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Reflecting on the Design Process for Virtual Reality Applications

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ABSTRACT

A reflective analysis on the experience of virtual environment (VE) design is presented focusing on the human-computer interaction (HCI) challenges presented by virtual reality (VR). HCI design guidelines were applied to development of two VRs, one in marine archaeology and the other in situation awareness simulation experiments. The impact of methods and HCI knowledge on the VR design process is analyzed, leading to proposals for presenting HCI and cognitive knowledge in the context of design trade-offs in the choice of VR design techniques. Problems reconciling VE and standard Graphical User Interface (GUI) design components are investigated. A trade-off framework for design options set against criteria for usability, efficient operation, realism, and presence is proposed. HCI-VR design advice and proposals for further research aimed towards improving human factor-related design in VEs are discussed.

1. Introduction

Several frameworks for virtual environment (VE) design have been proposed to guide designers (e.g. Blom & Beckhaus, 2014; Chen & Bowman, 2009; Sherman & Craig, 2003); however, advice on how and when to apply virtual reality (VR) design features has received less attention. VE interaction techniques and design are frequently presented as application examples (Bowman, 2013; Craig, Sherman, & Will, 2009; Stanney & Cohn, 2007), leaving designers with the problem of generalizing design principles from examples for application in their specific domain. Gabbard, Hix, and Swan (1999) collated guidelines for VE design based on the available experimental evidence, and further design principles were proposed by Sutcliffe (2003), with interaction models to place the principles in the perspective of cycles of user and system actions. Cognitively related design concepts such as embodiment (Kiltner, Groten, & Slater, 2014), place, and plausibility illusions (Slater, 2009) continue to be developed by VR researchers. Experimental evidence on VR continues to accumulate (e.g. Hecht, Reiner, & Halevy, 2006; Slater & Sanchez-Vives, 2014) which could update guidelines; however, as user experience has demonstrated (Hassenzahl, 2010; McCarthy & Wright, 2005; Sutcliffe, 2009), design involves trade-off decisions interpreting cognitive/human-computer interaction (HCI) principles in the context of users and their tasks.

Evaluations of VEs report a variety of good and bad user experience and effectiveness (e.g. Meyerbröcker & Emmelkamp, 2010; Seth, Vance, & Oliver, 2011); however, these studies rarely

reflect on how HCI/cognitive-experimental knowledge was applied to design or how design might be improved by application of design advice. Application of HCI principles to VE design has produced heuristics for evaluating VEs (Sutcliffe & Gault, 2004; Sutcliffe & Kaur, 1997, 2000), and a VE design method that applied design principles in the context of Norman's model of interaction (Norman, 1986) was proposed by Sutcliffe (2003). In a survey of VE design issues, Wingrave and LaViola (2010) list several outstanding gaps for further research, including human experience and perception, design knowledge, and user issues.

In this article, we revisit the above concerns: how to develop and apply knowledge from cognitive psychology and HCI to the VR design process. We describe a case study experience applying HCI principles, reflecting on the effectiveness of the methods applied and lessons learned. In the following sections of this article, related research at the intersection of VR and HCI is first reviewed; this is followed by a description of the case study context in the Cyprus CAVE project, including description of how the HCI methods were introduced. The next sections describe the VE applications developed in two CAVE projects: submarine archaeology and a vehicle-driving simulator for testing new situation awareness designs. The lessons learned in the case studies are summarized with reflection on the difficulties encountered in applying HCI design advice. This is followed by investigation of how human factors design advice might be more effectively organized to inform trade-off decisions involving efficient operation, usability, presence illusions, and effective immersive experience. The tension between realism and effective control in task-oriented VE is discussed, leading to

suggestions for further research on the trade-offs between user experience and usability in VEs.

2. Related work

VE design methods and frameworks (e.g. Blom & Beckhaus, 2014; Chen & Bowman, 2009; Essabbah, Bouyer, Otmane, & Mallem, 2014; Seo & Kim, 2002) have concentrated on analysis of VE design components in taxonomies organized in functional groups or levels, e.g. navigation, selection, manipulation, tools, graphical worlds, etc. The first set of VR design guidelines (Gabbard et al., 1999) offered advice on user interface (UI) design for VE components including navigation, manipulation of objects, visual and haptic feedback, technology trade-offs in design, and principles for immersion. Guidelines on use of components and interaction techniques have advised on user-oriented concerns such as the sense of presence, motion sickness, and perceptual feedback (Hix & Gabbard, 2002). Cognitive phenomena associated with VEs have been investigated leading to conceptual models of presence (Pares & Pares, 2006) and extensions thereof as place, plausibility (Slater, 2009; Slater & Sanchez-Vives, 2014), and the four-senses model of embodiment (sense of self-location, agency, body location, and engagement: Kiltner et al., 2014). While presence has been foremost in design desiderata for many years, articulation of presence in terms of concrete design features has been less straightforward. The multifaceted view of presence/immersion reflected in the evaluation question of Witmer and Singer (1998) has been challenged by evidence that absolute realism is not necessary (Garau et al., 2008). Slater (2009) has argued that the principles underpinning illusions of place, driven by sensor-motor coordination (Noë, 2004; O'Regan & Noë, 2001) and plausibility, relate to the credibility of perceived events. Both illusions and plausibility in particular may be associated with the theory of flow (Csikszentmihalyi, 2002) which argues for an optimal pace in interaction, balancing challenge and difficulty. Psychophysical measures of place and plausibility illusions have been proposed (Slater, Spanlang, & Corominas, 2010), and some design advice for achieving them has been reported; for instance, place illusion is augmented by first-person viewpoints, a dynamic virtual body, and a wide field of view, while plausibility is helped by realistic illumination and a virtual body (Slater, 2009).

Design affordances are discussed by Stoffregen, Bardy, and Mantel (2006) who argue for application of Vicente's (1999) ecological interface design to VEs. This would fit with the need for faithful integration of sensor-motor perception to enhance the place illusion (Slater, 2009); however, ecological interface design principles may clash with the need for overt, non-natural controls in VEs, e.g. navigation for information displays (O'Regan & Noë, 2001). Design heuristics for interacting with VEs proposed by Sherman and Craig (2003) included an approach to user experience design in general terms, with advice on design for audiences, pathways, and trajectory for interaction, although their guidelines did not reference cognitive or HCI design principles.

Chen and Bowman (2009) proposed a general approach to VE design describing three levels of system architecture: application, domain, and generic interactive features, with further advice on design for navigation, selection, manipulation, and system control. Bowman (2013) and Stanney and Cohn (2007) describe general frameworks for VE design and discuss user-interaction issues. Although these frameworks provide designers with classifications of VE functionality and system architecture, few investigations into design trade-offs to ensure usability and user experience have been reported. More detailed frameworks for VE design have been proposed by Essabbah et al. (2014) whose Constraints-Tools-interactive-Tasks framework advises on different means of implementing interaction, user controls, and constraints on object behaviors within VEs. Blom and Beckhaus (2014) propose a design space for dynamic interactive VEs based on taxonomy of modalities, which then inform design of controls and feedback within virtual worlds, with further advice on temporal dynamics, scene manipulation, and propagating effects from external applications to virtual agents. Chen and Bowman (2009)'s framework composed of three levels (application, domain, and generic interaction) provides more detailed advice on design of interactive controls for navigation, selection, and manipulation of objects, as well as system controls for changing VE properties and behavior, and interfacing to external applications and simulations.

Domain-specific design approaches have been reported for VEs in architecture and urban planning (Drettakis, Roussou, Reche, & Tsingos, 2007), proposing user-centered design with advice on viewpoint controls, evaluation, and iterative design. Another example in VEs for educational applications (Vosinakis & Koutsabasis, 2012) focused on a wider system-level socio-technical design, with some guidance on design of the VE system architecture for learning, collaboration, and communication tools, with avatars in a SecondLife implementation. However, domain-specific experiences and design approaches are difficult to generalize to other applications.

Based on a survey of VR application developers, Wingrave and LaViola (2010) described a list of 67 issues organized in 11 themes: design for human experience and perception, the need for design knowledge, prototyping, model representation, events and call-back handling, lack of early evaluation, hidden dependencies, poor design practice, user issues, and implementation problems. They identified five research challenges: natural representations, layered abstractions (e.g. system architecture and tools), creating models of systems, supporting reuse, and trade-off techniques to deal with difficult problems. This article reflects on VR design experience in attempting to apply human factors design advice with a particular focus on trade-offs, leading to further investigation into how design advice might be organized to deliver more effective immersive experience.

In conclusion, the literature provided several design frameworks and some design guidelines, but these were not apparently grounded on the psychology of interaction in VR environments. Our starting point was to apply more comprehensive design principles and guidelines which were grounded in psychology (Sutcliffe, 2003, 2009), with a systematic approach informing how such knowledge should be applied in design to maximize its effectiveness (Sutcliffe, 2000; Sutcliffe & Carroll, 1999).

3. Design experience case studies

Case studies were conducted under the umbrella of the Cyprus CAVE project which introduced VR technology into the Cyprus University of Technology as a research resource coupled with the aim of producing practical applications. The first author was engaged as a consultant on the project to provide research expertise in HCI. During the initiation phase of the project, HCI design knowledge was disseminated through presentations and seminars.

3.1. HCI design advice and training

Application of HCI knowledge was based on the models and principles approach described by the lead author (Sutcliffe, 2003), supplemented with user-centered design which was already practiced by some team members. User-centered VE design principles and guidelines from the literature (Hix & Gabbard, 2002; Sutcliffe, 2003; Chen & Bowman, 2009; Slater, 2009) were delivered by presentations and seminars with practical design exercises. The HCI issues addressed included: interaction design for navigation and manipulation, active objects in the VE, feedback from interaction, translating domain models into VEs, cross-modal feedback, realism and representation trade-offs, and scripting virtual actors. The psychological constraints on user interaction, e.g. selective attention, working memory limitations, visual dominance, and sensory integration, were explained to help understanding the design guidelines. Twelve HCI design heuristics for VR applications (see Sutcliffe & Gault, 2004) were presented with examples:

- (1) Natural engagement: mapping action and representation in the VE to the real world.
- (2) Compatibility with the user's task and domain: VE controls should correspond to the user's expectations and task action.
- (3) Natural expression of user's action by devices, metaphors, and UI controls.
- (4) Close coordination of action, feedback, and representation.
- (5) Realistic feedback using VE components rather than GUI components.
- (6) Faithful viewpoints: change in the VE display conforms to user's motion and expectations.
- (7) Navigation and orientation support.
- (8) Clear entry and exit points (into/out of a virtual world).
- (9) Consistent departures.
- (10) Support for learning.
- (11) Clear turn-taking, between user and system initiative.
- (12) Sense of presence.

Heuristics 1, 2, 3, and 6 related to making VE interaction correspond as closely as possible to the user's real-world expectations, and heuristics 4 and 5 extended these to advise on presenting immediate and clear feedback for user actions. Specific design features to support interaction were described

in heuristics 7–10, such as navigation techniques, helping users discover interactive features by active explanation within the VE, and clarifying designs which compromised presence and naturalness. Design advice was cross-referenced to evaluation methods for immersion/presence (Witmer & Singer, 1998) and to other measures for user experience in VEs (Slater, 2009).

In the reported case studies, the recipients of HCI knowledge were researchers and graduate students associated with the Cyprus CAVE project who developed the case study applications. HCI knowledge was presented in a series of workshops with examples of VR applications and design problems. The guidelines and user-centered design process were explained in PowerPoint presentations and then the participants were invited to apply the HCI design principles to a series of VR problem scenarios.

3.2. Project background

The VR CAVE installation consisted of four projection screens (three back-projections for the walls and one front-projection for the floor) with head tracking and active stereo glasses to provide the users immersive experience with stereoscopic images. The system was implemented on four Intel Xeon 64-bit CPUs at 2.60 Ghz, with NVidia Quadro 6000 graphics card, each one responsible for one screen and each with a resolution of 1600 × 1200 pixels. The infrared Vicon tracking system gave 6 degrees of freedom (DOF) tracking by markers placed on 3D glasses to render the scene from the user's point of view. The user was also provided with an Xbox controller, which was tracked and used for navigation and manipulation of the VE.

EON Studio software APIs were used for the development and presentation of VR applications. EON Studio 8 provides a library of predefined nodes and prototypes with ready-made functionality (such as for tracking, displays, and Xbox controller navigation), which were used to add interactivity. The prototypes were connected with the 3D models and UI via the Routes section of the EON Studio 8 environment to provide the functionality and interactivity for the developed application.

The EON graphical authoring tool, catering for non-programmers and programmers alike, was easy to learn and use. With the advantages of pre-programmed functionality, quick import of most generic CAD and 3D formats, the ability to quickly alter and reuse content, and its compact file format, this tool helped to minimize the development time needed for applications. The EON system's functionality was extended using script languages (Jscript, VBScript) to create custom prototypes and connecting VEs with simulation components and databases.

3.3. Case study 1. Marine archaeology

The application design approach was to engage the users, research archaeologists, from the beginning of the project. This user-centered approach, which aimed to produce an application with a high degree of usability, required collecting and analyzing as much information about the end users as possible, through a detailed user requirement process (Carroll, 2000; Drettakis et al., 2007; Rogers, Sharp, & Preece, 2011).

User-centered design process

User-centered design started with defining the user needs, information requirements, and functional specifications. These were developed through a series of interviews with the Archaeology Research Unit user team (University of Cyprus) at the Cyprus University of Technology. Users were involved in the design process through direct feedback, observation, and testing mock-ups and prototypes. Discussion in joint user–designer workshops established user research workflows and practices when they investigated their domain: submarine archaeology of ancient shipwreck sites where excavation of delicate amphorae was a critical task. The user teams worked collaboratively, with frequent meetings to exchange observations about the site findings and visual inspections of the documented data to investigate research questions. Site plans, maps, photographs, and drawings were used as tools to observe site features and excavated objects.

A problem with the users' existing research process was the inability to synthesize and examine data simultaneously. Photographs and artifact information had to be retrieved from databases, loaded into the 3D site model in a CAD system, and cross-referenced to geographic information system data. The lack of data integration, and the capability to place data in the 3D context of the underwater sites, made the process time-consuming and inefficient. Two problems were investigated in more depth to understand detail in the users' research.

The first concerned changes in seabed levels occurring at different stages of the site formation process. The users needed to be able to inspect photographic detail of excavated amphorae, mark where textures occurred on them, and locate the amphorae in the site so the history of erosion and biological activity revealed how the seabed might have changed. The suggested user controls for analyzing the distribution and correlation of texture clues and dividing the virtual domain model into layers to reflect change over time.

The second concerned amphorae positions in the bow area of the ship where the location and fragmentation of the amphorae may indicate a wreckage episode and/or deterioration of the ship's hull. Investigation suggested requirements for recreating amphorae based on their fragments and manipulation controls for artifacts in the VE.

The top-level user goals were the ability to integrate information from different data types and sources, within a 3D model of excavation sites, to be able to inspect data with flexibility, and to manipulate objects in a complex spatial environment to investigate different spatial distributions and how these might evolve over time. Manipulation facilities were needed to reconstruct objects (amphorae) from components (fragments) and place objects in a variety of hypothetical topographies; hence, there was a tension between realistic presentation, presence and immersion as VE qualities and usability/functionality in controls for information presentation and task-related artifact manipulations

Design trade-offs

The domain model was based on the 3D geography of the site and objects therein, structured in an excavation history that

could be revealed by removing layers, as well as the ability to create hypothetical layers representing possible seabeds and sequences of marine deposits.

HCI knowledge was applied to create an intuitive UI with wire-mesh frame layers to visualize different site topographies, and a set of overlays and pop-up panels displaying contextually appropriate information within the VE when the user selected amphorae, layers, and other active areas/objects, e.g. part of the ship. The decision to use an Xbox controller as the main physical user control device was justified by limitations on haptic feedback provided by data gloves, which could have created cognitive dissonance for the users, although a sense of touch is a vital part sensor–motor coordination necessary for presence and place illusions. The Xbox controller was a design compromise between the usability of controls for self-navigation, object manipulations, and information displays, at the expense of haptic feedback and some compromise for the sense of immersion and presence.

The interface consisted of menus, icons, and information panels (see [Figure 1](#)), through which the user could view research data. The information panels supplied artifact information from external databases and photographs, in sequences from original artifact discovery, during the excavation process to clean-up in the museum.

Navigation used the Xbox control stick with ray-casting interaction to select objects, while buttons enabled users to change views for layers and predefined locations, and manipulate objects.

It took four person-months to design and develop the VR application, from the user requirements specification to the user-testing phase.

Evaluation

The evaluation methodology drew on the structured framework discussed in several surveys (Bach & Scapin, 2010; Bowman, Kruijff, Laviola, & Poupyrev, 2004; Gabbard et al., 1999; Hix & Gabbard, 2002; Livatino & Koeffel, 2007) for conducting user testing to evaluate VEs. This included user needs analysis, user task scenarios, usability evaluation, and formative evaluation, prior to a summative evaluation. First a heuristic evaluation by two usability experts was carried out to identify usability problems. The experts inspected the UI against a list of usability heuristics (Sutcliffe & Gault, 2004) for VR applications. The findings led to the improvement of the interface and the application itself and were implemented in subsequent versions of the prototype.

This was followed by further formative evaluation, where users were observed carrying out a range of representative exploration and information search tasks with the VE, in which further design problems were identified leading to improvement in the manipulation controls and information displays. A summative evaluation using a questionnaire derived from previous VR evaluations (Kalawsky, 1999; Slater, Usoh, & Steed, 1994, 1995; Witmer & Singer, 1998) was carried out on the prototype to ascertain users' judgment on usability and their experience. User reactions to the UI operation and functionality were favorable; however, response to the interaction

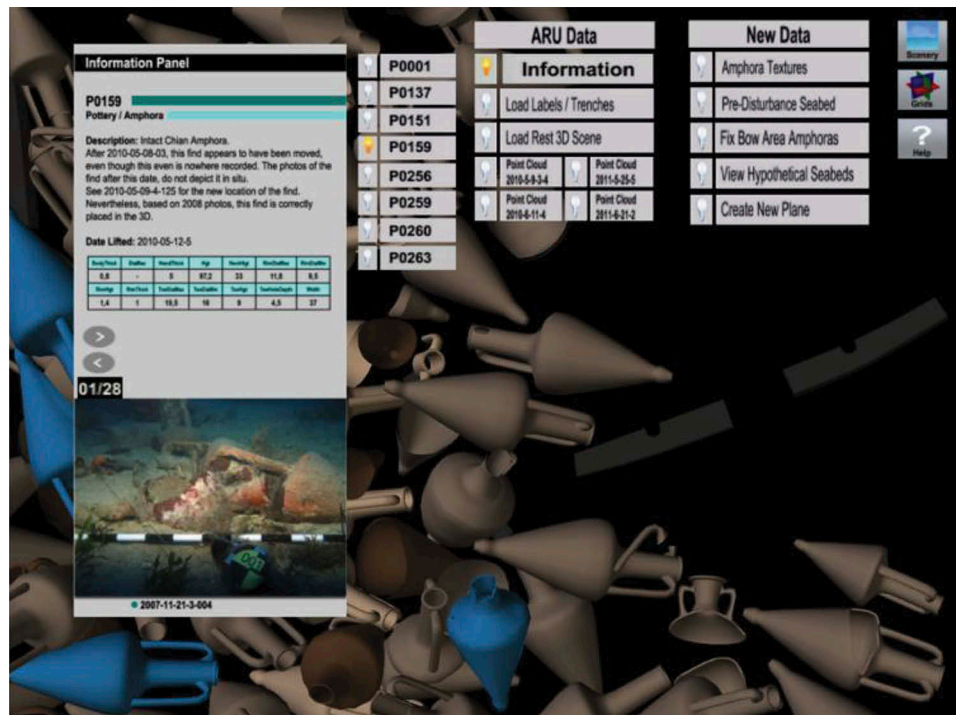


Figure 1. User interface of the Marine Archaeology VE, showing amphorae in situ, with information display panels and menus. Highlighted amphorae are associated with external data and photographs.

questions was mixed although the Xbox controller was considered to be easy to use. User ratings of application output, information displays, help, and guidance were good. The users agreed that the UI was consistent and the VE and overall ratings were very positive. Further details of the questionnaire and the results can be found in Katsouri, Tzanavari, Herakleous, and Poullis (2014).

In interviews, users commented that the application was a useful research tool because it enabled them to view and examine complex and visually rich data with ease and from new vantage points. On the other hand, doubts were expressed about whether clear, accurate answers could be obtained from using the application alone, as the archaeologists only trusted physical evidence. Comparing the VR CAVE application with their traditional workflow, all users considered the VE to be more time-efficient because it enabled them to view all types of data simultaneously in one environment. The users also suggested design improvements to incorporate in additional data, such as environmental information regarding sea currents, sedimentation, the hardness of the seabed, and other external data. They also noted that the application could stimulate new research ideas as well as being a valuable publicity tool for explaining their work to other researchers and the public. However, long-term work-related use did not occur beyond the proof-of-concept demonstration stage. Although we could not collect formal data on the reasons for longer-term user engagement, informal feedback suggested three reasons:

(i) Scale and data integration, a more comprehensive database and wider-ranging VE might be necessary for effective research use.

(ii) The VE was not sufficiently compelling for the users to change their current work practices with photographs, drawings, text, and database interaction.

(iii) User controls, although usable, interrupted the sense of VE immersion, suggesting a possible problem in their workflow (Csikszentmihalyi, 2002).

Overall, this project demonstrated some success for the user-centered design approach and application of HCI principles and heuristics. An effective and usable application was produced, but the longer-term failure to engage users indicated problems with integrating information-intensive systems architecture into CAVE environments.

3.4. Case study 2. VE for vehicle driver experiments

Research questions in safety engineering in the automotive industry motivated the Situation Awareness in Driving Technology (SADT) project: how to improve driver safety by advanced in-vehicle displays to provide warnings about potential road hazards. The project investigated the human factors-safety engineering of in-vehicle driver displays.

Design process

Guidelines for enhancing driver situation awareness (Endsley, 2004) were expressed in information requirements, visualization metaphors, and interaction styles. Two designs were produced for in-vehicle hazard warning display: first, a radar-like display showed a map of the immediate environment with streets, other vehicles, and potential road hazards. The second hazard warning design projected warning arrows on a head-up display (HUD) to direct the driver's attention to potential hazards, such as hidden vehicles and road junction

blind spots. The two designs tested hypotheses about the quantity and quality of information provided to the driver, i.e. is a minimalist hazard warning design better than the more information-rich radar display in helping drivers avoid accidents?

The VE represented a driver's in-vehicle first-person viewpoint, with HUDs for the two hazard warning designs coupled with a simulation functionality that could control the VE through different journeys within the domain space. Different routes were selected and elaborated with hazards drawn from accident reports. These baseline scenarios were then augmented with varying types of traffic conditions, road infrastructure, and signaling along the streets, such as speed limits and direction signs. Additional experimental research support requirements included data logging of driver behavior. A high degree of realism, with both place and plausibility (event-action) illusions (Slater, 2009), was necessary to simulate the driving experience as closely as possible.

Design

The VR design process consisted of three phases: first, development of the test environment with buildings, road infrastructure, and traffic flow. The second phase concentrated on scenario modelling in collaboration with the domain experts. These included atypical events in the simulation that would stress test the subjects in the experiment. The third phase included modelling of the VE and the agent scripts for vehicle controls and simulated hazards.

A section of the Nicosia road network was extracted from OpenStreetMap, and then a 3D model was generated through the manipulation of objects in CityEngine. The final model was exported into a Unity 3D game-development environment. Autodesk Maya graphics software was used for the 3D modelling and animation for the vehicles and other artifacts (e.g. traffic lights, advertisement billboards) that were imported into the Unity game engine used to program scripts to control the physical and environmental aspects of the simulation. The host vehicle controller enabled the user (i.e. participants in the experiment) to drive the vehicle in the virtual city environment using physical pedals and steering wheel controls. Autonomous vehicle controllers executed scripts to realize behavior of each vehicle to create different traffic conditions depending on the scenarios that needed to be modelled. Each autonomous vehicle dynamically decided its route, avoided obstacles, and altered its speed depending on the traffic. The data-logger component recorded the driver's behavior for each participant, along with additional data relating to the traffic conditions and physiological state of the driver, such as from electroencephalograms. The driver VE interface is illustrated in Figure 2.

Evaluation

Before the actual experiments, several evaluation sessions were carried out with professional drivers who were asked to drive in a modelled road section of Nicosia. These experts verified the sensitivity, steering, acceleration, and deceleration behaviors of the simulated vehicle, identifying several problems. In addition, the early versions of the driving simulator suffered from a low refresh rate that led to motion sickness



Figure 2. Driver VE view with the radar HUD depicting surrounding vehicles. The red circles are warnings about cars approaching on the left side.

and poor realism. To resolve these issues, the simulation scripts were improved until the vehicle behavior was satisfactory. The final version of the simulator was validated by five expert drivers who all agreed that its behavior was realistic and provided appropriate sensor-motor feedback. The subsequent testing involved collection of experimental data from the user behavior logs which were analyzed for performance data on safe driving and through several questionnaires to elicit the participants' awareness of road hazards. The 30 participants all rated the sense of immersion and realism favorably (means >3 on a 1–5 scale) and reacted rapidly to hazards showing expected emotions responses of anxiety and fear. The VE design appeared to deliver effective sense of presence and plausibility. Since the HUD task performance data do not relate to the VE design, it is not reported in this article.

4. Reflections on the case study experience

In this section, we reflect on the lessons learned during the case studies, followed by methodological recommendations to address some of the problems encountered in VE development.

4.1. Marine archaeology

The Marine Archaeology project followed a user-centered design approach with iterative development and evaluation which produced an effective and usable prototype. However, this project raised several problems for the design of complex information displays within the VE; little HCI design knowledge was applied to this problem, primarily because it was viewed as a specialized problem and no relevant design advice was available. In spite of this limitation, a usable interface was produced following principles of providing clear cues and metaphors to make it as intuitive as possible. The designers primarily focused on fusing the multi-modal information in such a way that the experts (marine archaeologists) would find it "acceptable". Requirements imposed by the experts, for example, for manipulating domain model layers, could have been realized by several different VR techniques, e.g. see-through transparent displays, viewpoints and navigation

controls in each layer, or controls to manipulate and assemble layered models. Standard menu designs as floating panels in the VE were chosen on the grounds of usability of familiar HCI operational metaphors (sliders, menu buttons, etc.). However, these components from traditional 2D GUIs did not blend well with the VE experience and made the immersive experience less compelling.

4.2. SADT in-vehicle virtual display

The SADT project also followed a user-centered design approach creating a usable and effective VR experimental system. Design in this application was constrained by the experimental requirements, so application of HCI knowledge was directed towards the need for realism and presence. This informed the choice of the physical driving controls, i.e. steering wheel, brake pedal, etc., as found in real vehicles. The VE design had to be realistic and provide a good sense of presence, but this was only realized after extensive user testing. No self-representation (i.e. arms, hands gripping the steering wheel) was included, and this may have hindered the action's plausibility (Slater, 2009). In retrospect, better application of VR design knowledge, in particular, use of head-mounted displays, might have improved place and plausibility illusion, although sensor-motor feedback and the driving experience were considered to be realistic.

4.3. Design implications

The case study experience of applying HCI knowledge to VR design produced mixed results. VR designers found HCI design principles were difficult to interpret; furthermore, general principles and heuristics did not inform trade-off decisions. An important issue identified from experience in both projects was the need for trade-off advice to guide designers' choice for several problems, e.g. selecting VR interaction techniques, designing agents and active objects within VEs, and controls for complex information displays in VEs. At a more fundamental level, the applications raised a question about integrating design in applications where the user's task, and hence user control, is dominant, in contrast to applications where the user's experience is the dominant concern.

In task-directed applications (e.g. marine archaeology), usability and intuitive easy-to-learn controls are important, although familiar controls might compromise the sense of presence since the user is acting on standard UI components or performing actions with insufficient haptic/kinesthetic feedback. These limitations could degrade both place and plausibility illusions (Slater et al., 2010) because sensor-motor feedback may be impaired by GUI components and floating menus by creating dissonance with the virtual world and the context of immersive interaction. In less task-oriented, experimental applications, VE design should enhance immersion and plausibility rather than usability, since the objective is to deliver an immersive experience where the user has less initiative and is guided through the VE. The Marine Archaeology application fell into the first category of user-initiative task-oriented applications, while

the SADT application was closer to the second even though the user was an active driver of the virtual vehicle. The balance of task and experience orientation could be traced to users' requirements and their roles. If users wished to explore the VE in an entertainment role, then experience was more salient; alternatively when users had specific objectives they wished to achieve with the VE in a work role, a task orientation was indicated.

This led us to consider how flow might be related to usability and task effectiveness on one hand and presence, place, and plausibility on the other. Trade-offs involving usability and VR user experience could be simplified into three qualities for presence/realism, intuitive actions or affordances, and flow in interaction (Sutcliffe, 2009). Cognitive dissonance, caused by unnatural and awkward controls, will disrupt flow in interaction and presence. Simulation and information display menus may impose artificial elements which do not belong in realistic virtual worlds, thus presenting a design dilemma: how to provide users with the necessary controls without reducing presence. In the SADT project, VE plausibility and flow in the driving experience was paramount. This was interrupted by the constraints of the Situation Awareness Global Assessment Technique (Endsley, 2004) experimental method which specified that situation awareness should be measured by questionnaire-based techniques at critical checkpoints in the driving scenario. Within these experimental constraints, the VE design did appear to achieve good flow, accompanied by presence-plausibility illusions. In contrast, flow in the Marine Archaeology application was disrupted by floating menus which changed the "frame" of interaction, from immersive exploration of the archaeological site to more task/information-based interaction. We suspect the transition between these two interaction frames may have made the VE design less compelling.

These reflections were refined into a set of interrelated design questions focused on interpreting the user's task into actions within the VE:

- (i) What strategy should be adopted for interaction within the VE? Options ranged from complete user initiative for achieving task goals to system initiative to guide users through an interactive journey within the VE.
- (ii) How active/passive should the user be? More active users will need sophisticated abilities to manipulate objects in the VE and control system functionality.
- (iii) How to implement users' task requirements as explicit controls and scripts for reactive agents/artifacts within the VE?
- (iv) How to provide feedback and information and associated search facilities?

In the SADT application, the answers pointed clearly towards a mix of user and system initiative constrained within the frame of the driving experience. Explicit driver controls with a mix of planned and reactive scripts for pedestrians were constrained by the experimental design.

The balance of user/system initiative focused attention on the role of external components which control behavior either of the whole environment or agents within simulation, decision-support sub-systems, and database applications. The

4.4. Reformulating design advice

The maps acknowledge that many trade-offs are not a discrete choice, as represented by claims and patterns; instead, many decisions are choices along a dimension.

The passive-self branch has implications for reactive artifacts and the VE itself, as well as for active agents within the VE. Both external components and the user task inform design choices. Generally, more active VEs should enhance both place and presence illusions (Kiltner et al., 2014; Slater et al., 2010), although inappropriate actions and effects can rapidly disturb illusions (uncanny valley?). The question marks on the arcs in Figure 4 denote open research questions about where design might create illusion-destructive dissonance, e.g. active agents with poor artificial voices, inappropriate appearance.

User-presence decisions are presented in a trade-off sub-map in Figure 4. Four design options are illustrated, which are

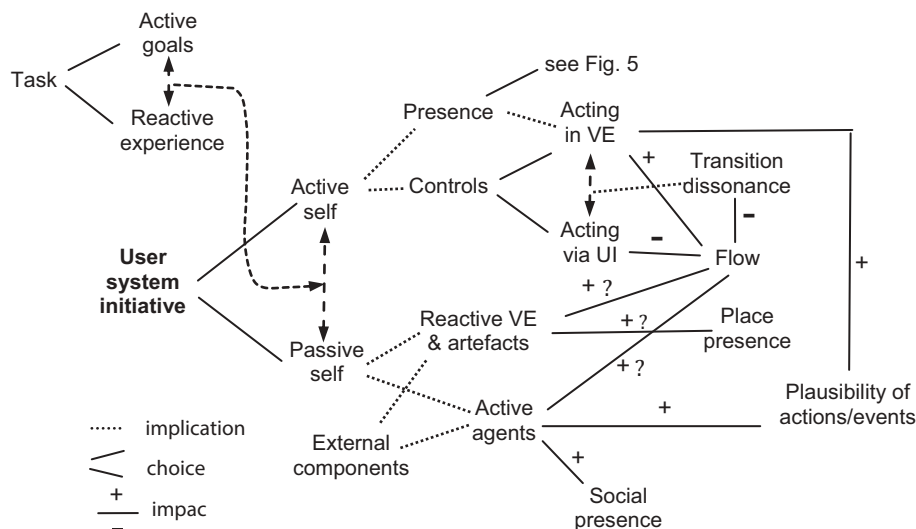


Figure 3. Design trade-off map for the system initiative question.

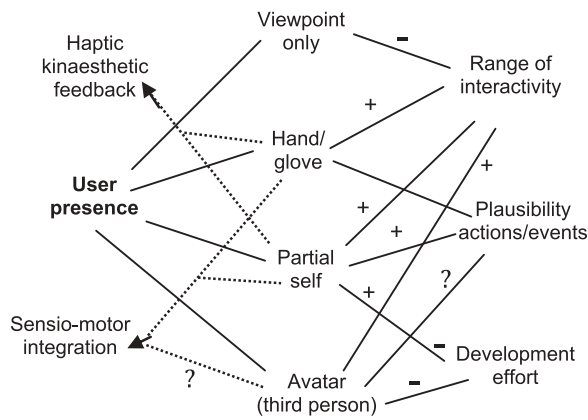


Figure 4. Presence design trade-offs, presented in a claims format graph.

cross-referenced to trade-offs according to three criteria: the range of interactivity, which will be a consequence of the user's task from Figure 3; action-event plausibility; and the more mundane development resource.

Richer presence options tend to enhance action-event plausibility, although incurring more development costs for implementations of partial self-representation of arms, limbs, and bodies. Haptic/kinesthetic feedback and sensor-motor integration become important design implications in delivering plausibility, particularly partial self-representation (Slater, 2009). Further research is required to inform these design trade-offs, particularly between choices of avatar self-representations which pose further issues of user controls, third-person versus first-person viewpoints, and the degree of self-visible in the VE.

Application domains may impose information requirements varying from minimal to intensive. In the Marine Archaeology application, there were considerably more quantities of object, location, and spatial information for research purposes. Design possibilities to satisfy the information requirements, such as floating panels in the VE, audio explanation by objects, and pop-up panels prompted by bounding-box algorithms, have their origins in multi-media design and visualization. The design trade-offs for this problem are

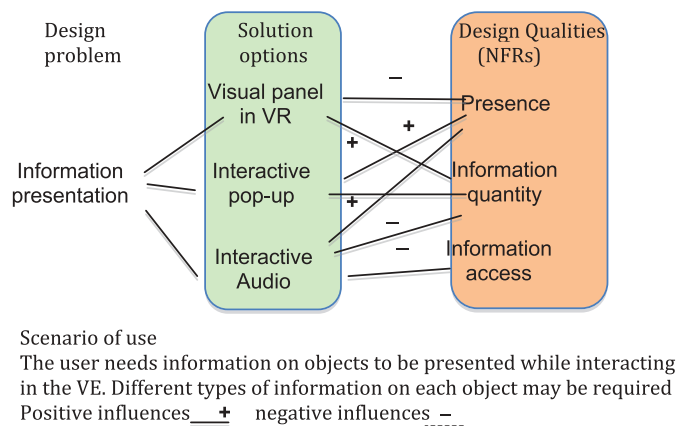


Figure 5. HCI design trade-offs represented as a claim.

summarized in Figure 5 in the claim format (Carroll, 2000; Sutcliffe & Carroll, 1999).

The claim shows the design context as a scenario of use linked to a design rationale diagram illustrating three possible design solutions. Links from solution options to the design qualities are arguments for and against each solution, so designers can trade off the best option given the desired design qualities. For example, the interactive pop-up display would have had a positive effect on presence and information quality and quantity, since only information relevant to the object encountered by the user would be shown. Audio feedback would also preserve presence, but information would not be persistent, hence less accessible and of worse quality and quantity. The choice of feedback modalities depends on the need for persistent information and minimizing interruptions to the user's presence. Audio feedback avoids interfering with visual perception. Haptic feedback is desirable when manipulations are pressure sensitive. The menus and panel displays chosen in the Marine Archaeology case study tended to obscure the user's view of objects within the VE, so the design could have been improved by, for instance, translucent information displays, although these might have impaired readability.

To supplement design decisions with claims, we propose new heuristics to enhance presence, plausibility, and flow, which should lead to a more engaging user experience.

- (i) Natural action-control mapping: to maximize plausibility. Object manipulation and controls related to the user's task need to leverage natural affordances for any known interaction metaphors. Actions are realized via a variety of devices (e.g. data glove, 6-DOF controllers) mapped to VE elements (hands, arms, and artifacts) combined with a choice of feedback modalities (audio, haptic, and visual). These design choices will be informed by the degree of presence and realism required and implementation cost. Behavior of artifacts within the VE intersects with the self-actions for selection and activation by ray casting and bounding-box intersection (Essabbah et al., 2014).
- (ii) Avatar competence: representation of other as avatars or Embodied Conversational Agents within virtual worlds leads to the expectation of a response. While realistic movement and appropriate facial expressions can enhance the sense of presence, interactive spoken dialog can rapidly exceed the capacity of natural processing implemented in most agent tools. Inappropriate responses will create dissonance leading to impaired presence and flow. The moded interaction principle ((i) above) should guide this trade-off.
- (iii) Interaction modes: in applications where unnatural VE components are necessary, e.g. VE simulations which have iterative parameters and are then run, structure UI dialog with separate sub-sections for simulations of environment controls. An explicit command to shift between acting in the VE and operating on the VE should be provided. This

extends the established HCI principle of “moded interaction” (Rogers et al., 2011) which advises design of sub-dialogs for separate user goals with obvious entry and exit points. For example, the VE can be set to immersive interaction mode, external parameter setting, or a less immersive mode with artifact explanation.

4.5. Final reflections

Having revisited the design process, we naturally considered hindsight-based revisions to our designs. The Marine Archaeology ideal was for users to be fully immersed in the VE with a strong sense of place to optimize engagement with the VE, one of the weak points discovered in the longer-term evaluation. However, this ideal was compromised by the need for database search and object manipulations to fulfil the user’s research task with the ability to view related information in the VE. A more optimal design choice might have been to employ context-sensitive pop-up information displays with translucence to improve flow and place illusions. Audio/speech delivery may not have been suitable because the information needs to be persistent for reading detail. Another trade-off could be between implementing the search interface either within the VE (as we did) or as an external UI to reduce dissonance and interruptions to flow. The user audience prompted other possible choices between a passive user, fully immersive VE for tourism applications (one of the user’s suggestions), and a research-oriented application. For example, investigating changes in the seabed over time could have been implemented by a simulation controlled by user-supplied parameters. The application could have been designed with more complex controls to replay the history of excavations or simulate the evolution of seabed deposits. Instead, a simpler implementation was chosen with UI controls to manipulate the layers. This trade-off was informed by the user’s role as researcher. Simple but flexible manipulations of amphorae artifacts facilitated dynamic exploration of research questions, whereas programming simulations would have interrupted the flow of research investigation. Displays of artifact information could have used proximity-sensitive displays within the VE or Xbox button display controls, so the user could take the initiative to change between the two modes, action in and action via the UI. Automatic display information from proximity of the user’s presence could facilitate better contextual analysis of artifacts, while audio-speech feedback might have reduced the amount of the VE obscured by information display panels.

In the SADT application, most design choices were constrained by the experiment, although a partial self-presence with visible arms and legs could have improved action plausibility. Tests demonstrated the importance of sensor–motor coordination for presence. Several information feedback/presentation options could have been used, for example, audio warnings, haptic feedback via the steering wheel, or other visual feedback designs showing the driver’s vehicle within the map display. The design choices made were informed by the experimental design and

reference to the human factors literature; however, cognitive principles (e.g. flow and plausibility) could have facilitated more effective reasoning about these trade-offs, both in the real world and the virtual simulation. In the radar design experimental condition, the conflict between scanning the road while driving or viewing the radar may have diverted the driver’s attention from the road. In contrast, the arrows design only appeared when a hazard was proximal, so this created an involuntary mode switch from driving to searching for the hazard. This may also have selective attention consequences and reduced situation awareness.

5. Discussion

VR design in the case studies did not follow a detailed method for specification and design; instead, an iterative user-centered development approach was adopted with cycles of prototyping and evaluation. This contrasts with structured method specifications (Seo & Kim, 2002); however, the difficulties we encountered in translating requirements into VR architecture components might have benefited from more detailed specification. The approach we adopted followed user-centered practice in HCI (Carroll, 2000) and it did produce usable applications. Others have used user-centered approaches in VR design reporting successful outcomes (Drettakis et al., 2007). A similar application to the vehicle SADT VR was reported by Kwon and Chun (2010) who focused on design advice to enhance perception of velocity in driving simulations. They produced guidelines on user viewpoint, display texture, and controls, although wider-ranging design guidelines were not applied.

The initial motivation to apply HCI knowledge to the scenario-based approach was only partially successful. HCI was presented as a set of minimal heuristics (Sutcliffe & Gault, 2004); however, our experience suggests a dilemma between presenting easy-to-assimilate HCI and giving designers sufficient background knowledge to interpret high-level heuristics. The lack of HCI/cognitive psychology background in the design teams was a major factor in restricting its influence. While our study focused on VR CAVE technology, we believe that the problem of HCI sensitive design for VR applications will apply across a range of technologies, e.g. Head Mounted Displays and desktop VR such as SecondLife. In collaborative VEs, further social knowledge may be necessary to plan the interaction between people in the real world and their presence and other entities in the virtual world, for example, in agent-based virtual worlds. (Chaturvedi, Dolk, & Drnevlch, 2011)

VR design frameworks and guidelines were not easy to apply. VR interaction design methods have tended to concentrate on design for generic actions, navigation, selection, and manipulation (Bowman et al., 2006; Chen & Bowman, 2009), with little advice on trade-offs related to the user’s task, e.g., design for usability and efficient operations versus realism and immersive experience.

Blom and Beckhaus’s (2014) extensive taxonomy of VE interactions provides further detail which could be used to extend our proposals. Their system controls extend Chen and Bowman’s (2009) conception, adding indirect controls on VE parameters, control of simulations, and direct

controls on object-object interaction. Constraints on object behaviors within the VE (Essabbah et al., 2014) can inform design of interactive behavior and feedback, such as responses to self/object proximity or deformation constraints when manipulate. However, these authors offer no advice on cognitive and HCI trade-offs when selecting interactive techniques, and this is one of the contributions of our work. While cognitive issues pertinent to immersion, presence, and embodiment have been extensively researched in VR (Kiltner et al., 2014; Kober & Neuper, 2013; Pares & Pares, 2006; Slater & Sanchez-Vives, 2014), advice on interaction design has received less attention. We have added the principle of moded interaction as a consequence of our design experience, although the case studies also demonstrated that applying HCI principles and guidelines is difficult. We argue that VR design needs contextually sensitive design advice, i.e., cognitively sound principles explained in the context of requirements and system design options. Jacob et al. (2008)'s realistic design framework proposes cognitive-based criteria of body, environment, and social awareness and argues for a trade-off between expressive power for fulfilling the user's tasks in an efficient manner, although this may compromise realism in VEs. Presentation of design advice has been debated extensively in HCI with the consensus leaning away from structured methods and complex design space taxonomies (Carroll, 2000; Sutcliffe, 2000; Sutcliffe & Carroll, 1999). Claims and design patterns are simpler informal means of presenting design advice in trade-off maps, and these representations might be profitably applied to VR design. Although a few VR design patterns have been presented (Jerald, 2015), these are a minimal starting point which need to be scaled up; furthermore, the concept of representing and managing design trade-offs has yet to be addressed.

While there are limitations in the generalizability of our findings from the specific case study context, we believe that ecologically based study of HCI in practice produced better insight than might have been gained from experimental comparisons of design practice with and without HCI knowledge. Such studies are fraught, are resource intensive, are difficult to control, and lack external validity. In conclusion, the contributions of our research are reporting experience and insight into the problems encountered when applying HCI knowledge to VR design. Our experience did not resolve these problems although it has led to a new proposal for context-sensitive design advice which we will develop in further research. In our future work, we will adapt VR design taxonomies (e.g. Blom & Backhaus, 2014) with scenarios describing the design context augmented with HCI advice and test the effectiveness of the claims format with VR designers.

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