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DEMYSTIFYING THE DESIGN OF MOBILE AUGMENTED REALITY APPLICATIONS

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Abstract

This research proposes a set of interaction design principles for the development of mobile augmented reality (MAR) applications. The design recommendations adopt a user-centered perspective and, thus, they focus on the necessary actions to ensure high-quality MAR user experiences. To formulate our propositions we relied on theoretical grounding and an evaluation of eight MAR applications that provide published records of their design properties. The design principles have then been applied to guide the development of a MAR travel application. We performed a field study with 33 tourists in order to elicit whether our design choices effectively lead to enhanced satisfaction and overall user experience. Results suggest that the proposed principles contribute to ensuring high usability and performance of the MAR application as well as evoking positive feelings during user and system interactions. Our prescriptions may be employed either as a guide during the initial stages of the design process (ex-ante usage) or as a benchmark to assess the performance (ex-post usage) of MAR applications.

Keywords: mobile augmented reality, design principles, field study, user experience

1. Introduction

The concept of Mobile Augmented Reality (MAR) was developed around the mid-1990s, applying Augmented Reality (AR) in truly mobile settings, away from conditioned environments, confined spaces, and the desktop [1]. MAR combines wireless communication, location-based computing and services (LBS), and augmented reality to create an integrated interactive environment. The ongoing rise of MAR has become evident with a large body of publications describing enabling development platforms and applications, such as Layar, Wikitude and Junaio [2]. MAR introduces a novel interaction system between the user and the system; users point their devices in the direction of an item of interest and the camera output augments the display with additional information about the environment [3].

Even though MAR applications and services present great potentials for deeper user-application interaction, existing literature proposes only but a few guidelines and principles for researchers and practitioners to design such rich experiences [4-6]. Indeed, the need for defining generic interaction design guidelines for MAR applications is not yet fulfilled, since their development is primarily technology-driven [7,8], addressing only a specific part of MAR design space, or they are adopting a theoretical viewpoint without applying the proposed principles in practice for the development of MAR applications [9,2]. A simplistic approach to design MAR applications would be to combine design approaches stemming from closely related fields such as mobile and distributed computing and augmented reality. However, a few issues arise for the MAR designer when attempting to follow that strategy.

On the one hand, even though various frameworks and generic design principles for mobile systems have been proposed (c.f. [10,11]), these principles could remedy only unique problems of MAR interaction design instead of universally addressing the entire class of MAR systems [7,12,8,3]. On the other hand, MAR, despite being closely related to AR and mobile systems, presents its own intrinsic challenges, which arguably must be taken into consideration during the design process.

This research aims at holistically investigating the interaction design of MAR. The key points of this work are summarized as follows:

- First, we provide a formal definition of MAR and we highlight its differentiating elements compared to contemporary desktop-based AR systems (DAR). We also present an overview of MAR interaction challenges and we provide a critical discussion of extant research on MAR interaction design.
- Second, we define the MAR design space, accompanied by a set of principles that may be followed to prescribe the generic design of MAR applications. We focus on experiential aspects of MAR design since we consider them to be of more importance due to the unique interaction modalities followed by MAR. Each principle tackles specific MAR interaction challenges and is supported with indicative design practices that may be followed by scholars and practitioners.
- Third, we report how existing MAR applications adhere to the proposed design guidelines. This evaluation reflects a first indication regarding the applicability and validity of our principles.
- Finally, we report the results of an empirical study in which we followed the design principles to develop a MAR travel application named CorfuAR. We also discuss the results of a field study in which CorfuAR has been evaluated in terms of its usability and performance. The results of the field study suggest that our

theoretical guidelines contribute to the development of highly acceptable systems that provide pleasant and sometimes, exciting, user experiences.

The rest of the paper is organized as follows. Section 2 describes the design challenges of MAR applications. Section 3 includes the core of our theoretical prescriptions. Section 4 discusses the application of the proposed principles on the design of a MAR travel system and the results of the user evaluation field study. The paper concludes with a theoretical and practical appraisal of the proposed design prescriptions (Section 5).

2. The design challenges of MAR applications

2.1 Overview of MAR

Augmented reality (AR) is a recent emerging computer science field considered as a subfield of the broader concept of Mixed Reality (MR) [3,13]. During the 1970s and 1980s, AR was a research topic at some institutions, such as the U.S. Air Force, NASA, the Massachusetts Institute of Technology, and the University of North Carolina [1]. However, only in the beginning of 2000 did AR receive significant attention as an independent research field [14].

The AR field exhibits a variety of AR systems and I/O devices. These range from mobile devices like cell phones or tablet PCs to head mounted displays or glasses (HMD) [15,16]. Likewise, the applications of AR range from individual-centric services (e.g. personal assistance, advertisement, navigation, and guiding services) to industrial, military, medical, gaming, advertising, and educational contexts [17].

This diversity of AR contexts of use reveals the need for defining where the MAR domain stands inside the AR field. Mobile AR extends the scope and prospective functionality of 'traditional' augmented reality applications whose interaction occurs primarily through the desktop. We coin the first-generation of AR with the term '*desktop* augmented reality (DAR)'. *Mobile* augmented reality (MAR) refers to systems that provide AR capabilities through wireless devices, such as smartphones and tablets.

Typically, a MAR system works by having the user pointing the device in the direction of an item of interest and the camera output augmenting the display with additional information about the environment [3]. In terms of architectural properties, the main components of MAR: A *computational platform* for the coordination of the tracking and the 3D registration of the real scene; *displays* to incorporate the virtual data in the physical world; *wearable or portable input and interaction technologies* to interact with the augmented world; *wireless networking* to communicate with the system's infrastructure; and *data storage and access technology* for the data to be stored and retrieved as necessary.

MAR extends the scope of DAR in two interweaved dimensions, namely *time* and *space*. We illustrate this distinction between MAR and DAR in Figure 1.

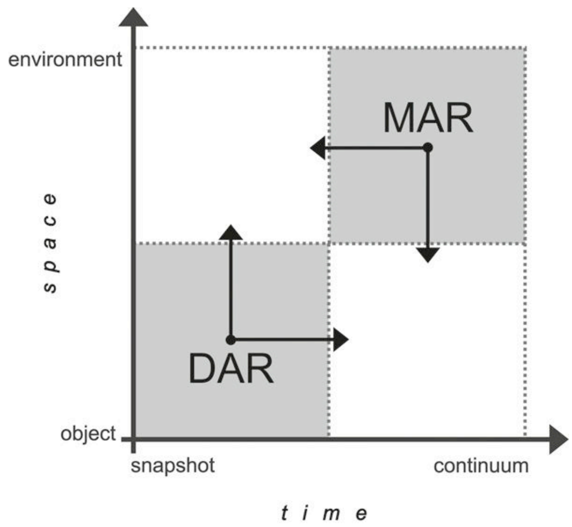

Figure 1: The dimensions which desktop AR (DAR) and mobile AR (MAR) use.

MAR applications are highly decentralized; they focus on multiple objects in the environment and, as such, they need to devise means to individualize each object of interest, search for information that may be semantically attached to it, and present this information in a user friendly manner. Because environments may be dynamically evolving (i.e. new objects may be included in the environment or updated information may be attached to an existing object in the environment) MAR applications face unique design challenges that may include real-time information retrieval [18], information visualization [19], object recognition and tracking (i.e. marker-based versus vision-based approaches) [20], and user interaction [21].

Opposed to MAR applications, DAR systems are highly localized and are usually super-imposing information on one object of focus. Moreover, DAR applications usually require on-demand information provision regarding the object of interest; MAR applications require real-time and continuous provision of information regarding *different* objects of interest, typically in a context-aware manner. The focus factor affects also the degrees of freedom for the user, since the wider the focus area, the higher the freedom degree of the user.

2.2 The need for addressing the interaction design of MAR applications

Recently, researchers and practitioners are becoming more and more engaged with how to design MAR applications. The development of MAR experiences is primarily technology-driven and user needs often remained designers' minor concern and were principally integrated in the later stages of development projects [7]. Furthermore, the innovation factor of MAR, made the user-centered design process very difficult, since the users of emerging technologies find it difficult to express their needs because of their lack of knowledge on the technology's potential [22,23].

The motivation behind this study comes from the notion that although MAR is a significant part of the AR and mobile computing fields, the design process of MAR applications may present unique elements mostly because of the philosophy underpinning their development. Instead of developing metaphors for embedding the real world in the mobile device, MAR *manipulates the real world, as is, by superimposing to it digital information*. As such, the built world comprises the design canvas that drives the application functionality and interactivity. Aggregating the content to menus and options might not be the effective design choice; designers are faced with a new challenge: *how can we associate, organize, and present information into a dynamically changing real world in a way that protects users from cognitive overloads resulting from the massive amount of available information*?

Indeed, this challenge is acknowledged by MAR interaction design scholars [8,21]. Scholars acknowledge that MAR addresses highly complex settings and infrastructures defined for very specific purposes [6]. That is why the majority of MAR applications follow a 'layered' approach of information filtering that users may choose to read or disregard. Likewise, the new interaction allegory requires designers to consider ways to improve the appeal and aesthetics of MAR. Interfaces may be viewed as panoramic sceneries that employ tactile-visual cues to facilitate user interaction and enhance overall experience [9]. Moreover, smartphones' small display size increases the complexity of devising comprehensive and usable interfaces therefore, a combination of graphical and tangible user interfaces coupled with content filtering structures might be required [21]. Similarly, manipulation of smartphones is limited; in a MAR setting users use one hand to hold the device and their other hand to interact with the application. To this end, it is necessary to incorporate design features that promote user support, such as low physical effort and application responsiveness.

Existing efforts to codify the challenges of MAR with associated design prescriptions are scarce, nevertheless we start to witness a growing interest in this subject. The following table (Table 1) summarizes a set of recent works exploring the design space of MAR applications.

Source	Investigation approach	Key design findings
[9]	Position paper based on literature review of MAR applications	• Emphasize on immersive user experiences. • Design for context-aware content delivery. • Aesthetically appealing interfaces may augment usability and overall user experience.
[2]	Study on shopping-center visitors	• Include in the design elements to protect user privacy. • Content delivery should be relevant to the task; personalization might be the key for pleasant user experiences. • Allow for flexibility and control in interactive objects; use visual cues to guide interaction.
[24]	Literature survey on interaction design principles	• Focus on placement of visual cues; create 'clean' interfaces. • Filter visualized information based on contextual data.
[25]	Study on MAR users to assess alternative design and	• Design and development of high-fidelity prototypes communicate better the design objectives of the

	evaluation approaches	application and are more adequate to collect user experiences. • Low-fidelity prototypes are better for probing alternative design requirements.
[21]	Heuristic evaluation of usability principles on MAR designers and users	• Minimize physical effort to interact with the application. • Support error-handling mechanisms. • Increase visibility of displayed information; use hierarchies of information layers and/ or personalize content.
[20]	Literature review on mobile augmented reality systems challenges and requirements for successful mobile systems	Review of existing infrastructure technologies and discussion on their applicability to support the development of MAR applications and services.
[8]	Examination of mobile HCI principles to the context of MAR	• Support error-handling mechanisms to increase user satisfaction; • Support flexibility in use and promote overall learnability; • Minimize physical effort and cognitive overheads.

Table 1: The analysis space of existing MAR applications used in this study

As evinced in Table 1, the state-of-the-art work on MAR design appears to be of diverse nature. Extant research consists of technology-driven efforts [25,20]; design efforts with solely experiential underpinnings of the proposed design approach [23,2]; as well as design approaches which are primarily focused on investigating MAR interaction design under the auspices of validated results from related disciplines, such as mobile HCI [8] and mobile usability [21]. This diversity constitutes an opportunity for researchers to organize extant research and isolate the key design elements of MAR in the light of its unique interaction challenges. Moreover, existing studies follow a primarily theoretical stance since they do not present empirical evidence regarding the applicability and value of the proposed principles in practice. Such evidence would require following the principles for the development of a MAR application in a given application setting.

In this paper, we consolidate the extant work on MAR interaction design into a set of generic principles that may be applied during the development process of MAR applications in order to create better user experiences. These principles are expected to act as a 'rule of thumb', thus providing MAR developers with a flexible and useful tool, and not a set of strict guidelines. Arguably, the proposed principles may be influenced by generic principles from the AR and mobile computing domains. However, such choices should be reshaped under the prism of MAR unique interactivity. We intentionally frame each principle in an abstract manner in order to allow designers to develop tailored interpretations based on their application context. Nevertheless, to demonstrate pertinent instantiations of our prescriptions we collect and present indicative design practices that apply them in various usage contexts.

We also posit that our work goes beyond a simple theoretical articulation of important interaction design features for MAR applications. In effect, we apply our recommendations in practice to guide the development of a MAR travel guide and we report the results of a field study in which we asked 33 tourists to share their experiences of using the developed system.

3. Design principles for developing MAR applications

3.1 Methodology and theoretical grounding

We employed a multi-analytical standpoint to devise the proposed design prescriptions. We used as starting point the design suggestions illustrated in Table 1 and we expanded our investigation lens to the existing literature on MAR interaction design. The outcomes of our analysis consolidated the interaction design properties of MAR into five guidelines that should be incorporated in the development process of MAR applications. It should be noted that our recommendations adopt a user-centered perspective and, thus, they focus on the necessary design actions to ensure high-quality user experiences. Arguably, some of the design recommendations may also be important for specific types of related systems (e.g. location-based services and mobile commerce). However, as a collection, they represent essential features of MAR design.

As a next step, we analyzed a selective set of published MAR applications and reported the degree to which they incorporate our recommendations. This step strengthened the practical validity of our theoretical propositions and supplied an atypical confirmation regarding the importance of our principles for the design of MAR applications. The following sub-sections briefly outline our theoretical propositions.

Principle #1: Use the context for providing content

Context-awareness ensures the utilization of the interaction context (i.e. user location, preferences, and object focus) to provide information, which is relevant to the user's task. In mobile systems, the task takes place inside the physical environment, whereas in MAR applications the task is "focused on" and inextricably bound with the physical environment [26,27]. The utilization of contextual sensory data to deliver various types of information directly to the user, or even to modify interface behavior according to the user's task, is of crucial importance for MAR applications.

MAR technology is intrinsically based on the utilization of various sensor technologies (e.g. digital cameras, accelerometers, GPS, gyroscopes, solid state compasses, etc.) in order to create the context of use. This context may be used to filter the information of the surrounding environment and keep only the content that the user currently needs. Researchers in the MAR domain coin this process with the term context immersion [28]. Apart from the dimensions of time, user, and location, which have been thoroughly reported and modeled in the domains of mobile and ubiquitous systems [29,10], the MAR space also includes the dimension of the object in focus which includes the semantic importance and relationships between real-world objects and users. Finger-based gestures and tracking [30] may interpret a personal association between the user and an object and adapt the application behavior accordingly. Likewise, MAR raises the importance of user orientation, which may be used as an additional filter of information provision.

Principle #2: Deliver relevant-to-the-task content

MAR, by default, occupies a considerable amount of the user's perceptive and visual abilities, presenting unique interaction characteristics. The intrinsic mobility factor, as well as the required simultaneous attention to the task and the environment (in contrast to solely the required attention to the task in the case of mobile systems), suggests that a MAR system should enable users to focus easily on the desired information, thus reducing the cognitive overhead needed to interact with the application [7,8]. The content of the system should include only relevant information to users eliminating the 'noise' of the coexistence of various types of information that are not necessary to them [23,2].

The practices of *filtering* and *personalization* may be employed to reduce aspects of cognitive overheads. Indeed, MAR developers can design the system in such a way that it filters and/or personalizes the content - according to certain criteria - in order to provide relevant and useful information to users while they are in motion [31,11]. Hence, MAR users would not be distracted by unwanted content and their perceptive abilities would be focused on and utilized solely by relevant content that could potentially facilitate their task and, thus, improve their experience. MAR literature exhibits some recent efforts to compile approaches supporting a wide range of personalization facilities in multimedia content management environments [32,33].

Principle 3: Inform about content privacy

MAR as an emerging, new technology has raised some privacy concerns. The features of location-awareness and the necessary filtering of displayed information based on contextual facts expected to cause new privacy risks to consider [34]. The uncertainty and credibility when using a MAR system must, also, be dealt by revealing which user data are private and which are not. Olsson et al. [2] studying the MAR user experience found that the participants were concerned about *"what information about their activity will be saved and where, how public is the interaction with the service, and who can eventually access the content they have shared themselves"*.

Users should recognize what information about their activity will be saved; where it will be saved; and who has access to the content they share [2]. Unable to address this challenge is likely to generate anxiety and deteriorate the overall user experience [35]. Consequently, users should be in control of their privacy; the system should be able to allow for changes that modify the manipulation of personal information (and, as such, the provision of personalized features) based on their preferences. Frameworks and solutions that secure the transmission of personal information might also be employed to ensure anonymity and privacy protection [e.g. Ray and Han [36], Shokri *et al.* [37], and Sigg *et al.* [38]].

Principle #4: Provide feedback about the infrastructure's behavior

The interaction offered by mobile applications is not solely dependent on the particular features of the mobile devices used. Rather, it is a product of the device and the infrastructure used to realize the application. In MAR systems the nature of the infrastructure is even more likely to change as the application is used. The interface in the mobile device is only but a window to a multitude of heterogeneous systems that provide alternative functionalities. Indeed, users may request information about a particular object in the real world or even initiate a business or financial transaction should such an action is allowed. The specific functionalities and content per object are made available by external service providers. This variability in the infrastructure can affect interaction, and it is essential that interaction styles and interfaces also reflect the state of the infrastructure.

Based on this, developers should provide different configurations of an application, each having different resource requirements and quality offered to the end users, thus achieving dynamic deployment and quality adaptation based on infrastructure changes [39]. Likewise, user should always be informed about communication errors in order for the designer to increase the feeling of certainty about the system's use and, also, increase the validity and credibility of the presented information and thus of the system, in general. A first step towards this direction is illustrated in Wei *et al.* [40] who proposed a cyber-infrastructure framework for augmented reality applications.

Principle #5: Support procedural and semantic memory

MAR applications should prevent the development of extra non-automatic cognitive effort, required to interact with the system, and that could serve as a distraction. A solution to this challenge is to use common and widely-used interface metaphors. A MAR system can support learnability, making it easy for the user to learn how to use the system [41,42]. For that, the system will need to assist the user's memory for procedures (procedural memory) [31]. Methods and interaction techniques that are akin to real world behavior or similar to what the users are used to are necessary. Along this line, Qian *et al.* [43] propose a framework that demonstrates the structure of a mental model and the role it plays in human-computer interactions.

Moreover, a MAR application needs to support context specific reference information (semantic memory) by presenting the information in a widely-used manner [31]. Symbols that may be easily perceived and related to the object in focus must be used to communicate a meaning and to preserve the learnability and usability of the interface [7,8]. The MAR designers can turn to the work of Papakonstantinou & Brujic-Okretic [44] for implementing this recommendation, who produced a sociotechnical framework to enhance the perception of the environment and promote intuitive interactions.

Table 2 summarizes the proposed principles. We provide a formal definition for each principle and we explain how they address important MAR interaction design challenges as raised by extant studies. Moreover, we include a selective set of design examples for each principle which illustrate indicative applications of the principles in practice. These examples consist of specific interpretations of the proposed guidelines in different application contexts.

Design principle	Definition	MAR challenges tackled	Indicative design practices
Use the context for providing content	Employ sensor and marker technologies to collect contextual information (i.e. user location, user orientation, object in-focus properties, current task) in order to augment real-world objects with contextual information.	• Minimize cognitive and information overload. • Expand the search range of desired information regarding an object in-focus.	• Use of tangible and reference markers to identify object properties [45]. • Use of finger tracking for gesture-based interactions [30]. • Interactive focus and context visualization [46].
Deliver relevant-to-the-task content	Filter (or personalize) interactive content based on multiple contextual criteria.	• Expand the search range of desired information regarding an object in-focus. • Enhance overall usability due to one-handed operation of the application and difficulties to interact with small-sized icons.	• Content personalization through embodied interaction [28]. • Development of user adaptive interfaces based on artificial intelligence algorithms [16]. • Development of adaptive interfaces based on camera and motion-based interactions [47].
Inform about content privacy	Design the functionality around different privacy spheres (i.e. public versus private content).	Minimize the emergence of negative user emotions (i.e. anxiety, confusion and discontent).	• Engineering-based approaches to protect user privacy [48]. • Empowering users to control the degree to which they disclose their personal information [49].
Provide feedback about the infrastructure's behavior	The application should inform users regarding its current state or regarding changes in its state.	• Enhance the learning curve of using the system. • Minimize user frustration from system slow or unexpected responses during user interactions.	• Provide real-time feedback regarding system and user/ activities state [50]. • Provide real-time feedback quality-of-service aspects and guide user actions [51].
Support procedural and semantic memory	Employ familiar icons and/ or interaction metaphors to communicate the application intended functionality and ensure smooth user interactions.	• Enhance the learning curve of using the system. • Increase familiarity with the system. • Minimize the emergence of negative user emotions (i.e. confusion and frustration).	• Use well-known metaphors for frequent interaction tasks (i.e. scrolling, focusing on an object, selecting an object, etc) [47]. • Use popular/ self-explanatory icons (i.e. icons that have been widely used in closely related applications) to communicate system functionality [44].

Table 2: Summary of MAR interaction design principles coupled with associating challenges and pertinent design practices

3.2 Relation between design principles and existing MAR applications

To assess the practical value and validity of our prescriptions we turned our attention to the design practices followed by existing systems. In essence, we were interested in exploring whether MAR systems adhere to these guidelines. To this end, we collected and analyzed a set of MAR applications that have been published in peer-reviewed sources and report their design properties. Table 3 provides a description of the examined MAR applications. We tried to analyze applications from different application domains in order to seek for possible variations in the design based on the context of use.

Application	Domain	Description	Reference
Archeoguide	Culture	The Archeoguide project is an MAR cultural guide that provides Augmented Reality reconstructions of ancient ruins.	[52,53]
ARQuake	Gaming	ARQuake is a first person outdoor/indoor mobile augmented reality application, which is an extension of the desktop game "Quake".	[54]
Bottari	Social Media	Bottari is an MAR Android application that recommends restaurants according to social media reviews.	[55]
Environmental Detectives	Educational Gaming	Environmental Detectives is an MAR, multi-player game designed to support learning in advanced introductory environmental science.	[56]
MobiAR	Tourism	MobiAR is a MAR tour guide application, which allows users to browse information and multimedia content about a city through their own mobile devices.	[3]
PromoPad	Shopping	PromoPad is an MAR e-commerce system that performs in-store personalized advertising and shopping assistance.	[57]
Sketching up the world	Social Media	A novel system allowing in situ content creation for mobile Augmented Reality in unprepared environments.	[5]
SwissPeaks	Navigation/Sports	SwissPeaks is an MAR application for providing users with information about mountains in sight.	[58]

Table 3: The analysis space of existing MAR applications used in this study

The majority of principles are followed by the examined set of MAR applications. Table 4 presents the results of our analysis.

	Design principles				
	#1	#2	#3	#4	#5
Archeoguide	●	●	○	○	●
ARQuake	●	●	○	○	●
Bottari	●	●	○	○	●
Environmental Detectives	●	●	○	○	●
MobiAR	●	●	○	○	●
PromoPad	●	●	○	○	●
Sketching up the world	●	●	●	◐	●
SwissPeaks	●	●	○	●	●

LEGEND
PRINCIPLES:
#1: Use the context for providing content
#2: Deliver relevant-to-the-task content
#3: Inform about content privacy
#4: Provide feedback about the infrastructure's behavior
#5: Support user's procedural and semantic memory

● = The principle is applied and mentioned in the related publication

○ = The principle is not applied and/or not mentioned in the related publication

◐ = The principle is partially applied and/or its application description is not fully informative

Table 4: A summary of the examined applications and the proposed generic MAR design principles they have applied

Three principles that relate to the manipulation and presentation of content based on contextual facts are commonly followed in all examined applications. It is a common thing for MAR applications to deliver relevant information, usually, either by filtering the information or by using a personalization algorithm or technique. This filtering is based upon elements that relate to users' context of use whether that would be their current location, preferences, or session behavior. Furthermore, the use of interface metaphors and symbols is a popular solution that designers follow. The degree according to which this approach is applied differs, however MAR designers take the approach into serious consideration, even though its implementation has a subjective nature, relying on the designers' expertise.

Interestingly, content privacy and notification about the status of the infrastructure are both strikingly ignored in the design of the examined applications. We can attribute this absence to the scope and development stage of the applications in our analysis space. Indeed, MAR is a rather novel technology and, as such, most published systems consist of prototypes. As a result, the design effort is placed to demonstrating the interaction capabilities of the technology rather than on the supporting system features. Furthermore, the mainstream MAR applications are primarily self-contained. This implies that their scope is restrained to one provider which is also responsible for distributing the content and adjusting the quality of the application. Hence, the need to develop feedback mechanisms that communicate privacy or infrastructure quality issues is restricted. We expect that as the user base of MAR applications evolves and users engage on more social interactions the importance of privacy will equally be raised. Likewise, the importance of notifications about changes in the system infrastructure will be more apparent when additional content providers participate in the same MAR landscape (e.g. each tagged object in the MAR interface will be associated with a web service of a dedicated provider).

4. Developing MAR user experiences: Designing CorfuAR

CorfuAR (Fig. 2) is an MAR travel guide for the island of Corfu, Greece. The application was developed using the Layar platform, between May and August 2012. Our intention was to apply the proposed design principles in practices and explore their effect on user experience. The application provides detailed information about historical monuments, museums, religious sites, restaurants, bars, shops, and other travel and leisure related POIs. Moreover, CorfuAR supports routing to selected locations and social media features (i.e. rating of places and showing users' peers that have visited each location). Finally, the system supports personalized recommendations of points of interests based on contextual data and user preferences. The personalized features are optional and may be deactivated should users feel that their privacy is violated.

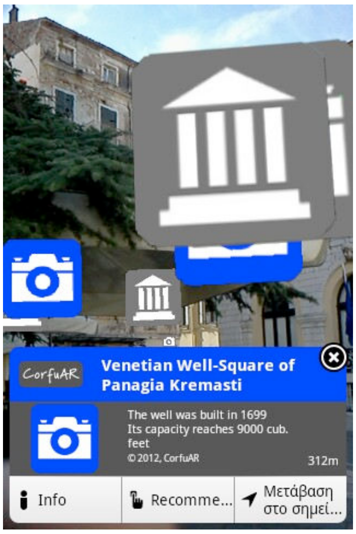

Figure 2: A screenshot of CorfuAR in action (www.corfuar.com).

An empirical field study took place between September and November 2012 in the city of Corfu aiming to evaluate the validity of the proposed design principles. In total, 33 individuals that visited Corfu were invited to download, install and use the service. Our sample pool consisted of friends and family who would visit the city of Corfu for leisure or business activities. The study examined both technology related (usability and system performance) and experiential (individual affections deriving from application usage distinguished among three feelings: pleasure, arousal, and dominance) factors. To measure the effect of some of the framework principles we divided the sample in two groups. One group was prompted to use the personalized version of the application while the second group was advised to use the non-personalized version. We performed this distinction to delve for differences between the two groups regarding the presentation of the content, privacy concerns stemming from the personalized features, and usability/ performance issues.

The empirical data was based on questionnaires completed by the participants at the end of their visit to Corfu and a short interview session discussing their user experience with the system. Usability and system performance were measured through the respective items in the second iteration of the Unified Theory of Acceptance and Use of Technology [59]. Affective qualities were captured through the Pleasure, Arousal, and Dominance emotions scale [60]. Items on the questionnaire were measured on a Likert scale anchored from 1 ‘do not agree’ to 7 ‘completely agree’. In the following sub-sections we briefly report our findings regarding the framework application.

Principle #1: Use the context for providing content

CorfuAR utilizes GPS sensory data (longitude and latitude) to place users in their environment and provide the content based at their proximity. The information is visualized as icons on top of the world view and their placement is updated in real-time based on GPS sensory data (Fig. 3).

Figure 3: The icons used in CorfuAR to visualize the categories of POIs.

The system is capable of tracking user interactions (e.g. requests to receive additional information regarding a POI or routing directions to a particular POI). Moreover, the system trails the physical movements of users (e.g. which POIs the users actually visited) and updates their profile accordingly. This information is used to highlight POIs that belong to categories which are most frequently viewed or visited and to better arrange the icons on the mobile device screen based on users’ contextual preferences.

Our design approach generated very positive responses. Indeed, participants praised the usability of the application (average score for both groups: 6.03, SD .819) and its usefulness for supporting them during their visit to Corfu (average score: 6.28, SD: .628). Moreover, CorfuAR evoked high degrees of positive emotions. Overall, participants received a pleasurable user experience (average score: 5.85, SD: .585), which also stimulated feelings of excitement and arousal due to the innovative and user-friendly way that they interacted with the system (average score: 4.55, SD: .676). According to our follow-up interviews, novice users with MAR technology were particularly impressed with the way the system presented the tourism-related information. Moreover, participants commonly thought that the use of the context assisted them into finding the necessary information easier and faster, compared to traditional mobile computing interaction modalities that are based on menus and forms.

Principle #2: Deliver relevant-to-the-task content

We implemented a personalization and information filtering algorithm to display only relevant information to the user preferences. This feature was exclusively available to the group that used the personalized version of the application. Personalization was operationalized by assigning users into one of three clusters based on their responses on a short questionnaire that was available the first time users opened the application (Fig. 4). The three clusters (business, leisure, activities) and the clustering process were based on a segmentation technique suggested by the World Tourism Organization [61].

Following users' assignment to a particular cluster the system would adjust its presentation layer to display primarily POIs that were associated with the respective user cluster. We also implemented a POI filtering system (Fig. 5) so that users may adjust the range of the visualized POIs in their proximity, as well as, further filter the categories of the places that interest them (e.g. museums, monuments, bars et al.). This would support further customization of the system to meet users' preferences.

The results of our study showed that the personalized version of the system received in almost all examined dimensions higher evaluations compared to the non-personalized version. Specifically, participants expressed that personalized CorfuAR was more user friendly (6.34 versus 6.23), more useful in terms of finding information that matches their needs (6.14 versus 5.91), and generates more exciting user-system interactions (4.70 versus 4.41). Although the differences are marginal in most cases, these findings provide a first indication that supporting content relevancy is an important element to drive enhanced MAR-based user experiences.

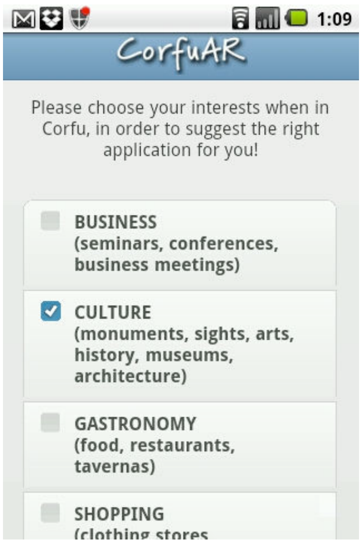

Figure 4: The questionnaire for the personalized version of CorfuAR.

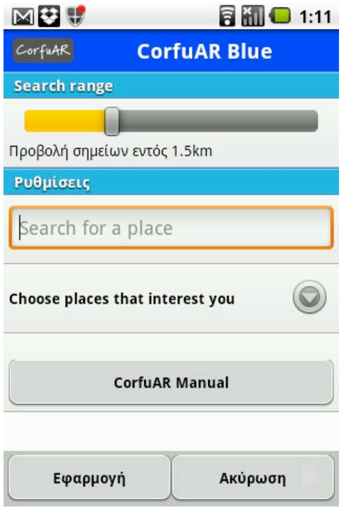

Figure 5: Filtering the content of CorfuAR.

Principle #3: Inform about content privacy

The issue of content privacy was highlighted through the empirical study. As mentioned previously, two different versions of CorfuAR were developed to examine, amongst others, the effect that notion of content privacy has on the use of MAR applications. The participants were informed that when using the non-personalized version, no preferences, recommendations or any other data would be going public, whereas when using the personalized version, their POIs' recommendations would be publicly available to users of the same cluster.

The results of the study showed that although the personalized version of the application triggered feelings of excitement and arousal, users of the non-personalized version were slightly more pleased (5.91 versus 5.8). To our surprise, both groups felt that they had almost equal control of the application especially pertaining the use of their personal information (non-personalized version: 5.30; personalized version: 5.28). We attribute this equality of opinions to the multiple layers of customization that we allowed for the personalization version group, which may have led them to perceive that they have excessive control over the application.

Principle #4: Provide feedback about the infrastructure's behavior

CorfuAR requires GPS signal and wireless broadband connection for its use. The application constantly informs users about the state of these technologies by producing warnings and pop-up messages in case the GPS signal or the wireless broadband connection is lost and about the loading status of the provided information.

The results of the study showed that users appreciated the provided feedback mechanisms. The overall negative feelings of anxiety and uncertainty were at low levels (even though there were slight differences for these emotions between the users of the two versions, as stated in the previous principle). The participants, even though were annoyed by the fact that sometimes the 3G broadband signal was lost, they were informed immediately about the issue from CorfuAR and they were not left in a state of uncertainty during the system use.

Principle #5: Support user's procedural and semantic memory

Since the multitude of available content on CorfuAR database might confuse users regarding the type of activity these POIs refer to we created icons that promote user familiarity and consistency based on icons that are widely-used in tour guides (Fig. 3). The study revealed that these icons were easily perceived, able to communicate a meaning, and enhanced the learnability and usability of the interface. In all cases, participants considered the interaction with the system to be clear and understandable and they thought that the usability of the application's interface would allow them to master it in just a few sessions.

Table 5 summarizes our approach on applying the MAR design principles for the development of CorfuAR and our findings following the empirical study.

Design principles	Application in CorfuAR	Summary of findings
#1: Use the context for providing content	• GPS sensory data (longitude and latitude) to place users in their environment and provide the content based at their proximity. • Support tracking of user interactions and physical movements.	• Applying this principle led to high degrees of usability and overall performance. • Novice MAR users were impressed by the technology. • The system provided a more intuitive and user friendly interaction modality compared to mobile computing metaphors.
#2: Deliver relevant-to-the-task content	• Implementation of two versions of Corfu AR (personalized versus non-personalized) based on segmentation and clustering proposed by World Tourism Organization • Support of information filtering based on POIs proximity and user preferences	Applying this guideline led to better user experience. Users evaluated more favorably the personalized version of the application (compared to the non-personalized version) in terms of its usability, usefulness in finding information that matches user needs, and prospect of generating exciting user-system interactions.
#3: Inform about content privacy	• Distinction on handling private information between personalized and non-personalized version. • No preferences, recommendations or any other data would be going public in the non-personalized version; POIs' recommendations would be publicly available to users of the same cluster in the personalized version.	• Minimization of privacy concerns. • Users of the non-personalized version were slightly more pleased than users of the personalized version. • Both groups felt the same degree of control pertaining the use of their personal information.
#4: Provide feedback about the infrastructure's behavior	Provision of warnings and pop-up messages in cases of connectivity problems and regarding the loading status of the provided information.	• Elimination of user frustration. • CorfuAR users expressed their satisfaction regarding the provided feedback messages.
#5: Support procedural and semantic memory	• Design of icons and symbols that are widely used in relevant systems (e.g. tour guides) and cultivate semantic associations in users' cognition. • Support the users with a simple explanation about the icons.	• Enhanced user-system interaction. • Participants considered the interaction with the system to be clear and understandable reducing their learning curve.

Table 5: Applying the design principles in CorfuAR and summary of findings

5. Conclusions and discussion

5.1 Summary and contribution

We propose a set of interaction design principles that should be followed during the development of MAR applications. Our design prescriptions rely on theoretical grounding and an empirical study in which we applied them for the development of a mobile augmented reality travel application. The results of a field study with 33 users revealed that our recommendations may lead to enhanced MAR user experiences in terms of system usability, user excitement, and minimization of user frustrations deriving from user-system interactions.

Our contribution is two-fold. First, we aggregate the extant literature into a set of five distinct properties that address the interaction design of MAR. We posit that our research represents an analytical perspective towards the design of mobile augmented reality applications. To our knowledge, it represents the first effort to codify the differentiating elements of MAR design in one integrated manner. Studies in the field primarily frame the interaction design of MAR under the prism of related disciplines, such as mobile HCI [8], and discuss their prospective applicability in the context of MAR. Our study draws from the unique interaction challenges of MAR to pinpoint the proposed principles. We also examine the degree to which published MAR applications adhere to our design guidelines. The results of this review process provide a first, internal, validation of our propositions.

Second, this work goes beyond a theoretically-driven articulation of important design features for MAR. Extant studies in the field frame their design recommendations primarily under the auspices of expert studies [21], literature reviews [9,24] and panels of candidate MAR users [2]. Instead, we apply our prescriptions in practice to develop a MAR travel guide and evaluate its performance through the execution of a field study. Our methodological approach further strengthens the external validity of our theoretical guidelines. Indeed, we demonstrate that our principles may be operationalized in real settings and may well influence the development of highly acceptable applications.

We acknowledge that the field study provides only partial evidence that our principles were the exclusive drivers of positive user experiences. Such a claim would require us to develop multiple MAR applications in which each principle would be applied differently (i.e. one application would follow a principle and another would not) and to provide comparisons of their performance. As such, we recognize that additional factors (i.e. overall design quality of the application and novelty of CorfuAR for Greek mobile users) might have positive effects on user evaluations. To this end, we kindly urge the design community of MAR to further experiment with our prescriptions on different application environments.

Nevertheless, we underline that our propositions comprise necessary design features for achieving valuable and acceptable MAR applications. Indeed, there are several MAR evaluation studies that attribute poor performance of the examined system (i.e. in terms of low levels of usability or user experiences) to the omission of one or more of our proposed principles from the design process. Such studies report cases of increased application complexity and user confusion due to not presenting content in a context-aware manner [5]; suboptimal user acceptance due to privacy concerns [62], lack of infrastructure feedback [58] or familiar cues [62] to guide user interactions; and information overloads from failing to apply information filtering and/ or personalization methods [24].

5.2 Implications and avenues for further research

Regarding the theoretical implications, our study is the first to relate the design of a MAR application with affective qualities evoked from system use. Extant work on MAR user acceptance focuses primarily on performance-related factors and their effect on usage intention (c.f. [42] and [63]). Our findings suggest that evaluation of MAR may also adopt an emotions-centric perspective in which researchers will investigate how specific design configurations of a MAR application may breed positive or negative feelings to its user base.

From a practical perspective, our guidelines may be employed to perform both ex-ante and ex-post assessments of mobile augmented reality applications. During an ex-ante assessment, designers may incorporate during the design process the necessary elements that would enhance the user experience of the MAR application or service. Likewise, during an ex-post assessment, designers may identify shortcomings of the application's functionality or infrastructure properties and proceed to corrective actions. An obvious improvement of our framework would be to develop a formative scale that would quantify the degree to which each proposition exists (or should be included) in the design of mobile augmented reality applications. Such a scale could be used as a benchmark to improve the design of the application.

Finally, scholars could extend our work in a more formal manner to develop a *design theory* for MAR applications. Design theories attempt to prescribe the development process of information systems from a two-fold perspective: the IT artifact and the design process to develop the artifact [64]. Our framework propositions may comprise the *meta-requirements* that mobile augmented reality instantiations should adhere to.

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