Applying HCI principles to AR systems design

Andreas Dünser, Raphaël Grasset, Hartmut Seichter, Mark Billinghurst

HIT Lab NZ

ABSTRACT

To date most Augmented Reality (AR) design guidelines that can be found in the literature are rather narrow suggestions derived from specific problems by researchers. Applying general HCI principles to AR systems has only been partially explored. In this paper we investigate how such general guidelines may relate to the emerging domain of AR application design.

CR Categories and Subject Descriptors: H.5.m Miscellaneous
Additional Keywords: augmented reality, HCI, design guidelines

1 INTRODUCTION

Until now most development in Augmented Reality (AR) is technology driven and the research is mainly focused on how to overcome hard- and software issues. There is little research on developing HCI guidelines or presenting results from formal HCI studies [36]. For example, Swan and Gabbard [38] analysed 266 AR related publications from 1998-2004 and found that only 38 of those (14%) addressed some aspect of HCI, while just 21 had any formal user-based experiments. Their review gives a good overview of the field and the role HCI related issues play in AR research. Clearly there is a need for more HCI and usability research in the field of Augmented Reality.

In current AR research the user is often not integrated into the system design process and there is little appreciation of user interface design principles in the development. This may partly be due to AR being a relatively new technology. A great deal of research focuses on exploring basic principles of this technology and to overcome technical problems, like optimizing tracking algorithms, computer graphics and visualization issues, or the problems of transferring AR technology to new devices or platforms. This is an important part of the development because certain technological challenges have to be solved in the first place in order to move on to further development stages.

There are different groups involved in AR research with different research focuses ranging from computer graphics or computer vision to human computer interaction. A phenomenon that may arise from a strong technology focus is that researchers develop new technologies and prototypes without having a specific problem in mind that this technology should solve. This process unquestionably drives technological advancement, but on the other hand often forgets the end user. For a successful development of AR systems all research domains involved have to be considered and integrated properly with a user centred design focus.

If AR is to be used outside of research laboratories and become commercially successful the systems have to be made more accessible and usable for the everyday end user. For example the notion of ubiquitous computing using AR technology will only be realized if the technology is mature enough to be used by less highly specialised users. Greater ease of use is necessary so that technologically advanced systems can make the step from the research laboratories into everyday life.

2 DESIGN PRINCIPLES AND GUIDELINES

2.1 Previous and Related Work

Gabbard [11] lists a comprehensive collection of design principles found in the AR literature. Such guidelines may be used by researchers interested in particular design issues for their AR system. However it is a matter of debate if such specific design guidelines are transferable to research regarding other AR interfaces. Thus the challenge is to extract these findings and to try to develop more general design principles.

An alternative approach is to take general HCI principles and see how we can apply them to AR systems development or how they already have been applied. This may result in relatively broad and general suggestions but can serve as a starting point. Specific issues and tasks may be refined in further steps. This paper is therefore an attempt to discuss the development of design guidelines for this yet relatively open field.

In process of developing guidelines we should not simply take GUI design and evaluation principles and try to apply them to AR interfaces. There are some fundamental differences between traditional GUIs and AR based interfaces. GUI design guidelines generally suggest that the user is interacting with a computer screen, keyboard and mouse. AR normally incorporates other means of interacting with the computer. Thus there are potentially different interaction possibilities that have to be taken into consideration.

However we may use the knowledge base of general Human Computer Interaction. We can find some basic principles in the HCI literature that are applicable to humans interacting with different kinds of interfaces.

Moore [26] makes an attempt to test the usability of a tangible AR system with a heuristic evaluation using a set of heuristics identified by Nielsen [27]. He found that, while general and vague, heuristics facilitated the identification of immediate tasks that needed to be improved.

When developing design guidelines for AR we can also use knowledge derived from the Virtual Reality (VR) literature. Compared to AR, within VR research there has been more effort to integrate HCI related issues into technology development [4]. Whereas several VR and AR systems share certain features from an interface and interaction perspective, there are also differences and researcher should consider the specific unique issues and requirements of AR systems.

2.2 The Generalization problem

A reason for user centred design principles being largely overlooked may be that there still is very limited knowledge in this area and very few design guidelines have been developed.

e-mail: andreas.duenser@hitlabnz.org
e-mail: raphael.grasset@hitlabnz.org
e-mail: hartmut.seichter@hitlabnz.org
e-mail: mark.billinghurst@hitlabnz.org

Most guidelines are rather specific findings by researchers. One problem of generating guidelines or tools to assess or measure usability related issues for AR applications is the vast number of different AR systems and I/O devices used. These range from mobile devices like cell phones or PDAs to head mounted display (HMD) based indoor and outdoor systems, or large fixed screen systems. In addition, AR is not limited to visual interfaces but also may occasionally include audio and haptic interfaces. Realization of user interfaces and the underlying interaction techniques proves to be a rather challenging part when developing an AR system [6]. The domain of AR has not yet defined its specific interface (and it is questionable if it ever will). While AR user interfaces are typically realized with a large variety of interaction techniques and interaction devices, most of them depend on specific hardware [6].

While for Web or desktop applications it seems rather manageable to find common design guidelines and design tools to help in the usability engineering process it is rather difficult to do the same for AR applications. When dealing with desktop systems we can rely on similar input and output devices and more or less standard interaction techniques. For example taking screen captures may be valid for analyzing navigation on websites.

As AR interfaces involve virtual information registered in 3D [2] desktop evaluation techniques are not applicable. Also the use of alternative input devices produces new challenges and demands. For example the notion of clicks has to be extended to the idea of any type of user input [18].

Rizzo et al. [32] argue that with the absence of an established design and interface methodology like it has emerged for 2D desktop environment over the last 30 years, we are still limited to an exploratory, trial-and-error-style approach to 3D interface and interaction design. The relatively fast changes in hardware capabilities, device availability and cost are additional obstacles for deriving general design suggestions.

2.3 Where to go?

Given the considerations discussed it may not seem meaningful to develop specific design guidelines. Bowman et al. [5] argue that no overall heuristics for 3D visualization currently exist, due to their variety of interfaces. Designers of AR systems will need to come up with specific solutions to their individual problems. Yet they should be able to rely on general design principles that have been identified so far. Certain design guidelines can be applied to all different kinds of human computer interfaces. Given a specific application they then have to be fine tuned to fit to the particular problem.

Applying guidelines should not be the only step in a user centred design process. Guidelines can help developers in an early stage of development and be used as a framework to build the prototype on. When used in heuristic evaluations or usability inspections of the system they can yield useful information and show possible shortcomings of the interface [12]. This step can help to identify and thus remove obvious usability problems at an early stage. Results of a heuristic evaluation can be the basis for user evaluations carried out later in the design process.

Using guidelines to develop AR interfaces is a rather rough step and can only give general hints how to avoid certain usability problems. All methods in evaluating an interface have their distinct advantages and shortcomings. They supplement each other as no single method can identify all problems [16].

3 Using common design principles and heuristics: some examples

In the HCI literature researchers can find a large number of different design principles and usability heuristics [18, 27, 30, 34, 37]. Discussing all of them in the context of AR systems would go beyond the limits of this present work. We therefore try to give a selection of these suggestions which is neither exhaustive nor complete. We don’t follow a specific set of guidelines but try to identify some important design principles and discuss how they relate to AR system design. The intent is to provide good examples of how to apply HCI design principles in an AR setting.

3.1 Affordance

The concept of affordance [13, 28] suggests that there is an inherent connection between a user interface and its functional and physical properties. AR systems incorporate new ways of interacting with digital media by overlaying meaning onto the real world. Accordingly, designers use interaction metaphors derived from real world examples. The foundational use of real world interaction metaphors may in fact facilitate the designer to comply with this guideline as it provides a low learning curve for the user.

Affordance, as such, provides a conceptual model describing a subject-object relationship. Integrating this model in the design principle for AR requires an extension to the notion of the subject-object relation. AR can, through Tangible User Interfaces (TUI) [19], augment, reverse or negate meaning perceived from physical objects. Hence, the relation can change and therefore it is necessary to precisely define it for a user study.

Appropriate interaction metaphors may easily communicate to the user what the device is used for; e.g. the use of a real paddle to arrange virtual objects in the VOMAR application [20].

Another example for an interaction metaphor taken from everyday interaction devices is the PIP (Personal Interaction Panel) which is used in the Studierstube environment [33]. Familiar shapes of the real props, like a pen and a tablet, provide the user with passive tactile feedback. This and the fact that the user can still can see their own hands help them to understand the functionality.

Applying this design principle into an AR systems one can take advantage of the affordance for direct 3D manipulation in AR systems [24]. Direct 3D manipulation provides an intuitive method for short range interaction with direct access for the user to the system and manipulation of content. This technique is useful in 3D learning and construction environments [10], where the direct perception of changes may foster the build-up of a mental model. Compared to conventional mouse interaction on a desktop computer, using interaction devices that are registered in 3D space for 3D interaction can be more intuitive because they do not need constant remapping of function and action.

3.2 Reducing cognitive overhead

As mentioned before, user interface design strives to enable the user to focus on the actual task and to reduce cognitive overhead needed to interact with the application. For the example of VR systems with new kinds of interaction techniques (e.g. giving the user “magic” or superhuman like interaction abilities) Rizzo et al. [32] argue that the extra non-automatic cognitive effort required to interact with the system could serve as a distraction. This might limit the value of a system for accomplishing a specific set of goals. The same may also be the case for AR systems with novel and yet untested interaction metaphors. Demands on cognitive load are possibly lower for experts and designers of the specific system. However dealing with the same systems could be quite demanding for novice users.

Researchers suggest that cognitive overhead can reduce training and learning effects in virtual learning environments [8]. If perceptual and cognitive load are too great, it is unlikely that AR will prove to be an effective training aid [36]. Kaufmann and Schmalstieg [22] argue that the main reason for putting a lot of effort into VR or AR interface design is to enable students to focus an the actual task and not on mastering the interface.

User performance mainly relies on being able to use features of the interface and less on having many features available. A problem for many AR systems is that such features are not fully tested yet [25].

Registration errors in AR systems also may degrade user performance when the virtual elements are not aligned to the real objects. Associating graphical elements with the real environment requires cognitive effort from the user which may reduce task performance [25].

3.3 Low physical effort

Users should be able to accomplish a task with a minimum of interaction steps. Using the systems should not involve making "unnecessary" interventions by the user. A system should react efficiently reducing the likelihood of fatigue. In order to facilitate a rewarding experience with the system and to decrease chances of fatigue, user worn parts of the system should be as lightweight and comfortable as possible [21].

Another aspect that has to be considered is the chance of users experiencing simulator sickness in virtual environments [23]. The symptoms experienced by users affected by simulator sickness can drastically diminish usability of a system. While simulator sickness is not as present in AR systems as it is in VR environments this phenomenon still should be considered when designing an AR application.

A transitional AR interface concept [3] allows the user's viewpoint to move from an AR representation to a VR representation by a smooth viewpoint animation between them. At the moment these interfaces pay little attention on the impact of motion sickness and disorientation which could be a valuable research topic for the future.

Using devices like HMDs will, at least for the near future, potentially always run the risk of generating a certain amount of discomfort when being used for a long time. Thus usage times should always be considered when developing systems using such interaction devices.

3.4 Learnability

It should be easy for the user to learn how to use a system. Issues with the learnability of 3D user interfaces can impact the acceptance and use of such systems by potential "everyday" users without prior training with such technology [32]

Using AR as a computer interface allows system designers to realize novel interaction techniques that users have not experienced and applied yet. These may be different from how people would interact in and with real environments and problems. Thus they need to be learned before the user can use the system efficiently.

Intuitive interaction techniques and methods that are akin to real world behaviour or similar to what the users already are used to (e.g. interaction techniques similar to traditional computer interaction techniques) can limit the learning needed. For example the basic interaction technique for the MagicBook [31] requires the users to turn physical book pages in order to interact with the system. This enables users to use the system immediately without having to learn new kinds of interaction.

When creating or labelling interaction elements, designers also should consider self descriptiveness. Kaufman [21] redesigned the menu structure and labelling of menu components of an AR based geometry education system in a way that they are similar to menu components of common desktop based geometry and design applications. This helps users experienced with such desktop based applications to use the new system because they can use commands and interaction steps they are already familiar with. Design elements and structures like this can improve a systems' conformity with user expectations and thus facilitate learnability.

Another prerequisite for learnability is consistency (it is important that the user interface is consistent in appearance and behaviour). Inconsistent use of interaction tools often confuses users. If for example navigation requires the user to switch between tangible paper-based interaction (turning book pages) and interaction with desktop computer interfaces (clicking on next with the mouse) users can have problems applying the right interaction mode at the right time [9].

Lee et al. [24] also stress the importance of consistency for immersive authoring. Interaction methods and interfaces should be as similar as possible to the ones used in the target application domain being authored.

3.5 User satisfaction

The perceived user experience is a large factor and becomes more important the closer an AR system engages the user in activities rather than solving tasks. The usability of an interface not only depends on objectives measurements. The subjective user perception of interacting with the system should also play an important role during the development of an AR interface [29]. Data on these criteria can be gathered during informal user testing, observations throughout demonstrations or formal lab evaluations. Hence for providing a satisfactory user experience subjective and objective measures have to be considered (efficiency/satisfaction trade-off) [14].

Various AR applications have been described to be "fun" and having a certain novelty or "wow" effect. For example, many AR games developed at the Mixed Reality lab at Singapore [35] have received positive feedback from users. Paramount for games is the game play and consequently the game logic. AR game development goes beyond the controllable logic of the game toward integrating the real context of the player. This consequences for an AR software developer as it affects the logic and the play concurrently. For example, enjoying the game does depend on the suspension of disbelieve and so registration errors can be a breaking point for natural interaction [1].

3.6 Flexibility in use

When designing AR user interfaces researchers should be aware of different user preferences and abilities. An interesting feature of AR technology is the possibility of integrating different kinds of input and output devices. Thus there is a potential to integrate different modalities to accommodate individual user preferences. On the one hand, certain input modalities are more useful to accomplish specific tasks. On the other, supporting different interaction modes provides the user with more choice.

Additionally, different modalities can complement each other. The tradeoff here is between time-multiplexed and space-multiplexed input devices. Time-multiplexed devices can change their modality in relation to the function (e.g. desktop mouse), whereas space-multiplexed interfaces have one tool per function. Multiplexing spatially can be overlaid with other media for input.

Irawati et al. [17] for example discuss on how to integrate speech and gesture interaction in a virtual furniture arranging task.

While each single interaction modality has its advantages and disadvantages in accomplishing certain tasks, multimodal input can increase user performance.

3.7 Responsiveness and feedback

Users only tolerate a certain amount of system lag [39]. For example if commands are not executed after a certain amount of time it is difficult for users to build up a persistent model of cause and effect. Using feedback to keep the user informed can help to minimize problems induced by poor responsiveness.

A problem with current AR systems can be slow tracking performance. This is mainly technology based and hopefully will be minimized in the future. Until this problem is solved, designers have to take it into account and try to design the system in a manner that poor tracking performance does not interfere too much with task performance. Henrysson et al. [15] found that their mobile phone AR application worked despite relatively slow tracking because of cooperative interaction between users.

Cohelo et. al [7] propose a solution which adapts the quality of visualization according to the error level received from the registration. Hence, the user has a ubiquitous feedback about the system status.

However, feedback should not only be used to overcome problems of responsiveness. When using an interface it should be obvious to the user when a control has been used and what the current system status is. In face to face AR gaming Henrysson et al. [15] argue that multi-sensory feedback—especially aural and visual—is important for increasing enjoyment in an AR system.

3.8 Error tolerance

Most AR systems are still in the early development stages and thus quite prone to instability. Developers still have to solve technological related issues before such systems may really be error tolerant and comply with this design guideline.

One of the biggest problems that we have already mentioned is tracking stability. Many efficient and accurate algorithms have been developed for high quality spatial registration of real and virtual information. However numerical error estimations, environmental conditions (e.g. changing light) or human errors can result in inaccuracies such as virtual information "jumping", jittering or suddenly disappearing.

Recently, efficiently combining different algorithms (hybrid tracking) [31], having multiple simultaneous trackers running in parallel, and identifying and resolving error scenarios can improve the robustness of the system and therefore reduce user frustration.

4 Conclusion

In this paper have we combined some known user-centered design principles with the demands of AR systems to identify issues that should be considered by AR interface researchers. It is an initial attempt to fill the gap that currently exists in this area. The presented design principles are just a small overview and the guidelines given are rather general and have to be further refined. Too little knowledge about AR systems design exists so far to generate generic rules for creating or evaluating AR systems. Implementations of AR systems and I/O devices used are quite diverse which complicates the process of finding and defining such a set of generic rules. It also may be difficult to develop more specific guidelines that would accommodate all AR system designers.

It is important to integrate research from different fields into the process of defining and applying AR related design guidelines. Multidisciplinary research allows us to combine different viewpoints and researchers with different areas of expertise can bring in their specific strengths. Clearly the future success of AR applications will depend on well designed user experiences.

References

[1] Benjamin Avery, Wayne Piekarski, James Warren, and Bruce H. Thomas. Evaluation of user satisfaction and learnability for outdoor augmented reality gaming. In *7th Australasian User interface conference*, Hobart, Australia, 50, pages 17-24, 2006.

[2] Ronald T. Azuma. A Survey of Augmented Reality. *Presence - Teleoperators and Virtual Environments*, 6(4): 355-385, 1997.

[3] Mark Billinghurst, Hirokazu Kato, and Ivan Poupyrev. The MagicBook: a transitional AR interface. *Computers & Graphics*, 25(5): 745-753, 2001.

[4] Dough A. Bowman, Joseph L. Gabbard, and Deborah Hix. A Survey of Usability Evaluation in Virtual Environments: Classification and Comparison of Methods. *Presence - Teleoperators and Virtual Environments*, 11(4): 404-424, 2002.

[5] Dough A. Bowman, Ernst Kruijff, Joseph J. LaViola Jr., and Ivan Poupyrev. *3D User Interfaces: Theory and Practice*: Addison/Wesley, 2004.

[6] Wolfgang Broll, Irma Lindt, Jan Ohlenburg, Iris Herbst, Michael Wittkamper, and Thomas Novotny. An Infrastructure for Realizing Custom-Tailored Augmented Reality User Interfaces. *IEEE Transactions on Visualization and Computer Graphics*, 11(6): 722-733, 2005.

[7] Enylton Machado Coelho, Blair MacIntyre, and Simon J. Julier. OSGAR: A Scene Graph with Uncertain Transformations. In *Third IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR'04)*, pages 6-15, 2004.

[8] Chris Dede, Marilyn C. Salzman, and R. Bowen Loftin. ScienceSpace: Virtual Realities for Learning Complex and Abstract Scientific Concepts. In *Proceedings of IEEE VRAIS '96*, pages 246-252, 1996.

[9] Andreas Dünser and Eva Hornecker. Lessons from an AR Book study. In *First International Conference on Tangible and Embedded Interaction 2007*, to be held in Baton Rouge, Louisiana, pages, 2007.

[10] Andreas Dünser, Hannes Kaufmann, Karin Steinbügl, and Judith Glück. Virtual and Augmented Reality as Spatial Ability Training Tools. In *CHINZ 2006*, University of Canterbury, Christchurch, New Zealand, pages 125-132, 2006.

[11] Joseph L. Gabbard, Researching Usability Design and Evaluation Guidelines for Augmented Reality (AR) Systems, vol. 2006, 2001.

[12] Joseph L. Gabbard, Deborah Hix, and J. Edward Swan. User-centered design and evaluation of virtual environments. *IEEE Computer Graphics & Applications*, 19(6): 51-59, 1999.

[13] James Jerome Gibson. *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin, 1979.

[14] Raphaël Grasset, Multi-users Augmented Reality Environment for small group configuration, in *iMAGIS, GRAVIR Lab*. Grenoble, France: Joseph Fourier University, 2004.

[15] Anders Henrysson, Mark Billinghurst, and Mark Ollila. Face to Face Collaborative AR on Mobile Phones. In *International Symposium on Mixed and Augmented Reality (ISMAR 2005)*, Vienna, Austria, pages, 2005.

[16] Deborah Hix and H. Rex Hartsons. *Developing User Interfaces: Ensuring Usability through Product and Process*. New York: John Wiley and Sons, 1993.

[17] Sylvia Irawati, Scott Green, Mark Billinghurst, Andreas Dünser, and Heedong Ko. "Move the Couch Where?": Developing an Augmented Reality Multimodal Interface. In *To be published in 5th IEEE and ACM International Symposium on Mixed and Augmented Reality*, Santa Barbara, USA, pages, 2006.

[18] Ellen Isaacs and Alan Walendowski. *Designing from both sides of the screen: how designers and engineers can collaborate to build cooperative technology*. Indianapolis: New Riders, 2002.

[19] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Conference on Human Factors in Computing Systems SIGCHI*, Atlanta, Georgia, United States, pages 234-241, 1997.

[20] Hirokazu Kato, Mark Billinghurst, Ivan Poupyrev, Kenji Imamoto, and Keihachiro Tachibana. Virtual Object Manipulation on a Table-Top AR Environment. In *International Symposium on Augmented Reality*, pages 111-119, 2000.

[21] Hannes Kaufmann, Geometry Education with Augmented Reality, in *Ph.D. Thesis*. Vienna: Vienna University of Technology, 2004, pp. 179.

[22] Hannes Kaufmann and Dieter Schmalstieg. Designing Immersive Virtual Reality for Geometry Education. In *IEEE Virtual Reality Conference 2006 (VR 2006)*, Alexandria, Virginia, USA, pages, 2006.

[23] Joseph J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1): 47-56, 2000.

[24] Gun A. Lee, Claudia Nelles, Mark Billinghurst, and Gerard Jounghyun Kim. Immersive Authoring of Tangible Augmented Reality Applications. In *ACM International Symposium on Mixed and Augmented Reality 2004 (ISMAR 2004)*, Arlington, VA, USA, pages, 2004.

[25] Mark A. Livingston. Evaluating Human Factors in Augmented Reality Systems *IEEE Computer Graphics and Applications*, 25(6): 6-9, 2005.

[26] Antoni Moore. A tangible augmented reality interface to tiled street maps and its usability testing. In *12th International Symposium on Spatial Data Handling*, Vienna, Austria, pages 12-14 July, 2006.

[27] Jakob Nielsen and Rolf Molich. Heuristic Evaluation of User Interface. In *Conference on Human Factors in Computing Systems, CHI'90*, pages, 1990.

[28] Donald Norman. *The Psychology of Everyday Things*. New York: Basic Books, 1988.

[29] Donald A. Norman. *Emotional Design: Why We Love (or Hate) Everyday Things*: Basic Books, 2003.

[30] Whitney Quesenbery. Dimensions of Usability, in *Content and Complexity: Information Design in Technical Communication*, M. Albers and B. Mazur, Eds., 2003.

[31] Miguel Ribo, Peter Lang, Harald Ganster, Markus Brandner, Christoph Stock, and Alex Pinz. Hybrid tracking for outdoor augmented reality applications *Computer Graphics and Applications, IEEE*, 22(6): 54- 63, 2002.

[32] Albert A. Rizzo, Gerard J. Kim, Shih-Ching Yeh, Marcus Thiebaux, Jayne Hwang, and J. Galen Buckwalter. Development of a Benchmarking Scenario for Testing 3D User Interface Devices and Interaction Methods. In *11th International Conference on Human Computer Interaction*, Las Vegas, Nevada, pages, 2005.

[33] Dieter Schmalstieg, Anton L. Fuhrmann, Gerd Hesina, Zsolt Szabolcs Szalavári, L. Miguel Encarnaçäo, Michel Gervautz, and Werner Purgathofer. The Studierstube augmented reality project. *Presence - Teleoperators and Virtual Environments*, 11(1): 33-54, 2002.

[34] Ben Shneiderman and Catherine Plaisant. *Designing the user interface*: Pearson/Addison-Wesley, 2005.

[35] Mixed-Reality Lab www.mixedreality.nus.edu.sg/.

[36] A. W. Stedmont and R. J. Stone. Re-viewing reality: human factors of synthetic training environments. *International Journal of Human-Computer Studies*, 55(4): 675-698, 2001.

[37] Debbie Stone, Caroline Jarrett, Maek Woodroffe, and Shailey Minocha. *User Interface Design and Evaluation*: Morgan Kaufmann, 2005.

[38] J. Edward Swan and Joseph L. Gabbard. Survey of User-Based Experimentation in Augmented Reality. In *1st International Conference on Virtual Reality*, Las Vegas, Nevada, pages, 2005.

[39] Colin Ware and Ravin Balakrishnan. Reaching for objects in VR displays: lag and frame rate. *ACM Transactions on Computer-Human Interaction*, 1(4): 331-356, 1994.