# Survey of User-Based Experimentation in Augmented Reality

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## Abstract

Although augmented reality (AR) was first conceptualized over 35 years ago (Sutherland, 1968), until recently the field was primarily concerned with the engineering challenges associated with developing AR hardware and software.  Because AR is such a compelling medium with many potential uses, there is a need to further develop AR systems from a technology-centric medium to a user-centric medium.  This transformation will not be realized without systematic user-based experimentation.  This paper surveys and categorizes the user-based studies that have been conducted using AR to date.  Our survey finds that the work is progressing along three complementary lines of effort: (1) those that study low-level tasks, with the goal of understanding how human perception and cognition operate in AR contexts, (2) those that examine user task performance within specific AR applications or application domains, in order to gain an understanding of how AR technology could impact underlying tasks, and (3) those that examine user interaction and communication between collaborating users.

## 1    Introduction

Twenty-five years ago a computing revolution occurred as computers moved to the desktop. Today, a similar revolution is beginning that will fundamentally transform how we access information.  As computers become ever lighter and less expensive, they are moving off the desktop and are becoming mounted in vehicles, appliances and tools, as well as worn on our bodies.  In twenty years, embedded and worn computers will provide "information everywhere," and they are going to require fundamentally new paradigms for displaying and interacting with information.  An important sub-category of display and interaction, especially for worn and vehicle-mounted computers, will be augmented reality (AR), where information is rendered onto see-through glasses or windshields so that it overlays relevant parts of the real world (see Figure 1).

As Figure 1 demonstrates, AR devices provide *heads-up viewing*: information is integrated into a user's view of the real world.  To date, paradigms for displaying and interacting with computerized information assume the user is looking at a screen and manipulating various devices such as keyboards, mice, or (particularly for hand-held devices) the screen itself.   From our experiences with mobile outdoor AR, these traditional user interaction devices will simply not suffice.

### 1.1    Motivation for User-based Experimentation in Augmented Reality

For AR devices to reach their full potential, what is now required are new paradigms which support heads-up information presentation and interaction, seamlessly integrated with viewing and interacting with the real world.  An example of such a new paradigm would be a multi-modal combination of pointing gestures (to select relevant graphics) and voice commands (to perform operations upon selected items).  This would be similar to how two people viewing the scene in Figure 1 would discuss the information with each other.  However, to develop this or any other new paradigm, the AR community needs a much better understanding of the fundamental perceptual and ergonomic issues involving AR display and interaction.
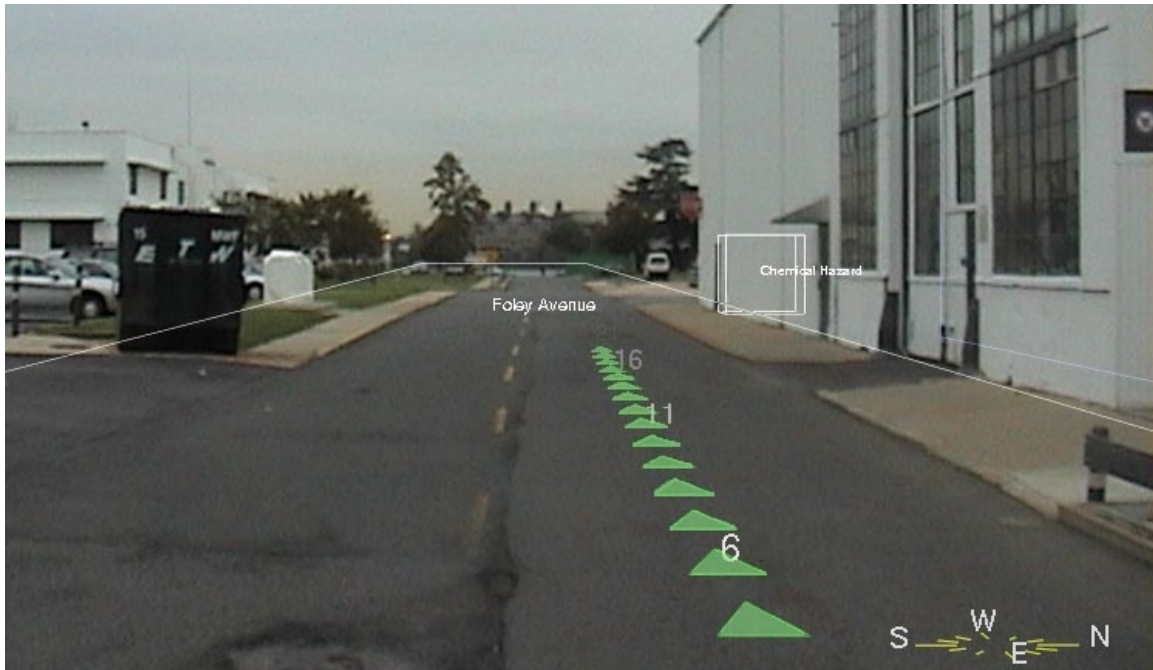
**Figure 1:** An example of augmented reality (AR), where graphical information overlays the user's view of the real world. In this example, a compass shows which direction the user is facing, the triangles indicate a path the user is following, the numbers on the path indicate distances in meters in front of the user, a hidden chemical hazard is annotated, and the name of the street is given. The graphics are registered with the world, so for example the triangles appear to be painted onto the road surface. The result is an integrated display that allows heads-up viewing of the graphical information.

Encouragingly, traditional HCI methods, such as domain analysis, user needs, tasks analysis, as well as use case development, can be successfully applied in AR to determine *what* information should be presented to users (Gabbard, 2002). What these approaches do not tell us, and what, to date has not been researched, is *how* information should be presented to users. Only by applying user-based experimentation to AR user interface design challenges (such as those inherent in perception of the combined virtual and real-world visual scene and those associated with mobile, hands-free user interaction techniques), will AR evolve to the point where its applications are widely developed and adopted.

An important step in understanding what user-based experimentation is needed in AR is to examine the set of user-based studies performed to date. This survey is one mechanism we have used to better understand the scope of past and potential AR user-based experimentation. It is a useful reference for those who wish to undertake user-based research in AR, since it provides not only a single point of entry for a representative set of AR user-based studies, but also implicitly indicates research areas that have not yet been examined from a user's perspective.

## 2 Survey Overview and Approach

### 2.1 Description of method

We systematically reviewed papers from the primary publishing venues for augmented reality research. Specifically, we reviewed papers from:

- *International Symposium on Mixed and Augmented Reality (ISMAR)* proceedings from 1998 to 2004 (Note that in previous years, the symposium was held under the following names: IEEE/ACM International Workshop on Augmented Reality (IWAR) in 1998 and 1999, IEEE/ACM International Symposium on

Augmented Reality (ISAR) in 2000 and 2001, International Symposium on Mixed Reality (ISMR) from 1999 to 2001, and finally the International Symposium on Mixed and Augmented Reality from 2002 to 2004),

- *International Symposium on Wearable Computers (ISWC)* proceedings from 1997 through 2004,
- *IEEE Virtual Reality* (VR) proceedings from 1995 to 2004 (Called VRAIS – Virtual 1 Reality Annual International Symposium from 1995 to 1998),
- *Presence: Teleoperators and Virtual Environments* journal publications from 1992 to 2004.

We only considered peer-reviewed papers, and did not include posters, demonstrations, invited talks, or invited papers. Further, due to page limit constraints, we did not include (at this time) a small handful of AR-related conferences that are no longer organized. Thus, since the scope of our survey is limited to the primary publishing venues listed above, this survey is neither exhaustive nor complete, but is a representative sample of the existing user-based AR literature.

To expedite the survey, and to ensure greater accuracy, we distilled the descriptions of specific research efforts (presented in Section 3) from language contained in their respective abstracts and publication bodies.

## 2.2    Summary of User-based Experiments in AR

The following table summarizes the number of AR-related publications, HCI-related publications and user-based experiments identified during the survey. Note that the number of HCI-related publications is taken out of the publications identified as AR-related. Thus, we do not count an HCI-related publication that is not AR-related. Similarly, the number of publications describing user-based experiments is taken out of those publications identified as HCI-related, and we do not count, for example, publications that describe user-based experiments that are not related to HCI, or performed within an AR context.

**Table 1:** Numerical Summary of User-based Experiments in Four AR Publication Venues

| AR Publication Venue | Years | Total Publications | AR-Related Publications | HCI-Related Publications[1] | User-based Experiments[2] |
|---|---|---|---|---|---|
| ISMAR[3] | 1998-2004 | 181 | 181 | 14 | 9 |
| ISWC | 1997-2004 | 170 | 28 | 12 | 5 |
| IEEE Virtual Reality | 1995-2004 | 301 | 24 | 3 | 3 |
| Presence | 1992-2004 | 452 | 33 | 9 | 4 |
| **Total** | | **1104** | **266** | **38** | **21** |

As shown in Table 1, to date there has been very little user-based experimentation in augmented reality. Out of a total of 1104 articles, we found that 266 articles describe some-aspect of AR research (~24%). Of those 266 AR articles, only 38 addressed some aspect of HCI (~14% of AR articles, ~3% of all articles), and only 21 describe a formal user-based experiment (~55% of HCI articles, ~8% of AR articles, and ~2% of all articles).

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[1] We counted the number of HCI-related publications from the pool of AR-related papers only.

[2] We counted the number of user-based experiments from the pool of HCI-related (and thus AR-related) papers only.

[3] We considered ISMAR publications to include those published in: IEEE/ACM International Workshop on Augmented Reality (IWAR) in 1998 and 1999, IEEE/ACM International Symposium on Augmented Reality (ISAR) in 2000 and 2001, International Symposium on Mixed Reality (ISMR) from 1999 to 2001, and finally the International Symposium on Mixed and Augmented Reality from 2002-2004

# 3    Detailed Descriptions of User-based Experiments

Although AR was first conceptualized over 35 years ago (Sutherland, 1968), until recently the field was primarily concerned with the engineering challenges of AR hardware and software. Within the past five or so years, the capability and cost of AR equipment has reached levels that have made sustained user-based experimentation possible. Our survey finds that user-based experimentation in AR dates back to as early as 1995, and since then has been progressing along three complementary lines of effort: (1) those that study low-level tasks, with the goal of understanding how human perception and cognition operate in AR contexts, (2) those that examine user task performance within specific AR applications or application domains, in order to gain an understanding of how AR technology could impact underlying tasks, and (3) those that examine generic user interaction and communication between multiple collaborating users. Within each section, we present the related work in chronological order.

## 3.1    Human Perception and Cognition in AR

To date, user-based studies of human perception and cognition in AR examine issues such as perceptual effects of alterative rendering techniques (such as those that employ realistic lighting and shading), depth-perception in AR and effects of AR display viewing conditions and/or display hardware specifications on perception. We found twelve publications that describe user-based studies that examine perception and/or cognition in AR.

Rolland et al. (1995a) presents one of the first user-based studies in AR. The authors examined the effect of see-through AR display design on depth perception. In this experiment, two objects of varying shapes and sizes were presented to users under three different presentation conditions: one in which both objects were real, one in which both objects were virtual, and one in which one object was real and one object was virtual. The experimental task required users to judge the relative proximity in depth of the two objects, and answer whether or not the object on the right was closer or farther from them relative to the object on the left. The results indicated that virtual objects were perceived systematically farther away then real objects. The authors provide some discussion on how their experimental setup and computation model of depth perception may have affected results.

(Rolland et al., 1995b and Rolland et al., 1998) describe another early user-based AR experiment that examined user task performance using a prototype video-based AR display. The study looked at the effects of sensory rearrangement caused by a HMD design that displaces the user's "virtual" eye position. The authors collected data to measure hand-eye coordination and speed on a manual task. Their results confirmed that user's performance (speed and accuracy) decreased when using the AR display, however, the data suggests that users were also able to adapt to the sensory rearrangement. The study also reports evidence that exposure to the video-based HMD environment resulted in negative after-effects in the form of greater errors in pointing accuracy.

Smets and Overbeeke (1995) describe a series of experiments that examined user task performance using a systematically constrained video-based AR system. Specifically, the experiments artificially varied (i.e., reduced) the display's spatial and temporal resolution. Results showed that although spatial and intensity resolutions are very important in static viewing conditions, subjects were able to complete the task in conditions with very limited resolution.

Ellis et al. (1997) detail a pair of experiments that examined the effect of viewing conditions of fatigue, and the effect of rendering latency on user task precision. In the first study, the experimental task required users to visually trace either a physical path or a virtual path with the cursor presented to their dominant eye. Users were exposed to monocular, binocular and stereoscopic viewing conditions, and self-reported how realistic the virtual object appeared, how dizzy, posturally unstable or nauseous they felt, and how much their eyes, head, or neck ached. Their results showed that viewing difficulty with the biocular display was adversely effected by the visual task. The authors suggest that this viewing difficulty is likely due to conflict between looming and stereo disparity cues. The second experiment examined the precision with which operators could manually move ring-shaped virtual objects along virtual paths without collision. Accuracy of performance was studied as a function of required precision, path complexity, and system response latency. Their results indicated that high precision tracing is most sensitive to increasing latency.

Ellis and Menges (1998) found that the presence of a visible (real) surface near a virtual object significantly influenced the user's perception of the depth of the virtual object. For most users, the virtual object appeared to be nearer than it really was. This varied widely with the user's age and ability to use accommodation, even to the point of some users being influenced to think that the virtual object was further away than it really was. Adding virtual backgrounds with texture reduced the errors, as did the introduction of additional depth cues (e.g., virtual holes).

Ellis (1999) describes an initial experiment that examined the effects of three different viewing conditions on users' ability to position a physical pointer under a virtual object. The viewing conditions studied were monocular, biocular, and stereoscopic viewing using a see-through HMD. The study employed a localization task that was intended to closely match the expected visual-manual manipulation task common in numerous AR applications (e.g., surgery and mechanical assembly on a production line). The results showed that users could set a mechanically displaced, physical pointer to match the distance of physical targets with several millimeter accuracy and that this accuracy corresponded to their ability to match target distances with their fingers. A strength of this work is that results of the user-based experiments are distilled into a set of design considerations. As an example, the authors suggest that AR displays should have a variable focus control and that designers and supervisors should be aware that operators over 40 will generally not benefit from the variable focus adjustment. Another design consideration suggests that biocular and stereo displays should be used with a bore-sighting procedure in which focus is adjusted to a reference target so as to correct for any errors in depth due to inappropriate vergence.

Rolland et al. (2002) describe an experiment in which the accuracy and precision of rendered depth for near-field visualization were measured using a custom-designed bench prototype HMD. The authors compared their experimental results to a set of theoretical predictions previously established from a computational model for rendering and presenting virtual images. Three object shapes of various sizes were investigated under two methodologies: the method of constant stimuli modified for random size presentation and the method of adjustments. Their results showed performance increases for the accuracy and the precision of rendered depth in HMDs.

Livingston et al. (2003) describe a detailed user-based study to examine sets of display attributes used to visually convey occlusion in outdoor, far-field AR. The study varied drawing style, opacity, and intensity of the drawing styles used to represent objects in the scene and used three different positions for the target stimuli. The results of the study identified a drawing style and opacity settings that enable the user to accurately interpret up to three layers of occluded objects, even in the absence of perspective constraints.

Azuma and Furmanski (2003) examine four placement algorithms for placement of 2D virtual labels. The evaluation included an 8-subject empirical user study that suggested users were able to read 2D labels fastest with algorithms that most quickly prevented visual overlapping of labels, even under conditions where 2D label placement wasn't ideal.

In another paper that examines drawing styles of virtual objects in AR, (Sugano et al., 2003), describe the effects of using virtual shadows in AR. The study aims to assess how the inclusion of accurate, realistic shadows effect user performance and virtual object presence. The paper describes two experiments that verify the following assumptions: shadows of virtual objects provide a stronger connection between the real world and virtual objects, and shadows of virtual objects provide important depth cues. Subjective data analysis further suggested that a characteristic shadow shape provides more virtual object presence in spite of inaccurate virtual light direction.

Belcher et al. (2003) examine the effect of using AR for three-dimensional graph link analysis. The paper describes two user-based experiments that employ 16 subjects each: a study that compares a tangible AR interface to a desktop-based interface, and a study to test the effect of stereographic viewing conditions on graph comprehension. The results of the studies indicated that a tangible AR interface is well suited to link analysis, and that stereographic viewing has little effect on user comprehension and performance.

## 3.2   User task performance and interaction techniques within specific AR applications or application domains

Due to the recent maturity of AR technology, we expect to see an increase in the number of AR applications developed for real-world use (as opposed to research-based laboratory use). While there have been a small number of emerging AR applications developed to date, very few of these applications have been developed in concert with systematic user-based evaluation. In this section we describe six user-based studies that examine specific AR applications or application domains.

Lehikoinen et al. (2002) present a map-based wearable computing application called WalkMap. The authors employed a user-based study to examine visual presentation techniques. Specifically, the focus of the evaluation was on the feasibility of the perspective map as a visual interaction technique. They describe the results of a user-based study using ten users performing a target finding task. The results showed that while a perspective visualization is feasible for some navigational tasks, for other tasks a regular map is preferred.

Fjeld et al. (2002) compare a previously designed AR user interface with two alternative designs: namely a 3D physical user interface and a 2D cardboard user interface. In each case, users were tasked with solving a positioning problem. The authors measured trial time, number of user operations, learning effect in both preceding variables, and user satisfaction. The results showed that the 3D physical tool user interface significantly outperformed the 2D cardboard user interface, as well as the previously designed user interface (but only in user satisfaction). A noteworthy aspect of this work is that the authors describe how they used a pilot study to refine and direct the design of the major experiment. Finally, the authors argue that the results justify the value of carrying out usability studies as part of a successful software development strategy.

Guven and Feiner (2003) present an authoring tool for creating and editing 3D hypermedia narratives that are interwoven with a user's surrounding environment. The authoring tool is designed for non-programmers, and allows them to preview their results on a desktop workstation, as well as with an augmented or virtual reality system. The paper describes a user-based formative evaluation that employed eleven subjects. Their evaluation results are mostly qualitative, and were used to iteratively improve the authoring tool.

Another application-based user study is presented in (Benko et al., 2004). The authors describe a collaborative mixed reality visualization of an archaeological excavation. The paper (appropriately) discusses the architecture of the VITA system followed by interesting discussion on user interaction (including gesturing and 3D multimodal interaction) and user interface design considerations. The authors also describe a usability evaluation that used six domain (archaeology) users.

Lee et al. (2004) describe an approach to user-centered development of AR applications they term "immersive authoring". This approach supports usability evaluation concurrently throughout the development process, by providing a WYSIGIG-like AR authoring environment. The paper further details the user-centered approach to development by identifying elements of their domain analysis, task analysis, design guidelines and interaction design for the "tangible augmented reality" domain. Lastly, the paper describes a pilot usability evaluation of the authoring system that employed 24 participants over the course of 3-4 days. Time to task-completion and the number of task errors was counted, and some summary statistics are given. The user study was aimed at assessing the overall usability of the system (i.e., gestalt), as opposed to identifying the degree of variability (i.e., in task time or errors) associated with a set of experimental factors and levels.

Wither and Hollerer (2004) present techniques designed to allows users to quickly and accurately annotate distant physical objects not yet represented in the computer's model of the scene. The paper presents a user-study that evaluates four techniques for controlling a distant 3D cursor. The paper assesses these techniques in terms of user task speed and accuracy at varying target distances. The authors also collected data via a post-experiment questionnaire.

## 3.3  User Interaction and Communication between Collaborating Users

An interesting application of AR technology can be found in the subset of human-computer interaction research known as computer-supportive cooperative work (CSCW). We describe three publications that study social and communication issues for collaborating users, where user communication is at least in part mediated by the AR user interface.

Billinghurst et al. (1997) presents one of the earliest AR user-based studies to examine collaboration and CSCW. The authors describe two pilot studies which imply that wearable AR may not only support 3D collaboration, but that users will perform better with AR interfaces as opposed to immersive collaborative environments. The users' collaborative task required one user to find the virtual objects needed to complete the target configuration and make them visible using voice commands. The second user had to find the objects (made visible by the first user), pick them up, and drop them over the targets. In the first pilot study, subjects performed better when they could see each other and the real world. In the second pilot study, both subjects donned wearable displays and communicated almost the same as in face-to-face collaboration.

Billinghurst et al. (1999) describe a very thorough study that examined communication asymmetries and their potential impact on the design of collaborative wearable interfaces. The study engaged 12 pairs of subjects (within subjects design) performing a collaborative task; specifically users had to construct plastic models out of an Erector set with the help of a remote desk-bound expert. The study compared collaboration with AR and desktop interfaces to more traditional audio and video conferencing in three conditions: audio only, video conferencing, and AR. Within the AR condition, the study varied communication asymmetry to assess its effects on user performance. The study found that functional, implementation, and social asymmetries were present in the AR condition and that these asymmetries significantly impacted how well the subjects felt they could collaborate. In some cases, the impact was rendered that AR condition less useful than audio alone.

Kiyokawa et al. (2002) describe two experiments that compared communication behaviors of co-located users in collaborative AR environments. The experiments employed 12 pairs of subjects (24 users total). The first experiment varied the type of AR display used (optical, stereo- and mono-video, and immersive HMDs) with users performing a target identification task. This study concluded that the optical see-through display required the least extra (verbal) communication needed. The second experiment compared three combinations of task and communication spaces using a 2D icon-designing task with optical see-through HMDs. Both studies include a rich set of quantitative performance measures, as well as subjective user questionnaires. The study concluded that placing the task space (physically) between the subjects produced the most conductive and productive collaborative working space.

## 4  Future Work

An obvious extension to this survey is to expand the publication-base to include venues such as the annual ACM CHI Conference Proceedings, Eurographics – the annual conference of the European Association for Computer Graphics, ACM SIGGRAPH, and so on. Since there are a limited number of published AR user-based experiments, this extension is tractable, at least for the time being. It is our hope that in the coming years, the number of user-based experiments will be so large that any new survey of this work would not only be challenging, but would be unable to give detailed descriptions of individual publications in a reasonable number of pages.

With respect to user-based experimentation in AR, what is still needed is extensive user-centered domain analysis to further identify AR technology, user interface and user interaction requirements specific to known usage domains (e.g., manufacturing, surgery, mobile military operations). These activities in turn will help focus user-based experiments – by identifying domain-specific user interface design challenges and associated perceptual issues of interest. A thorough domain analysis also ensures that user-based studies are centered on representative (e.g., actual end-) users performing representative tasks in realistic settings.

We plan to extend our current body of work that focuses on user-based experimentation in AR. Currently, we are pursuing two parallel lines of user-based experimentation to examine perceptual issues in outdoor AR – specifically depth perception and text legibility.

To date, all of the reported work related to depth-perception in AR is for tasks in the near visual field. Such near-field tasks are natural when a user employs their hands. However, most of the outdoor usage domains we are interested in require looking at least as far as across a street, and thus use far-field perception. While it is true that far-field perception has been studied with VR and other optical stimuli (and the same is certainly true for near-field perception), with AR tasks the view of the real world behind the graphical annotations, and the interaction between the graphics and the real world, make far-field AR perception qualitatively different from anything previously studied.

We also intend to continue our user-centered experimentation on visual perception of text legibility in dynamic outdoor environments. A challenge in presenting augmenting information in outdoor AR settings lies in the broad range of uncontrollable environmental conditions that may be present, specifically large-scale fluctuations in natural lighting and wide variations in likely backgrounds or objects in the scene. In (Gabbard et al., 2005) we present a user-based study that examined the effects of outdoor background textures, changing outdoor illuminance values, and text drawing styles on user performance of a text identification task with an optical, see-through augmented reality system. This work is the beginning of a series of research efforts designed to increase legibility in outdoor AR user interfaces. In the future, we intend to examine other potential dynamic text drawing styles to identify text rendering techniques that are flexible and robust enough to use in varying outdoor conditions. .

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