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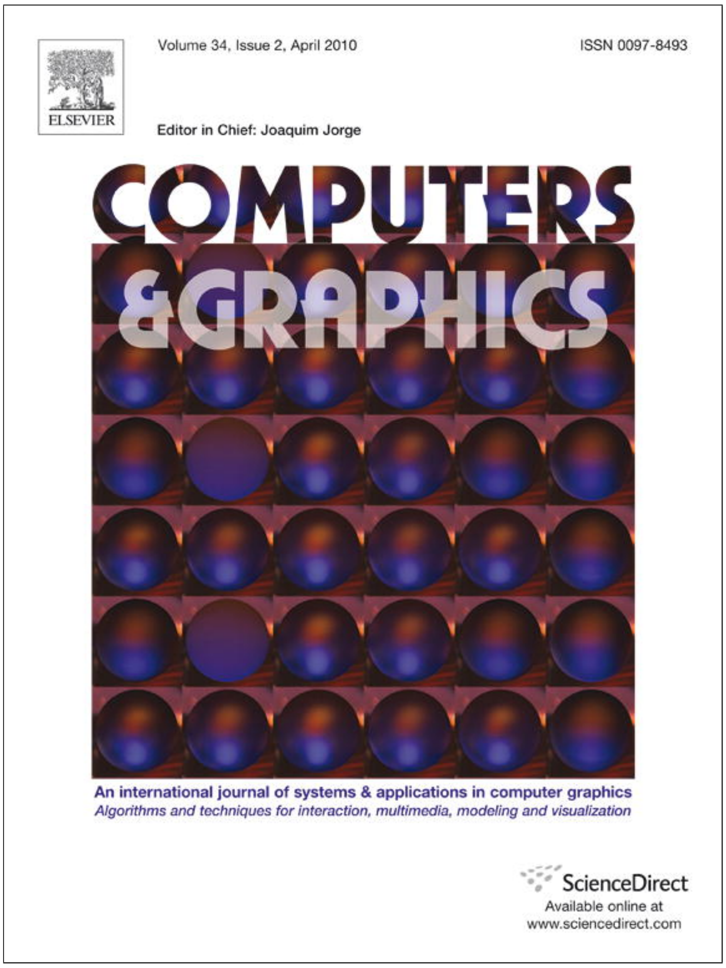
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Mobile Augmented Reality

Collaborative use of mobile augmented reality with paper maps

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A B S T R A C T

The popularity of augmented reality (AR) applications on mobile devices is increasing, but there is as yet little research on their use in real-settings. We review data from two pioneering field trials where MapLens, a magic lens that augments paper-based city maps, was used in small-group collaborative tasks. The first study compared MapLens to a digital version akin to Google Maps, the second looked at using one shared mobile device vs. using multiple devices. The studies find place-making and use of artefacts to communicate and establish common ground as predominant modes of interaction in AR-mediated collaboration with users working on tasks together despite not needing to.

1. Introduction

Real-time video see-through display and processing of a mobile phone camera stream have become efficient enough to enable a variety of augmented reality (AR) applications on mobile platforms. A unique characteristic of mobile AR is the dual-presence of information; where aspects of the physical background (at which the camera is pointed) are overlaid simultaneously with extra information on the mobile screen, supporting an expanded understanding of one's immediate environment.

With this increased popularity of mobile AR applications [1], it becomes important to invest in empirical studies in this area. Field studies in particular are still scarce, but may impact heavily on development and design with many as yet unknown outcomes.

We are interested in applications using AR to augment physical artefacts (in this case paper maps) with real-time information, including user-generated content. Our system is called MapLens and uses the phone's viewfinder screen, or the "magic lens" [2], to augment the phone's live video with digital information registered in 3D and in real-time. From results that arose in an initial pilot study, we investigated how successful mobile AR would be as a platform to support collaboration. Laboratory based studies have shed light on some aspects of mobile AR based interaction, but we find three critical aspects still need to be addressed: (a) mobile interaction while embedded and mobile in the referred-to environment; (b) interaction in groups; and (c) suitability for real-world use. Furthermore, field studies allow us to address typical shortcomings with laboratory experiments such as the absence of interruptions and disruptions, the use of brief and artificial tasks with individual users in controlled isolation or tasks that do not involve physical aspects of the environment [3]. The field trials reported in this paper lasted 1.5 h, involved a variety of inter-related and sequential tasks, and the teams needed to interact with the physical environment and with other people in order to succeed.

MapLens was tested by single users, pairs and/or small teams in a pervasive game that was held in Helsinki centre in two studies. The game requires players to complete a range of different tasks (with diverse levels within the tasks), carry multiple artefacts and coordinate joint action, all echoing everyday use. Both studies involved 37 participants in field trials and collected multiple kinds of data: video/photo recordings, field notes, logs, interviews, and questionnaires to understand the person-to-person, person-to-technology, direct and technology-mediated and person-to-environment interactions.

The results of these studies inform us about the practices teams spontaneously adopt. Our first study [4] was one of the first few field studies on the topic, and it showed that team members

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naturally started using MapLens in a collaborative way by clustering around the physical map and mobile device and negotiating and establishing common ground to solve tasks. We called this the honeypot effect, which stood in strong contrast to our comparative condition. Here the teams used a digital map application akin to Google Maps, but worked individually by divided up the tasks.

For our second study, we improved MapLens' interface design and underlying technology (see 3.2) and conducted one of the first field studies to test the synchronous use of multiple mobile devices by adding multiple devices as the new comparative condition, in addition to collaboration through sharing devices and solo use. We wanted to see whether people in teams, each with their own devices, still collaborate even though it was not necessary to do so. We observed that teams with multiple devices (multi-device teams) still shared and collaborated and that teams naturally and rapidly devised a method for collaborating and establishing common ground understandings of what was beneath their devices: "a multi-lens common ground". By contrast, single-device teams exhibited more switching of attention between AR, the paper map and the real environment, and more communication work overall.

From here on, we refer to the first study [4] and the first version of our application as MapLens1. We refer to the second study and the second version of the application as MapLens2. The system is referred-to as MapLens, and involves three components used in concert: the device, the physical map and dynamically overlaid data.

In the remainder of this paper, we summarise related work, describe the system, detail the field trial and game scenario and argue the rationale for changes in MapLens2 study. We then discuss the evaluation, analysis and findings. We close by drawing implications and conclusions from our findings on how differences in collaboration across the systems and conditions may impact for future AR work.

2. Related work

The concept of the magic lens was first introduced in 1993 [2] as a focus and context technique for 2D visualisations. This was later extended to 3D [5]. The NaviCam system [6] introduced magic lenses on handheld displays (see also [7], [8] and [3]), including so called peephole interaction, where the background surface was used to position the phone in virtual space [9].

McGee et al. [10] used a real paper map in a stationary laboratory setting to allow for gesture and speech interaction with post-it-like, augmented objects. Bobrich and Otto [11] used head mounted displays in a video see-through AR setting to present 3D overlays of digital elevation models over a real map. A projection-based system by Reitmayr et al. [12] augmented a paper map directly with dynamic, geo-referenced information. Transition to mobile devices has placed special demand on light-weight methods of localising. Reilly et al. [13] used RFID tags to associate locations on the map with digital information. Rohs et al. [14] describe a computer vision-based method using sparse fiducial markers on a map.

While this research advances the field of (mobile) AR technology development, reports on user trials – let alone field trials – are scarce. Among the few existing user trials for mobile AR, Henrysson et al. [9] piloted positioning and orientation of 3D virtual objects using a mobile phone. They observed that the users sat down rather than stood up in order to stabilise the phone. Reilly et al. [13] reported a laboratory study where subjects performed pre-defined tasks on an RFID vs. non-augmented PDA version. Usability depended on the size of the map, information tied to it, and the task of the user. The authors point out that the tasks required little or no spatial knowledge as the trial was conducted in a single location and involved no routes, landmarks or navigation. Rohs et al. [3] compared map navigation between joystick, static peephole and magic lens interaction. The study showed switching of attention between the surface and background affects task performance, yet static peephole and magic lens clearly outperform joystick navigation. A recent study by Reilly et al. [15] researches the implications that type and layout of an augmented map have on searching while using a handheld device. They analyse sequences of gaze patterns studying a city street map with a grid layout, and a landmark-heavy city tourist map. The study shows how the map layout influences the interaction technique chosen. Generally speaking, technical difficulties have mostly prevented ethnographic studies of outdoor AR use in uncontrolled environments.

There is a body of work on the importance of maps in social interaction. Brown and Chalmers [16] show for the case of urban tourism, how maps are used in concert with other artefacts and for a variety of tasks, including but not limited to finding the shortest route from A to B. In this context, maps are shared between fellow tourists and also between tourists and locals. The maps act as mediation objects for multimodal discourses providing resources such as a context and facilitation for embodied communication. Our first comparative study of Morrison et al. [4], echoed these findings for the mobile AR application MapLens. Introducing a map and a mobile device into group interaction scenarios opens up a variety of research questions particular to technology use in social situations.

Pervasive games and locative media. There is a growing interest in the use of pervasive games, both as a worthy scenario for use and for the implementation of fieldwork evaluation methods [17]. Recent work shows how pervasive games can be interwoven into daily life situations [18] and points out that the results can bring forth the aspects that tell of the issues beyond the game itself; such as interface design [19] or how the users learn in these scenarios [20]. As such, we find a pervasive game setting useful as a designed set of circumstances to use for evaluating mobile AR map use. The key challenge is to create a game that is not only motivating, but also engages the users with the environment in a way that can reveal real-world behaviour and phenomena normally not occurring in more controlled forms of evaluations. Our game was designed to encourage players to be more aware of environmental issues and the environment while exploring their surroundings in a competitive but friendly game (see [21] and [22] for similar approaches). The game required managing multiple levels – with constant interruptions and shifts in focus – and involved several aspects of real-life situations including coordination of team effort, role-taking, sequential tasks, feedback, social interaction [23] and time-urgency. In these ways we were able to extend standard task-oriented testing, to emulate the messiness and pressures of real-settings and ensure the system was evaluated both inside and outdoors under less-predictable circumstances.

3. Design and implementation

MapLens is an AR application for Nokia camera phones (Symbian OS S60) with GPS. The phone camera and the display are used as a viewer in combination with a paper map, which is augmented with location-based data.

When a paper map is viewed through the camera, the system analyses the video frame and determines the GPS coordinates of the visible portion of the map. This geo-referencing process is dictated by the tracking technology, which provides sub-pixel accurate measurements [24]. MapLens uses predetermined map data files to identify the paper map and associates its visible area to geographical coordinates. First, we create a database of distinct feature points in a representative template image of the paper map. Then, we find these feature points again in the live-image captured by the phone's camera. The 3D pose – position and orientation – of the phone with respect to the map is then estimated from the correspondences between the live-image feature points and the feature points in the database. This is called a natural-feature tracking method. Our solution is among the first optimised to perform well on platforms with limited processing power, such as mobile phones [24]. We used unmodified images from Google Maps with MapLens.

Once the 3D pose is known, MapLens is able to virtually position location-based media on the paper map accurately. Based on the visible map area, location-based media (photos and their metadata) is retrieved from an online HyperMedia Database (HMDB) and superimposed on the paper map using video see-through AR overlay. The HMDB allows for location-based queries from the mobile phone to media and associated metadata based on location, date/time and user name. Users on the mobile phone can upload GPS-tagged photos they took to the HMDB server using the standard newsfeed protocol ATOM.

3.1. MapLens1

The first design of MapLens is called MapLens1 (Fig. 1). Users browse the augmented information by physically panning the phone's camera over the paper map. MapLens1 overlays the map with red icons that identify location-based images. Hovering over an icon shows a thumbnail of the related image. When a thumbnail is visible users can click to see a full-screen version of the image. A freeze function helps the selection when multiple icons are close together. When a user clicks over more than one icon, the view is frozen and the icons de-clustered (pulled away from each other) so the user can more easily select the correct icon.

MapLens1 also functions as a photo camera. Photos are automatically labelled with their GPS location and uploaded to the HMDB. The user presses $*$ key to enter camera mode, 0 to capture a photo, and $*$ again to return to MapLens1. All other MapLens1 users receive the new photo within five minutes. By pressing 1, one can see photos taken by other users. Pressing 1 again turns that layer off.

MapLens1 operates with a visual screen update rate of 5–12 frames per second, allowing for interactive use. Operation is possible within a distance of 15–40 cm between the printed map and the camera. Tilt between the map and the camera is possible within a range of $+/-30^{\circ}$ from the perpendicular view. In-plane rotation (around the viewing axis) is handled over 360°. MapLens1 operates on A3 printouts of Google Maps (street layer).

Fig. 1. MapLens1 augments a paper map by superimposing registered icons and labels onto live video stream on the phone.

Fig. 2. MapLens2 is the second design of our MapLens application.

3.2. MapLens2

The second design of MapLens is called MapLens2 (Fig. 2). Similar to MapLens1, MapLens2 interaction is also based on hovering over the location-based icons and clicking to visualise a full-screen version of the related image. In MapLens2 we visualise predetermined game clues and user-generated photographs with different icons.

Using an iterative design cycle, we set out to improve the technology evolution from MapLens1 to MapLens2. First, keypad interaction was removed. With MapLens2 users can take photographs using the built-in camera button of the phone. Second, we added a "you are here" icon to show the position of the user on the map. Third, we replaced the freeze function of MapLens1 with a thumbnail bar: an array of all preview images available at that location. For MapLens2, green lines maintain the connection between the thumbnails and their location on the paper map. Once the icons are selected, the non-AR thumbnail bar allows browsing and zooming any chosen image without the need of the paper map.

MapLens2 runs at frame rates of 16–20 frames per second and allows for a much smoother interactive experience compared to MapLens1. Further, the improved tracking technology [25] is robust to changes in illumination (sunlight), blur in the camera image and allows for viewing tilts of up to almost 90°. The new tracking technology supports camera distances from the map between 10 cm and 2 m. MapLens2 operates on A1 printouts of Google Maps satellite images with street overlays.

3.3. Comparative system: the 2D DigiMap

As a comparison baseline in the first user trial, we implemented a purely digital map application called DigiMap (Fig. 3). The digital map uses the same map as the physical map used for MapLens1. As in MapLens1 red icons indicate location-based data.

We used joystick navigation for scrolling the map and two buttons to zoom in and out. DigiMap does not access the phone's camera, so users switch to the native camera application to take photographs.

4. Field trials

We conducted a pilot and a subsequent full trial using a marker map while executing a 40 min environmental-awareness

Fig. 3. DigiMap application, similar to Google Map with icons.

game in central Helsinki in March, 2008 [26]. For the pilot study, we did not limit the study by testing specific hypotheses. Rather, we were more generally observing what happens when we put mobile AR "in the wild" to see what would be uncovered. A surprising find of this pilot was how readily people collaborated around the technology. Bearing this in mind as a focus for investigation and including feedback and observations, we then improved the game, tasks, evaluation and technology, and implemented the same improved game and evaluation for MapLens1 and MapLens2 studies.

For the MapLens1 study we compared three conditions. We recruited 37 users; where 24 shared MapLens grouped in nine teams, 11 used DigiMap in 5 teams and 2 used MapLens solo in an urban game over three trials.

For the MapLens2 study we compared three conditions recruiting 37 users, where 21 had their own MapLens devices in seven multi-device teams, 12 shared MapLens in four teams and 4 used MapLens solo in an urban game over two trials. With each trial we tested new conditions that had emerged from the findings of the previous trial. In the MapLens1 trial we deliberately tested more AR teams and in the MapLens2 trial, we deliberately tested more multi-device participants, as these were the new focus and untested conditions. Solo players were included in each trial to ensure individual use of the system and game play was possible.

Each trial in both studies lasted for at least 90 min. For all MapLens1 trials the weather conditions were similar (sunny), meaning participants needed to shade the screen for use (and themselves). By contrast, for all MapLens2 trials the conditions were cloudy and windy, cold but dry, meaning participants had to protect themselves and game artefacts from the wind and cold. So while conditions varied between the two studies, they were comparable within each study and tested use in different ways. Respectively, sun on the screen for MapLens1 and the map being caught by the wind for MapLens2, were the biggest obstacles brought about by weather conditions.

Each team was accompanied by a researcher who made photo/video recordings and observed the team for the entire trial. The researchers focused on sharing, turn taking and object handling of the device, and on instances where the participants were (a) using the system outdoors for the first time, (b) developing or changing strategy, and (c) working on selected tasks that required extensive system use.

4.1. Participants

The 37 MapLens1 participants we enlisted comprised 20 females and 17 males, with ages ranging from 7 to 50 years. The 37 MapLens2 users comprised 19 females and 18 males between the ages 14 and 44.

For both MapLens1 and MapLens2 trials, the players were largely professionals with university qualifications, working in related fields, early-adopters and/or researchers working with environmental issues. Prior work found that specialist audiences often engaged more strongly and provided more fruitful feedback [27]. We had a general exception with DigiMap players, where we recruited from a scout group and found these younger participants self-reported as being less aware of environmental and/or technology issues. We report on any subsequent limitations and impact for findings for DigiMap [4]. Consequently, MapLens2 players comprised a broad mix of internationals and locals with equal distribution of gender across the teams.

4.2. Environmental Awareness Game

The trials were run as team-based, location-based treasure-hunt type games designed to raise awareness of the surrounding urban environment and to promote awareness of local environmental issues. The goal of the game was to bond players with urban nature by positioning tasks near interesting elements so the players would be drawn by the "attractions of the terrain" [28]. In this way, we hoped their connection to urban nature coupled with indicated environmental issues could become personal and endure beyond this more organised instance of the game.

With the assistance of the technology, the players followed clues and completed the given tasks within a 90 min period. We included three different prizes aimed at encouraging a variety of approaches to the game: one for speed and accuracy of task completion, a more traditional approach to a game; another for the best photography; and another for inventing a convincing environmental task using mobile AR technology. An element of friendly competitiveness was established in the pre-phase game-orientation. Our intention was to focus and motivate our participants, as well as instigate time-pressure while they managed a broad range of divergent tasks simultaneously.

The game began at the Natural History Museum where players completed non-AR indoor tasks, two of which included follow-on components outside the museum. As GPS works outside only, participants found items in the museum by literally exploring the environment. The indoor tasks served as a 'warm-up', in order for teams to get to know each other and become coordinated to some degree to notice their surrounding environment.

For tasks outside the museum, players could use the paper map alone to navigate the city and the phone (without AR) to take photos or to browse the Web. However, AR was necessary to see dynamic information on the map; game clues and other people's photos. AR then, was fundamental in order to explore the dynamic information on the map and to identify the majority of the outdoor game tasks locations.

The players solved a variety of types of tasks (14 in all, Fig. 4), some of which were sequential problem chains. For example, one connected series included: find a leaf in the museum; find the same leaf outside the museum; take a sunlight photo of the leaf using water to develop (supplied in kit, see Fig. 5); test the pond water and test the sea water for chlorine, alkalinity and pH balance (supplied in kit); record all readings by uploading photos or entry into the clue book and bring back results. In addition, the game required players to visit green areas in the city with a task such as, for the whole group to walk bare-foot in the grass, and upload a photo as evidence.

How tasks were completed and in what order was up to the players. Some tasks could be completed in several places, where

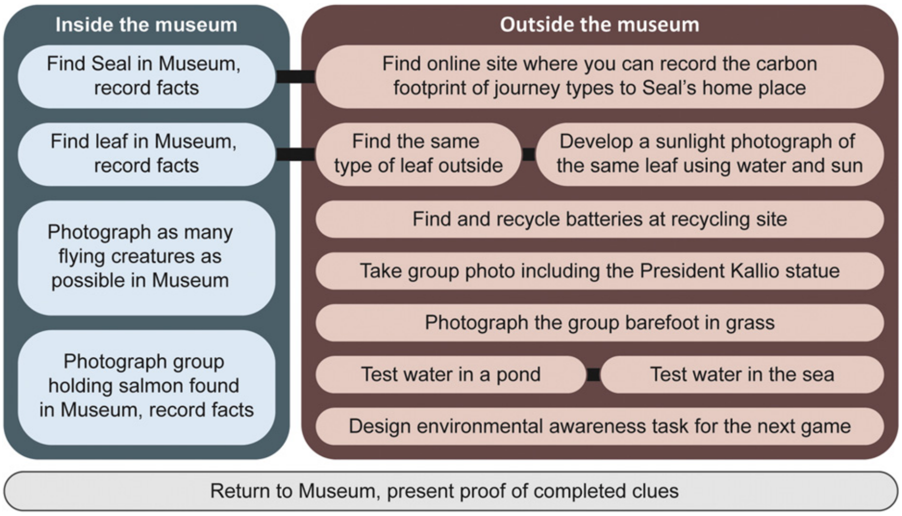

Fig. 4. Tasks for environmental awareness game. Interconnections indicate sequential tasks. Tasks outside the museum generally require AR.

Fig. 5. Kitbags contained 7 items that needed to be managed: sunlight photographs, map, phone, water testing kits, voucher for Internet use, clue booklet and pen.

series of tasks required visiting places sequentially. Photographs that participants took outside were uploaded to the HMDB server and were synchronously added to the (augmented) maps of all players.

Each team worked with a kit that contained seven objects (Fig. 5). The large physical maps, expanding clue booklets, manipulating the phone over the map, writing in the clue book and managing the bag, meant that the participants needed to self-organise into a system of use. There were no ready-made solutions and in-situ creative problem-solving was required. Solutions varied where for example, a tree, a team mate or a near-by bench might be used as a steadying, leaning or resting prop.

There was a particular emphasis on the mix of different types of experiences ranging from digital and augmented, to tangible and tactile. For example, one task required team-lifting of a 27kg museum object. Such tasks encouraged physical proximity, team bonding and 'jolted' users away from small-screen absorption. Our aim was to re-position physicality at the core of the players' AR experience by designing a game that obliged embodied interaction with artefacts, team members and the physical world [29]. The game tasks were designed to promote: internal and external group activities and awareness; negotiation of tasks and artefacts; higher level task management; and awareness of physicality, proximity, embodiment and physical configurations around artefacts.

4.3. Rationale for changes to MapLens2 study

We identified four factors that may have contributed as extenuating factors forcing collaboration in the MapLens1 study and focused on these for the MapLens2 study. The four factors we identified and eradicated were:

(1) Technology: We needed to ensure that collaboration was not just the by-product of poorly working technology that forced people to collaborate. For MapLens2, the robustness of the tracking and the system supported a less constrained interaction.
(2) People in teams: With MapLens1, we noted that personalities and gender distribution impacted phone use and collaboration methods, but had no solid evidence to support these observations. For MapLens2 we ensured an even gender distribution and video-recorded all teams using researchers trained in observation, to obtain detailed data on team dynamics and situated collaboration.
(3) Shared artefact: With MapLens1, there was one shared map per team, where for MapLens2 each player had their own map. For MapLens1 unless players divided tasks into those not involving the map, they were forced to share one map in order to use MapLens. For MapLens2, we gave each player a map to use, so there was no necessity to share maps under any circumstance.
(4) Shared devices: Providing some teams with multiple devices and maps meant these players could work independently. We could then investigate the comparative benefits of multi-device use for AR and scrutinise this multi-device use to see if it changed the way people collaborated.

4.4. Data collection

As these were exploratory studies by nature, we largely employed qualitative methods. To a smaller extent, we also employed quantitative methods, particularly to place qualitative observations in context.

Each team was accompanied throughout by one researcher taking notes, photographs and/or videos. On return from the game, participants completed a three-page questionnaire from Flow et al. [23], Presence [30] and Intrinsic Motivation [31] research to gauge reactions to the technology and the game. Each participant then described their experience in semi-structured one-to-one recorded interviews, highlighting aspects that had caught their attention. Throughout the trial, the participants took photos as an evidence of completing tasks. These images were synchronously uploaded from the phones to a server, and assisted researchers to build an overview of activities undertaken during the trial.

5. Observations

We now report our observations. From here on, we refer to DigiMap as D and MapLens as M. We denote findings specific to MapLens1 as M1, and for MapLens2 as M2.

5.1. Collaborative use

With collaborative use, we refer to joint efforts of players to achieve given task goals. We look at place-making, establishing common ground, device and map sharing, and the roles that developed within the teams.

5.2. Game tasks

We identify four principal game task divisions:

- Device use: the player uses the device to view and make agreements through.
- Map use: the player carries, orients and holds out the map. Having a map available to access AR information through the device begins and ends the use of M2.
- Navigation: the player decides where to go next, often several times for each use of M2.
- Scouting: the player explores the environment, points on the paper map, uses the clue booklet and the kit, takes photos, discusses with the others.

We found that multi-device teams used the device comparatively more to other tasks than single-device teams, who by contrast engaged in comparatively more scouting activities (Fig. 6). This suggests multi-device teams work more through the device while single-device teams perform more activities

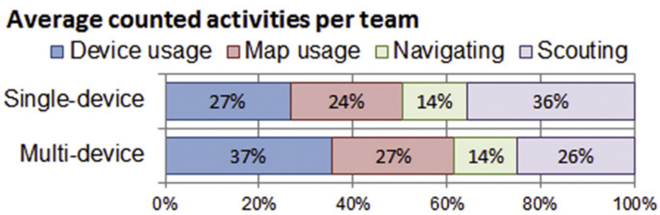

Fig. 6. Division of the activities in single-device and multi-device teams.

outside the device.

For M2 single-device teams, the average duration of sessions was slightly longer and the sessions more frequent than in multi-device teams. We observed that multiple devices support reaching quicker decisions than for single-device teams because of faster establishment of common ground methods to negotiate understandings. The contrast between multiplayer teams and solo players is larger. M2 use sessions of solo players were slightly more frequent and almost half-a-minute (about one third) shorter.

5.2.1. Place-making

Stopping and briefly gathering around the paper map created an opportunity to focus on a problem as a team. During the M1 study we observed a form of place-making with mobile use of technology, a phenomenon previously observed in studies of mobile use [32]. The physical map acts as a place where joint understanding can be reached, and the players can collaborate using M1. In contrast, D teams only needed to stop at places where the tasks themselves dictated.

Yet, the technology of M1 also restricted the movements of M1 players. M1 users had to stabilise the physical map and the device to be able to use the system. They favoured places where they could place the map on a table or a bench (Fig. 7, right). They also often laid the map on the ground or held the map for their group members. In contrast, in D teams often one person using the device was the "navigator" while the others observed the environment and led the way. The bodily configuration with D was individual. That the team members did not share around the map, in turn induced less sharing of the screen (Fig. 7, left).

M2 teams across all conditions also used the system while standing and holding a map (Fig. 8, right) or after setting down the map on a supporting surface. Three of the 15 teams (2 single-device, 1 solo) only used M2 while standing up and never put the map down. The improved technology of M2 changed the place-making behaviours. We observed a more agile parking activity (stopping briefly to check a detail before moving on) in contrast to the stopping activity of M1 (standing for longer periods or setting down the map). Many M2 players never set down items. Teams who made longer stops and set down items did so more in the museum and in the green areas than on the street. This temporary agile parking is a new phenomenon not found in M1 teams where stopping was the place-making practise.

5.2.2. Establishing common ground

A typical M1 team gathered around the physical map to use the system. Thus, establishing common ground by pointing to the physical map with finger or pen, and with MapLens itself was easier for M1 teams than for D teams. The location of M1 on the paper map and the contents revealed to others on its display helped players to understand the points under discussion without

Fig. 7. Pictures from the MapLens1 field trial. (Left) DigiMap was not easily shared. (Right) Stopping, place-making and sharing with M1 often required laying the map on a stable surface.

Fig. 8. Establishing common ground in single-device and multi-device teams. (Left) Single-device players communicated and established common ground more around the system. (Right) Multi-device players established common ground more through the system. Here, the players are using two devices, and keeping them on different heights to avoid collisions.

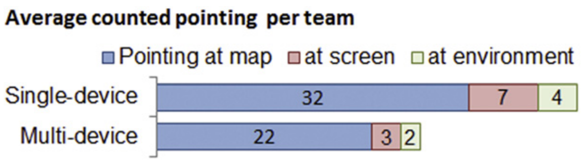

Fig. 9. Communication work (pointing at map, device's screen and environment) in single-device and multi-device teams.

explicitly needing to ask. The map-device combination triggered collaboration in a physical way using fingers, pens and other objects. However, some M1 players found it challenging to identify the location on the map through the screen of the device, especially while the device was in use by another player.

D teams were not able to share the map that easily. D players often referred more directly by pointing at their surroundings. For one D team we observed constant pointing at the mobile screen. In another D team one player looked at the screen behind the shoulder of the player using the device. In the remaining three D teams this did not occur.

In the M2 study, we looked at how the availability of multiple devices impacts on establishing common ground (Fig. 9). Single-device players communicated more around the system by sharing information on the map, the screen and the environment (Fig. 8, left). Single-device players shared the device screen largely throughout all sessions by tilting their screen for others to see, pushing the device closer to others, handing the device over and standing closer together. In addition, pointing to the screen of another team member, and looking and pointing to the environment and the map were more common for single-device players (Fig. 9).

Multi-device players communicated less and shared information more while looking through their own devices (Fig. 8, right). In multi-device teams the intentional sharing of screens happened less, typically only a couple of times during the game, and only for a few seconds. Multi-device players focused more on the device and less on communication, as they could all synchronously experience the same view of the information—a shared AR experience. Pointing on the screen could often be replaced by looking through MapLens(es) screens to the augmented information or at a finger pointing on a map. Single-device players required more communication work to access the same degree of shared information.

5.2.3. Device and map sharing

M1 players handed over the phone to other team members more often than D players. As an example, when a M1 player made an error another player verbally corrected the error and made a gesture of holding out her hand. In this case the phone was passed over. In a mother–son D team, the son kept the device perhaps to re-address power status. In general, the holder of the phone had the most agency in the team at that moment in time.

In the M2 study while starting the game, the multi-device teams typically used two or three devices simultaneously, but once familiar with the game and the system the use of multiple devices decreased or altered. Where two teams consistently used only one device throughout the game, four teams continued to use two or three devices simultaneously, but the use of one main device with supporting secondary or tertiary devices clearly emerged.

We counted the activity incidents for each M2 player and identified three types of teams according to the number of active players as follows:

- Agile: equal activity count between players. In these teams roles flow from one player to the other almost seamlessly.
- 2-share predominant: two players have larger activity count than the third.
- Controller: one player has much higher activity count than the other two. Roles are often fixed from game start.

The multi-device teams were made up of two agile, two 2-share predominant and one controller team. The single-device teams comprised one agile, two 2-share predominant and one controller team.

In the controller teams the dominant player often hid the device from the other players while using it and put it back in their pocket afterwards. We rule out shading from direct sun, as we saw no other instances of this kind of use. We conclude that the other players did not intervene as they were too polite, happy to take a lesser role or unfamiliar with outdoor use of the device. In 2-share predominant teams, the predominant two players either knew each other beforehand or connected while playing the game, but also made sure they included the third person. In agile teams, players did not necessarily know each other beforehand, but managed the sharing of tasks in an equitable manner.

Obviously a controller in a single-device team impacts on the team experience more heavily than in a multi-device team, where the other devices can be used. Anyway, we found no obvious correlation of team type to condition (multi or single-device) across this size sample. We reason that team type was not determined by the number of devices but rather by the personalities in the teams. We can see that the team types impacted on how the device and tasks were shared (or not) and how collaboration occurred. Having multiple devices available supports more independent and flexible use of the technology and exhibits potential as a way to circumvent for example, controller behaviour, or for use where multiple tasks require synchronous attention. However, in MapLens2 instances our findings show that having multiple devices did not prevent personality impact.

5.3. Embodied interaction

With embodied interaction we refer to the use of hands and body to position oneself and the technology in the context of other people and the environment. M and D both enable and constrain embodied interaction in different ways.

5.3.1. Usage of the AR system

M1 requires users to hold the camera at a distance of 15–40 cm from the paper map. Consequently, our players typically held the device with arms stretched out. By placing the device in this way, other players could see what area of the map was being examined and at times contents on the screen. The use of M1 with the paper map often required two hands. The device was sometimes held in the dominant hand and the map in the other. In other cases players used both hands to stabilise the phone, with another user holding the physical map or laying the map onto a stable surface (Fig. 7, right). There were two solo users who worked with M1 and completed the game within the allocated time, so solo use of the system was proved possible. By contrast, M2 users had greater flexibility with camera distances from the map allowable between 10 cm and 2 m, higher frame rates, increased robustness and greater flexibility with tilting of the device. Subsequently, M2 users did not cluster so closely together around the device (although while sharing the map they still continued to do so, but took more space around the map; Fig. 8, right). Four solo users completed the game successfully, so solo use of the system was feasible.

In contrast to M players, D players typically kept the device lower and closer to the body—a natural posture for holding a phone. However, this posture made the phone more private as others could not see the contents on the display (Fig. 7, left). After familiarising themselves with the system, most of the D players used the device single-handedly. Consequently, D players tended to have their non-dominant hand free, which allowed them to switch artefacts between hands more flexibly. Because D users found problems reported elsewhere [3] with joystick navigation, they largely relied on one zoomed-out version of the map that allowed them to view all game locations at one glance.

With multi-device teams, two phones seemed to be the maximum amount of devices that could efficiently and simultaneously fit over that map surface size. Devices were used in a panning motion over the map and needed space around them in order to move freely. When the devices collided one user moved the device to a different height above the map (Fig. 8 right), moved alongside the other device on the map, withdrew the device and looked through the other device, or looked sideways under the device with the naked eye. Some players explored different areas of the map with multiple devices. However, we observed decreasing multiple phone use over the span of the game.

Players usually grouped together to work on the same task. We found that because of (1) the space around the physical map and how much movement that allowed for players;(2) the size of the map itself and how much hovering device space that allowed; and (3) teams choosing to discuss and work on problems together rather than dividing up tasks and working solo over time; the more efficient use that emerged over time, was with one or two devices over the map. We reason that one or two devices were the maximum number of devices for that size of map (and the kind of movement of devices and clustering of bodies this size naturally allows). This suggests that other sizes of physical artefacts and numbers of people could find different results.

5.3.2. Usage of the map alone

M players must use the physical map and the device in tandem. Most M1 teams used the map-device combination to identify target locations and for route planning. A few M1 groups unfamiliar with the surroundings used the map-device combination to identify the target destination and then the map alone for route planning. While use of the physical map was optional for D players, two of the five D teams used the physical map for the entire game, two for most of the game and one team more experienced with mobile phones only in the training period.

M1 players had to constantly negotiate the physical map and became very familiar at handling the map, which affected the way they generally managed all the physical artefacts. In contrast to M1 players, each M2 player had their own map. Yet, we found that M2 teams typically deployed just one map. Two or three maps were used in the early training stages; however, teams quickly switched to one shared map as a frame of reference. If we identify the map as the frame of reference that enables all AR activity, having multiple frames of reference was not useful in this instance.

Finally, in windy conditions M2 teams predominantly held the map in their hands and used it while standing on the street to stabilise it against the wind. Teams who put the map down often placed objects or put their feet on the map corners to keep it in place. Despite stressing that the map is an inexpensive item only four of the fifteen M2 teams folded it, making it easier to handle (2 multi-device, 1 single-device, and 1 solo).

5.3.3. Usage while walking

Seven of the eleven M1 teams tried using the system while walking, but all faced difficulties. First, even a light trembling of the device hinders M1 usage. Second, awareness of the environment is challenged while using M1 (e.g., one player walked into a lamp-post). Other variations were initiated. For example, in a team of three young girls one walked behind using M1 while the others guided her from front to prevent her running into anything. When she found something, she called them to look. Overall we found that M1 does not support usage while walking. Indicative of this, some teams used M1 while waiting at traffic lights and used the walking time to converse or to discuss tasks.

For M2 players, we observed use while walking made possible (Fig. 10, left) as there was no need to shade the display for tracking to work, or to keep a steady hand while standing still. Particularly solo users and multi-device teams used the device while walking. However, much like reading a book and walking, reading the display and map and taking care not to walk into the surrounds acts as a preventative factor. Instead, we observed more agile forms of place-making on the fly.

Difficulties with use while walking were not as common for D players. Three teams used the system while walking, and one team even ran while watching the map. D teams used the walking time to watch the map and work out the next steps, with subsequent less for discussion.

M2 allows for selecting an area of the map through the AR interface and loading a thumbnail list of all the photos in said area. The thumbnails can then be browsed without using the paper map. Users are therefore free to use the AR interface (map-device combination) or the non-AR interface (device-only thumbnail list), depending on the task they want to perform. In the M2 study this new feature allowed exploration of information while walking (Fig. 10, right), and eradicated the need for recurrent stopping. In general we noticed that this feature supports more agile forms of use.

Overall, we observed both improvements on the previous design (MapLens1) and effects of the number of available devices

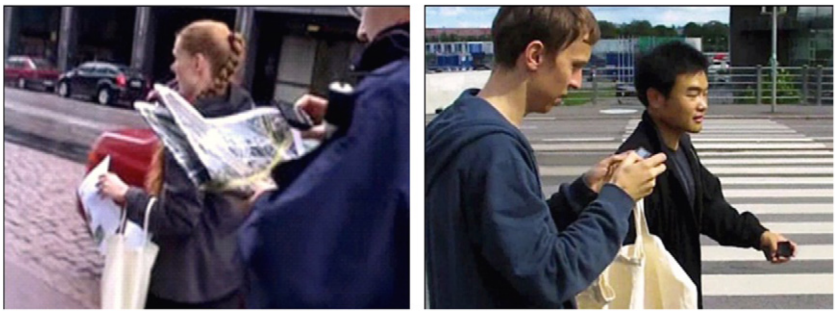

Fig. 10. Using M2 while walking. (Left) Walking and using M2 was possible with a folded map. (Right) Walking and browsing photos in M2 did not require usage of the paper map.

Table 1
Questionnaire items showing statistically significant differences between MapLens1 (M1) and DigiMap (D) groups. Presence (P) results on a 5-point Likert scale, Flow (F) and Motivation (M) on a 7-point Likert scale.

First Study: Questionnaire item (items related only to use of the **system**)	Result	Mean diff.
P. I was able to imagine the environment and arrangement of the places presented using the map system well.	D > M1	0.23
P. I concentrated on whether there were any inconsistencies in this mapping system.	M1 > D	1.00
Items related both to use of the **system** and to the **game**		
P. Task and technology took all my attention.	M1 > D	1.00
P. I felt I could be active in my surrounding environment.	D > M1	1.66
F. How to play the game and how to work the technology was easy.	D > M1	1.00
F. My skill level increased as I progressed.	D > M1	2.00
M. I think I am pretty good at these tasks.	D > M1	1.00
M. I found the tasks very interesting.	D > M1	1.00
Items related only to the **game**		
F. The difficulty level got easier as the game progressed.	D > M1	2.69
F. I knew how I was progressing in the game as I was proceeding.	D > M1	0.65
F. I helped other players in other groups.	M1 > D	1.08

Table 2
Questionnaire items showing statistically significant differences in between solo users (S), single-device (SD) and multi-device (MD) teams for MapLens2. Presence (Px) results are on a 5-point Likert scale, Flow (Fx) and Motivation (Mx) on a 7-point Likert scale.

Second Study: Questionnaire item (Items related only to the **game**)	**Result**	**Mean diff.**
P2. The game took most of my attention	SD > S	2.17
P8. I felt I could be active in my surrounding environment.	MD > S	1.83
P10. I thought whether this map and phone system could be of use to me.	SD > S	3.00
	MD > S	2.83
F8. How to play the game and how to work the technology was easy.	MD > SD	0.83
F10. I understood how to play the game when I left the meeting room.	SD > S	1.17
	MD > S	1.42
F19. I understood what the immediate tasks were and what I needed to do to achieve them.	SD > S	2.17
	MD > S	2.25
F20. I knew how I was progressing in the game as I was proceeding.	SD > S	2.00
	MD > S	2.17
F21. I was not as aware of time passing or of other people outside of the game as I feel I would usually be.	SD > S	2.67
F23. I enjoyed putting my feet in the grass, looking at the leaves, testing the pond water and similar	SD > S	2.33
	MD > S	2.42
M1. I enjoyed doing the game tasks.	SD > S	2.33
	MD > S	2.33
M10. I think I am pretty good at these tasks.	SD > S	2.00

on the collaborative behaviour. We observed a more agile usage of MapLens2 as compared to MapLens1: We reason this is due to the improved tracking technology. Photo browsing while walking is made possible by the introduction of a non-AR interface. While we eradicated the need for collaboration by providing multiple maps and devices, teams still collaborate mostly on one single map. Single-device teams seem to share information more through direct communication, whereas multi-device teams seem to share information more through the devices.

6. Questionnaires

We used MEC-SPQ [30], GameFlow [23] and IMI [17] to measure user experience. Statistically significant differences (at the 0.05 level) are shown for MapLens1 in Table 1 and for MapLens2 in Table 2.

By comparing the Presence, the Flow and intrinsic motivation score medians between M1 and D we found that both systems activated user motivation, being present to the game and/or map system, and engagement. Three main conclusions can be drawn from the comparison between M1 and D: (1) While M1 players felt confident using the technology and enjoyed the experience, D players reported they did so even more. (2) D players were more aware of their surroundings than M1 players. M1 players concentrated more on the technology and on the game as a whole. (3) M1 players felt more socially active and more helpful to others.

In the M2 study we found statistically significant differences between solo and multiplayer conditions mainly for the game experience. The only significant difference between single-device and multi-device team conditions was how easy they found the game (F8).

Multi-device teams found the game easier than single-device teams. Comparing multiplayer teams with solo players we found higher levels of attention (P2) and higher activity in the environment (P8) for teams. Teams also had higher challenge-skills balance (F10, F19 and F20), enjoyment (F23) and loss of self-consciousness (F21) and Intrinsic Motivation (M1, M10). While solo users were more efficient, the questionnaires show that their enjoyment level was lower. We reason there was more cognitive load for solo users, with less workload and more opportunities for discussion and playful activity when sharing tasks in a team. For technology, the only significant difference was in thinking about future use of the system (P10). Teams scored higher than solo players on this question.

7. Conclusions and discussion

For both studies differences in embodied interaction imposed by AR impact and define how an individual user orients to the environment and how teams can operate. Based on our studies, it is not possible to conclude that a team's performance with AR is better or worse than with alternative means, neither is it our intention to do so. Rather, the contribution lies in detailing interactions with shared, multiple, solo and digital lenses and in using ethnographic field study evaluation methods for Mobile AR studies.

The typical team-level response for MapLens users was stopping movement and clustering around the map-device combination, "like bees around the hive". With the increased facility and stability of the technology in M2 trials, a more nimble system of use emerged with more agile place-making on the fly. In both studies, we see establishment of bodily configurations in close proximity. We noted the importance of pointing to the physical map, the device and the environment, with finger or pen and with MapLens itself, and propose that both support establishment of common ground. In the second study, we observed that the multi-device teams shared differently than the single-device teams, as they shared more through the device screen. Consequently multi-device teams needed to point less to the map, the screen and the environment by using the devices to establish a multi-device common ground system of use on the fly. For multi and shared device conditions, we find a more transitory use of the improved M2 system.

As a general overview, the questionnaires, interviews, game results and photographic usage in both studies show that the MapLens teams concentrated more on the interface and the game itself, whereas DigiMap users were more aware of the environment around them. Also, MapLens users were more concentrated on the combination of the technology and the game—which involved problem-solving via negotiation, physical and social interaction. The way place-making affects attention to the task and technology, vs. the surroundings is a plausible explanation for this observation. Our conclusion is that although MapLens requires more cumbersome use for an individual, cooperative group work benefits from the sharing of tasks and place-making that MapLens elicits and common ground that it supports. The MapLens2 study substantiates the MapLens1 result that AR on mobile phones proves to be a natural platform for collaboration, demonstrating a useful result for Mobile AR design, generally. In the presence and experience questionnaires, single and multi-device teams scored higher on attention, activity in the environment, challenge-skills balance, enjoyment or loss of self-consciousness and Intrinsic Motivation than solo users. Team-sharing increases enjoyment and offers more opportunities for 'feel-good' experiences. AR on mobile phones is easily used in multi-user situations and multi-user teamwork has more 'feel-good' factor than solo use.

The findings point out a couple of obvious opportunities for improving mobile AR interactivity in the wild. First, from the user's perspective, robustness of the tracking algorithm is a worthwhile investment. Second, regardless of the availability of multiple devices and multiple maps, people chose to work on the same problem together despite not needing to. Dividing up and/or distributing tasks or working alone did not occur. Rather, multi-device teams figured out how to collaborate. Given the opportunity to establish a common ground through shared space, groups of people appear compelled to do so. Bearing this in mind, it would be sensible when designing future AR applications to ensure the design affords ease of place-making, and establishment of common ground.

As we used state-of-the-art tracking technology and designed a game where exploratory navigation is fundamental, we believe our findings extend to general collaborative use of augmented maps for exploratory navigation.

8. Implications and further work

With this technology, any map or paper poster can be used for mobile location-aware applications. For example, maps or posters on billboards or in bus stops can be augmented with dynamic and personalised digital information. In the trials the participants carried a card map as a lightweight prototype, as a representation standing in for what would be a personal map or a series of maps, posters and flyers that in real use would be placed in public places. The augmented system could read and update information from these. This task is more difficult in green areas, where there are less spaces that posters and maps can be placed, and the card map proved a pragmatic shortcut stand-in solution. Bearing this in mind, generally speaking, mobile AR applications need to be designed and developed with a view to the 'real physical environment' they are going to be used within, not just the digital one. This means that the design of applications needs to take into account their context of use in the physical and social world.

Field trials should become the standard for evaluation and experimentation, especially once the technology has passed laboratory performance testing and is sufficiently mature to sustain continued use in outdoor conditions.

Our studies lend evidence that mobile phones can be adopted as collaborative tools for small groups, despite expectations around their use as a small personal device. If AR device use changes the way people interact with each other and the environment, then we need to design to compensate, enhance and/or detract with ways to manipulate this newly-learnt factor.

Our studies also suggest a number of further questions to be examined. One question concerns the relationship of multiple devices to physical form factors, such as the size and structure of the shared space. This will impact heavily as more A5/A4-size devices become available. It is also important to understand how customised augmented content on individual devices – subjective views – effects simultaneous use. In these studies, the input was limited to photographic contribution only, but this would become particularly interesting where users could create or manipulate virtual content in the environment. The positive results of spontaneous, voluntary, expanded and agile place-making with these observed intense collaboration styles suggest potential for further interaction design solutions for AR interfaces with multiple devices.

Finally, a broader implication for mobile AR research is to identify tasks that require modes of cooperation supported by applications like MapLens. These tasks might include social gaming and public social tasks such as crisis response that require mobility, interaction with the physical environment and connected information (via tangible artefacts such as maps, flyers and/or architectural structures, for example, known cross-roads or building facades). Spontaneous group puzzle-solving – involving chains of complex sequential tasks or unexpected circumstances – requires discussion, negotiation and up-to-date information.

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