Phone*, *Push2AR*), and participants solved the training task for each condition. Then, participants completed four tasks (i.e., two per condition) using one of the four item sets. Conditions were presented in alternating order (e.g., *Phone*, *Push2AR*, *Phone*, *Push2AR*) and item sets were counterbalanced using a Latin square. After each task, participants completed the NASA TLX and UEQ. The study sessions ended with a semi-structured interview and took approximately 90 minutes. Participants were compensated with a \$25 gift card. The study was approved by the local IRB.

4.5 Apparatus

During all tasks, participants remained seated at a table holding the smartphone (iPhone 14 Pro) in portrait orientation and used the standard Safari mobile browser to solve the task. We intentionally instructed them not to use tabs or the browser's back-and-forth navigation but to rely on the shopping cart for bookmarking to focus on traditional bookmarking compared to our interaction concept. Prior to the study, we tested *Push2AR* with different state-of-the-art AR HMDs and phone tracking methods. For optical see-through

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[1] https://ogp.me/

[2] https://augmented-perception.org/publications/2024-push2AR.html

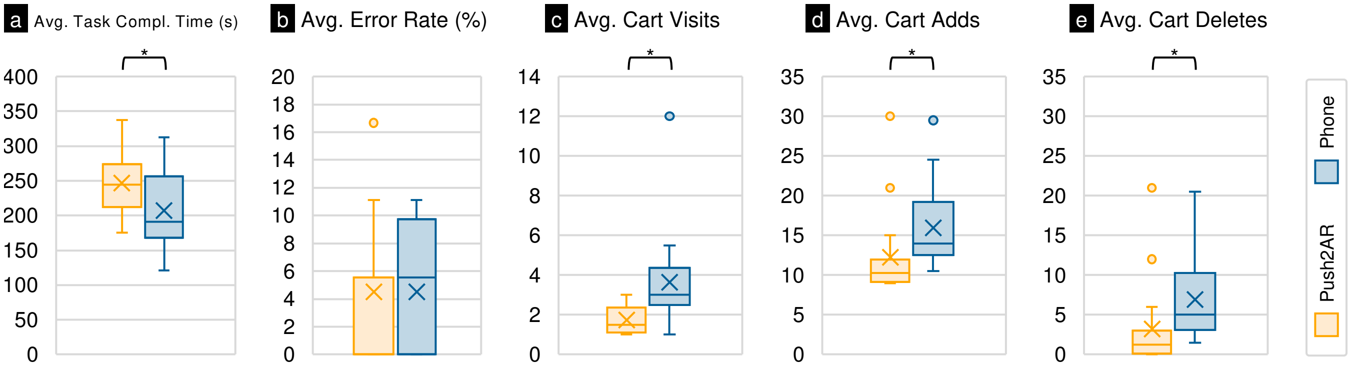

Figure 4: Boxplots for average performance-related measures across both tasks: (a) task completion time in seconds, (b) error rate (%), i.e., the rate of incorrect items in the cart at checkout, (c) cart visits, (d) number of items added to the cart, and (e) number of items removed from it.

(OST) HMDs such as Microsoft's HoloLens 2, our results align with prior work [41], which concluded that their FOV is not yet sufficient for a smartphone-aligned VESAD. Thus, we decided to use a Varjo XR-3 video see-through (VST) HMD for its high FOV and to avoid problems with different focal planes [11, 15, 41] common in OST HMDs. To isolate the effect of the interaction concept, we required participants to wear the HMD for both conditions and adjusted font sizes of our simulated online store to ensure good legibility (see Fig. 1). The HMD was connected to a state-of-the-art computer (Intel 11th Generation Core i9-11900KF, RTX 3080) that served as a server for the task's online shopping website and established communication between headset and phone. We used a Vive Tracker 3.0 to guarantee accurate and fast phone tracking, as other tested methods (e.g., marker-based tracking, shared coordinates) induced jitter, drift, or latency. We attached it to the back of the phone using a phone grip affixed with double-sided tape, allowing users to comfortably hold the smartphone in one hand. The HMD and Vive Tracker were tracked using three Valve Base stations. We used a dedicated router with no connection to the internet to minimize network disturbances. The PC was connected via ethernet cable and the smartphone via 5 GHz Wifi. We used a camera on a tripod and screen capture to record video data.

5 MAIN FINDINGS

In the following, we present the main findings of our study. For analysis, we calculated the average of the quantitative results from the two tasks for each condition for every participant. To indicate conditions, we use subscript $_{AR}$ for *Push2AR* and $_{Ph}$ for *Phone*. Further, we assume an alpha level of .05 for statistical significance. Descriptive statistics for the interaction counts, the NASA TLX scores, and the UEQ scores can be found in Appendix A.

5.1 Performance

We measured task completion time and task accuracy. As an accuracy measure, we calculated the error rate, i.e., the proportion of incorrect items in the cart at checkout. An incorrect item is one that is not among the three least expensive in each category and does not have at least a 3-star rating.

5.1.1 Task Completion Times

The average task completion times are visualized in Fig. 4a. Shapiro-Wilk tests indicated that the values for both conditions do not significantly deviate from normality. Consequently, we used a parametric approach for further analysis. A paired-samples t-test revealed that participants solved the task significantly faster ($t(15) = 3.477$, $p = .003$) with *Phone* ($M_{Ph} = 207.47\,\mathrm{s}$, $SD_{Ph} = 54.13\,\mathrm{s}$) compared to *Push2AR* ($M_{AR} = 247.26\,\mathrm{s}$, $SD_{AR} = 40.96\,\mathrm{s}$).

5.1.2 Accuracy

Fig. 4b shows boxplots of the average rate of incorrect items in the cart at checkout. Shapiro-Wilk test for the distributions of *Push2AR* and *Phone* indicated significant deviations from normality, and we followed a non-parametric approach for statistical analysis. A Wilcoxon signed-rank test ($Z = -0.119$, $p = .905$) revealed no statistically significant differences between conditions ($Mdn_{AR} = 5.56\,\%$, $SD_{AR} = 5.06\,\%$, $Mdn_{Ph} = 5.56\,\%$, $SD_{Ph} = 4.63\,\%$).

5.1.3 Interaction Counts

We counted the number of times participants accessed the cart (Fig. 4c), added items to the cart (Fig. 4d), and removed them again from it (Fig. 4e). Shapiro-Wilk tests for all measures indicated significant deviations from normality. Consequently, we used a non-parametric approach for statistical analysis. Wilcoxon signed-rank tests showed that participants visited the cart significantly less often ($Z = 2.937$, $p = .003$) and also added ($Z = 3.327$, $p < .001$) and removed ($Z = 3.328$, $p < .001$) significantly fewer items to and from the cart with *Push2AR* compared to *Phone* (see Fig. 4c–e). On average, participants pushed 15 items to AR and removed 12.28 items from AR again with *Push2AR*.

5.2 Workload

The boxplots in Fig. 5a show the overall scores of the NASA TLX as well as the scores broken down into subscales. For the overall scores, a Shapiro-Wilk test did not indicate significant deviations from normality for *Push2AR* and *Phone*. Consequently, we used a parametric approach [5, 40] for further analysis. A paired-samples t-test ($t(15) = -2.590$, $p = .020$) indicated significantly lower scores for *Push2AR* compared to *Phone*. For the analysis of subscales, we followed a non-parametric approach for *Physical Demand* and *Performance* as Shapiro-Wilk tests indicated significant deviations from normality for the distributions of these dimensions. A Wilcoxon signed-rank test did not indicate statistically significant differences for *Physical Demand* ($Z = 1.879$, $p = .060$) or for *Performance* ($Z = 1.509$, $p = .131$). For all other dimensions, the Shapiro-Wilk test indicated that distributions do not significantly deviate from normality, and we followed a parametric approach. Paired-samples t-tests revealed that participant rated *Effort* ($t(15) = -3.252$, $p = .005$) and *Frustration* ($t(15) = -2.583$, $p = .021$) to be significantly lower with *Push2AR* compared to *Phone*. We did not find significant differences for *Mental Demand* ($t(15) = -2.092$, $p = .054$) and *Temporal Demand* ($t(15) = -2.091$, $p = .054$).

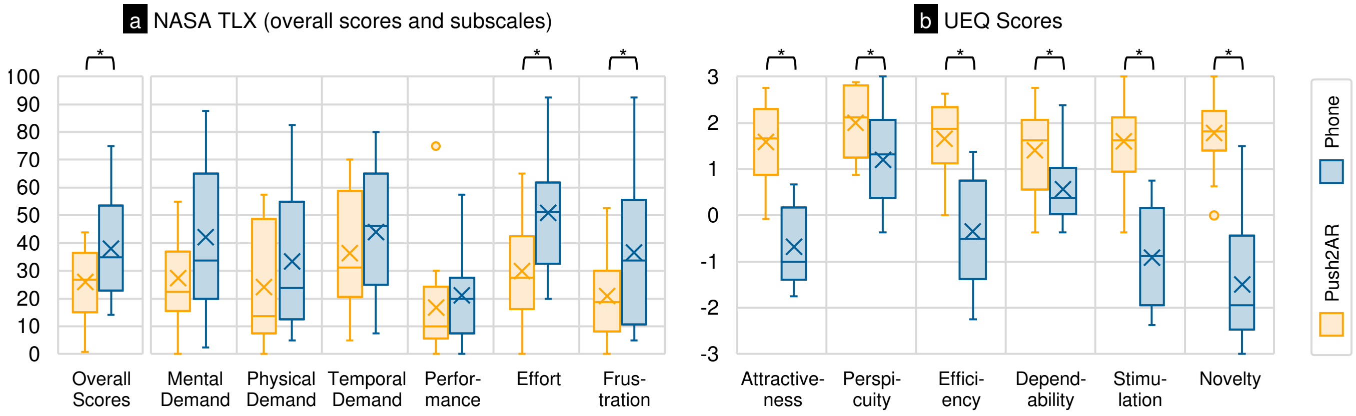

Figure 5: Boxplots for measures related to workload and user experience: (a) NASA TLX scores (b) UEQ scores.

5.3 User Experience

We assessed user experience through the UEQ and a final semi-structured interview, in which participants were asked to indicate which condition they preferred. Further, we asked them to list advantages and disadvantages of each condition and think about possible improvements and application scenarios.

5.3.1 User Experience Questionnaire (UEQ)

The scores of the UEQ are visualized in Fig. 5b. Shapiro-Wilk tests revealed that only the score distribution of *Perspicuity* significantly deviated from normality. Consequently, we used a non-parametric approach for further analysis of this dimension. A Wilcoxon signed-rank test showed that participants rated *Push2AR* significantly better than *Phone* ($Z = -2.216$, $p = .027$). For all other dimensions, the Shapiro-Wilk test did not indicate that the distribution of scores significantly deviates from normality, and we used a parametric approach for statistical analysis. Paired-samples t-tests revealed that participants rated *Push2AR* as superior to *Phone* in terms of *Attractiveness* ($t(15) = 6.014$, $p < .001$), *Efficiency* ($t(15) = 5.101$, $p < .001$), *Dependability* ($t(15) = 3.335$, $p = .005$), *Stimulation* ($t(15) = 5.663$, $p < .001$), and *Novelty* ($t(15) = 7.267$, $p < .001$).

5.3.2 Preference

All but one participant (15 out of 16) indicated that they preferred *Push2AR* over *Phone*. 13 participants also agreed that they would use *Push2AR* as part of their daily browsing habits if AR HMDs became more commonplace and comfortable to wear (e.g., similar to prescription glasses or contact lenses).

5.3.3 Concluding Interview

We asked participants to list the advantages and disadvantages of each technique, consider possible improvements, think about spatial anchoring, and reflect on application scenarios.

Advantages and Disadvantages. For *Phone*, participants ($n = 6$) mainly valued the high familiarity they associate with this common user interface, which they have used *“over and over again for my whole life”* (P14). Further, they ($n = 3$) appreciated its portability and ease of use in a real-world setting where it *“probably would be easier just to do it the ‘normal’ way”* (P12) without the *“cumbersome”* (P12) equipment. Two participants valued the cart for providing a clear overview and easy modification of the selected items. Additionally, they perceived it as mentally engaging ($n = 3$) and being *“less physically demanding”* (P08).

However, participants ($n = 11$) also reported that they perceived a higher mental load in *Phone* compared to *Push2AR* as they had to memorize the items, e.g., it is *“just more mental load, gotta keep track of more things”* (P12), which led to uncertainty about making correct choices ($n = 2$). Two participants even said that they would use external tools or need additional functionalities to make an informed selection. Further, it was more difficult to compare items on the small screen ($n = 3$), and the task required more scrolling ($n = 2$) and button presses, e.g., for repeatedly opening the cart ($n = 3$). Consequently, participants perceived *Phone* as less accurate ($n = 2$), more error-prone ($n = 3$), and time-consuming ($n = 2$). As further general negative sentiments participants ($n = 6$) described *Phone*, e.g. as, *“restrictive”*, *“inefficient”*, *“tedious”*, *“frustrating”*, or *“painful”*. Two even stated that they *“don’t find any particular advantages”* (P01) with the *Phone* condition.

On the contrary, participants valued *Push2AR* for being less mentally demanding ($n = 7$), as it allowed them to display all relevant items simultaneously ($n = 8$), thus enabling easier comparisons ($n = 5$). They appreciated the AR space as screen extension or temporary storage ($n = 4$), which not only provided points of reference for more efficient comparisons ($n = 5$) but also eliminated the need to memorize items ($n = 4$) and allowed for more informed decisions ($n = 2$). Based on that, participants perceived *Push2AR* as less time-consuming ($n = 7$), also because the cart needed to be opened less often ($n = 2$), and noted its higher accuracy ($n = 2$) and increased efficiency ($n = 3$). Further, they valued that our system was *“easy to learn”* and *“understand”* ($n = 3$) and described it as *“very intuitive”* ($n = 2$). Many participants stated that solving the task was easier ($n = 7$) and expressed further general positive sentiments ($n = 7$), describing *Push2AR* e.g., as being *“helpful”*, *“cool”*, *“nice”*, *“beneficial”*, *“less tedious”*, or *“great”*.

However, participants ($n = 6$) also stressed that they needed some time to get used to the AR features and figure out a successful strategy for solving the task. They also noted ($n = 2$) that the system’s tethered HMD lacks practicality and portability.

Features and Improvements. Regarding the different features of *Push2AR*, many participants ($n = 8$) positively highlighted the scroll indicators and the quick scrolling, e.g., saying that *“the scrolling is definitely the one I like most because I can jump really quickly”* (P05). However, they ($n = 8$) also said that the scroll indicators were too small and hard to tap.

Participants ($n = 2$) found the swipe interaction *“natural”* (P11) and *“convenient”* (P02), though some ($n = 3$) also highlighted that deleting multiple AR items was tedious. To address this, they ($n = 4$) requested a “delete all” function for faster and easier deletion. Additionally, participants ($n = 2$) highlighted that pushing items to AR required additional interaction steps and they ($n = 4$) suggested a function for sending multiple AR items directly to the cart.

Further, participants ($n = 7$) appreciated the visual links connecting scroll indicators and AR items as *"important"* (P03) and *"necessary"* (P05) for orientation. While some ($n = 2$) especially appreciated the color coding, others ($n = 3$) suggested that colors could be more distinct and signify information such as item category, rating, or price ($n = 3$).

The stacking feature was seen ($n = 6$) as necessary to limit the height of the AR list, but participants also noted ($n = 9$) issues with items occluding each other. Proposed solutions include avoiding stacking altogether ($n = 3$), reducing the size of AR items not visible on the phone screen ($n = 3$), or employing different layout strategies, such as a carousel, multiple columns, or expanding more into the AR space ($n = 8$). Related to that, some participants ($n = 5$) expressed concerns about the AR view becoming cluttered and crowded when many items are pushed. Suggestions to mitigate this issue include independent scrolling through the AR list ($n = 2$) and the ability to push items to both sides of the phone ($n = 4$).

Additionally, more than half of the participants ($n = 9$) requested to be able to directly interact with the AR items via gestures. This could help with quickly jumping to items, scrolling through them, deleting them, and adding them to the cart. Participants ($n = 6$) also requested to be able to group or categorize items in the AR space.

Many participants also saw a need for sorting ($n = 6$) and filtering ($n = 8$) functionalities within the online store, and some ($n = 3$) even argued that this could potentially make the augmentations unnecessary. However, others ($n = 6$) emphasized that *Push2AR* still would offer value, as sorting and filtering *"don't give you very targeted results"* (P03) and only help to narrow down the choice, particularly for long lists. This preselection then still would need to be manually filtered, especially since some decision criteria as style preferences remain *"pretty subjective"* (P07).

Lastly, participants expressed overall satisfaction with the system's tracking quality ($n = 2$) and the interplay between phone and AR HMD ($n = 6$), describing the features, e.g., as *"nice"*, *"pretty nice to look at"*, *"useful"*, *"valuable"*, and *"helpful"*.

Spatial Anchoring. During the concluding interview, we also asked participants if they would prefer world-anchored AR items over *Push2AR*'s phone-anchored AR items (cf. [49]). Ten participants indicated a clear preference for phone-anchored augmentations and expressed general positive sentiments describing it as *"intuitive"*, *"better"*, *"useful"*, and *"as expected"*. They mainly argued that the mobile setting requires items to be anchored to the phone, as users are typically using it on the go ($n = 4$), stating that *"I usually go [online shopping] when I'm (...) in the bus"* (P09) or *"when I'm making a groceries list, I move through the kitchen"* (P10). For these scenarios, participants ($n = 3$) further highlighted that having items anchored to the phone prevents users from losing track of them. Two participants also noted that they could imagine using both, depending on the setting and the task at hand, such as the available space surrounding the user and the number of items that need to be pushed to AR. In contrast, two participants indicated a clear preference for items being world-anchored, as it would allow grouping items in space and could reduce occlusion caused by stacking items on top and bottom of the AR list.

Application Scenarios. Participants identified a wide range of list-based application scenarios where *Push2AR* could offer advantages. For personal productivity, they mentioned online shopping ($n = 6$), creating grocery lists from recipes ($n = 5$), managing watch lists ($n = 4$), or travel planning ($n = 3$). Professional and academic use cases included collecting related works and managing reading lists ($n = 7$), browsing for job postings ($n = 4$), managing and sorting e-mails ($n = 2$), notes ($n = 2$), and extracting text snippets from documents ($n = 3$). Additionally, it could enhance browsing web pages ($n = 3$) and managing social media and messaging ($n = 5$).

Besides these, participants proposed a multitude of applications beyond linear lists, such as pushing browser tabs to AR ($n = 4$), providing virtual screens for multitasking ($n = 5$), spatial mood boards and whiteboards ($n = 2$), and potential for collaborative scenarios ($n = 2$) – each showcasing the potential of transferring traditional interfaces to the AR space surrounding the phone.

6 DISCUSSION

In the following, we discuss our insights based on findings from our user study regarding *performance*, *workload*, and *user experience*.

6.1 Performance

Unlike comparable studies from prior work (cf. [15, 23]), participants solved the task faster with *Phone* while achieving the same level of accuracy, even though they opened the cart significantly more often and added and deleted more items from the cart. While the practical relevance of this difference in task performance might be limited, we see two potential reasons for the higher task completion times with *Push2AR*. (1) Interviews and observations suggest that deleting AR items slowed participants down, as it required scrolling back to the respective item on-screen. Participants noted that interactions to efficiently delete or directly interact with AR items e.g., via mid-air gestures, might improve this aspect. (2) Users' high familiarity with the baseline, as indicated by a high average smartphone experience rating, also significantly contributed to their performance. Once participants get more familiar with AR, we believe that the difference will decrease substantially. We hope to explore this in longitudinal studies in the future.

Despite the objective differences in task completion time, participants did not perceive any significant subjective differences as measured by the NASA TLX scales for *Temporal Demand* and *Performance*. This discrepancy may be attributed to the benefits of our approach in reducing subjective perceived workload and user experience, which are discussed below.

6.2 Workload

We found that participants perceived less workload when using *Push2AR* compared to *Phone*, as indicated by the significantly lower overall NASA TLX ratings. While average ratings were lower for all subscales, the significant difference in overall scores can mainly be attributed to participants perceiving significantly less *Effort* and *Frustration* with our approach.

We identified two factors that potentially contributed to the significantly reduced *Effort*: (1) Pushing items to AR reduced the need for memorizing items and enabled direct comparison without the need to switch pages. Consequently, participants accessed the cart significantly less often and also modified its content (i.e., adding or removing items) significantly less frequently. (2) The scroll indicators of *Push2AR* arguably also reduced the effort for scrolling as it enabled user to quickly jump back to an item, which is in line with findings from prior work [1]. In addition, by visually linking each scroll indicator to the item in AR, *Push2AR* was able to improve orientation within the list.

With *Push2AR*, participants performed additional steps of pushing items to AR and removing them again. As these actions were only possible on the smartphone screen, participants had to scroll back to the respective items (e.g., using scroll bar indicators). However, due to the novelty effect, participants might have subjectively perceived these actions as being less tedious. Participants rating *Push2AR* having a significantly higher novelty compared to *Phone* might be another indication for that.

We attribute participants significantly higher rated *Frustration* with *Phone* mainly to difficulties in remembering items. For instance, one participant expressed: *"I can't build a mental model of all the prices I saw"* (P02). Because of that, they opened the cart more often to repeatedly check on the items they already added.

Interestingly, while *Mental Demand* ratings were lower on average for *Push2AR*, the differences between both conditions were not statistically significant, despite more than two-thirds of participants expressing that they perceived *Phone* as mentally more demanding ($n = 11$). One possible reason for the statistically insignificant differences in *Mental Demand* might be participants' high familiarity with smartphone UIs in contrast to their only moderate AR experience. Because of that, they arguably had to put some mental effort into familiarizing themselves with *Push2AR* first and think about a suitable strategy for solving the task. Consequently, we expect the difference in *Mental Demand* to be more pronounced once participants become more experienced with our system and AR in general, and also for more complex tasks (e.g., with longer lists).

6.3 User Experience

Participants clearly preferred *Push2AR* over *Phone*. While this may be partially attributed to the presence of scroll bar indicators (cf. [1]), the qualitative feedback clearly highlights the advantages of using the surrounding AR space: *"I really liked the AR version for the [...] affordance it gave in terms of cross-referencing [...] and not having to go into a whole new screen [...]."* (P14).

Participants also highlighted the wide applicability of *Push2AR* and indicated that they would use the extension as part of their daily browsing habits once AR HMDs were commonplace and more comfortable: *"I think [that AR glasses are not commonplace] is the only thing keeping from using it."* (P03). However, while our stacking algorithm was intended to improve the usability of the virtual screen extension (cf. [24]), our findings reveal that the resulting occlusion was a hindrance. Therefore, more research is needed to investigate different layouts of AR items and better utilize the surrounding AR space (e.g., multi-column layout).

Lastly, we intentionally designed *Push2AR* to be phone-anchored to strengthen the connection between the smartphone and its surrounding AR space (cf. [32, 60]). Yet, some participants also see potential in world-anchored interfaces to better utilize their surrounding space (cf. [36]). Similarly, exploring a hybrid between both could further open up the design space, for example by first anchoring the AR item to the smartphone, then anchoring the item in the world (e.g., see [58]): *"Maybe it'd be nice to have both actually again [...] like ones that are anchored, but maybe you can remove them from the anchoring of the phone"* (P14). However, since visual links are an important factor for linking items between the smartphone and AR space (cf. [53]), such world-anchored or hybrid approaches could lead to substantial visual clutter.

7 LIMITATIONS AND FUTURE WORK

We believe there are a number of limitations with our current prototype and evaluation, opening a space for further research.

First, *Push2AR* currently uses only the right side of the phone screen for stacking visualizations. Future work could better leverage AR space with a variety of visualization techniques. For instance, the space surrounding the phone might be utilized to display open tabs, detailed item pages, or secondary lists. There is also potential to enhance individual item visualizations, perhaps using 3D models or summarized key attributes when pushed. Exploring other layout strategies such as carousel, gallery, chart, and table formats could offer more dynamic interactions.

Secondly, we intentionally focus on the familiar touch interaction with the smartphone. However, our findings show that there is much potential for also making the AR items interactive (e.g., through mid-air gestures, see [6]). While prior work has explored this in terms of offloading menu items [6, 32, 50, 60], the interplay between AR space and smartphone navigation could be further explored (e.g., putting AR items directly into the shopping cart).

Thirdly, the scalability of *Push2AR* could be broadened to encompass more websites, applications, and even different devices like tablets, laptops, and desktop monitors. Currently, the storage of pushed items is confined to a single website. Future work might include pushing whole tabs to AR and improving interoperability across websites and apps, especially as more websites develop dedicated apps where our current web extension might not directly apply. Applying UI understanding techniques such as "Screen Parsing" [57] could facilitate the context-aware, automated extraction of UI elements beyond list items, including menus and navigation components. Feedback from our user study indicates that extending these capabilities to other computing devices would be beneficial.

Regarding the study design, the comparative performance of *Push2AR* may have been influenced by legacy biases [47] and the novelty of the AR interaction. Mobile users are accustomed to efficiently navigating lists via traditional scrolling, whereas adopting AR involves a learning curve due to its novelty. Conducting a longitudinal study could provide deeper insights into the long-term usability and effects of *Push2AR*.

Lastly, the current implementation uses the Varjo XR-3 HMD, which is quite heavy, to ensure high-resolution see-through display quality. To isolate the effect of the interaction technique from the physical burden of the headset, participants wore the HMD in both test conditions. Also, the Vive Tracker 3.0 remained attached to the phone during both conditions. We acknowledge that this technical setup might be impractical for real scenarios. As our contribution lies in the interaction design and its evaluation, our study intentionally trades off external validity for high internal validity, overcoming current OST HMD limitations and evaluating *Push2AR* without technological confounds. Future advancements could reduce hardware demands by integrating phone tracking systems (e.g., [3, 38]) into lighter VST or OST AR HMDs with a high FOV, potentially alleviating physical strain and enhancing wearability.

Beyond this, our findings' generalizability might be limited by the size of our sample, which was not gender-balanced and consisted mostly of students who were all right-handed. Future research should address these aspects, and our results should be interpreted with these factors in mind.

8 CONCLUSION

We introduce the novel interaction concept *Push2AR*, which improves upon list interaction on smartphones by allowing users to seamlessly "push" list items through touch gestures into the phone's surrounding space when wearing an augmented reality head-mounted display. Items in augmented reality are visually aligned with the smartphone and synchronized to their original position on the smartphone, facilitating curation and comparison of pushed list items. To strengthen the connection between smartphone and augmented reality, pushed list items are visually linked to the smartphone through scroll indicators, which also allow for quick navigation between pushed items. We implemented our interaction concept as an open-source web extension, showcasing how *Push2AR* can be applied to a wide range of real-life webpages. To validate our approach, we conducted a user study ($n = 16$), investigating the performance, workload, and user experience of *Push2AR* in an online shopping scenario. Our findings show that *Push2AR* significantly reduces the number of page switches when browsing through lists online, leading to less frustration and, thus, improved user experience. While our prototype did not yield faster task completion times, participants were enthusiastic about using *Push2AR* as part of their daily browsing. With our work, we contribute towards a better understanding of cross-reality interactions between a smartphone and augmented reality as well as utilizing the screen-aligned space for user interface elements.

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