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Review

# Pervasive gaming: Status, trends and design principles

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ABSTRACT

Pervasive games represent a radically new game form that transfers gaming experiences out into the physical world, weaving ICTs into the fabric of players' real environments. This emerging gaming mindset is rather challenging for developers exploring technologies and methods to achieve a high quality interactive experience for users, and designing novel and compelling forms of content. This paper follows a systematic approach in exploring the landscape of pervasive gaming. First, we present 18 representative pervasive game projects, following a generations-based classification. Then, we present a comparative view of those projects with respect to several design aspects. Lastly, we shed light on technological status and trends, design principles, developer guidelines, and research challenges for pervasive games development.



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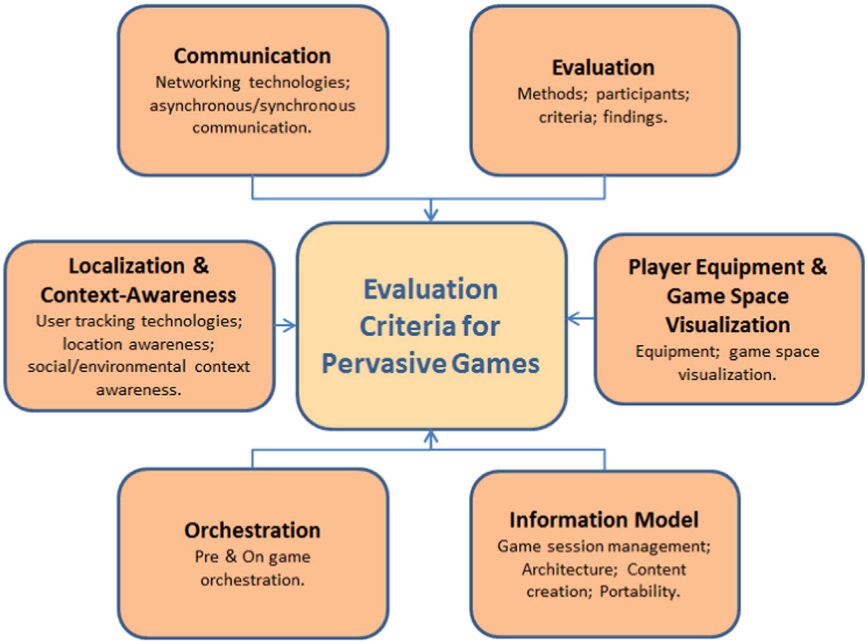


**Fig. 1.** Design and evaluation aspects of pervasive games.

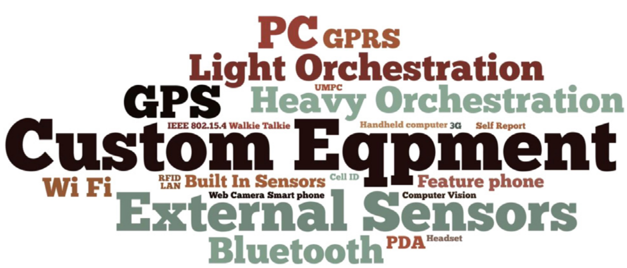


**Fig. 2.** Tag cloud depicting most frequently used terms in 1G pervasive games.

## 1. Introduction

Pervasive computing is a post-desktop model of human–computer interaction in which information processing is thoroughly integrated into users' physical environments (both objects and activities). Pervasive gaming represents an emerging field within the context of pervasive computing, defining a major evolutionary step from traditional 'electronic/computer games', i.e., electronic systems that employ some kind of computational machinery to create an interactive interface controlled by players (Magerkurth et al., 2005). Pervasive games shape an exciting and commercially promising new form of computer games that builds upon a combination of hybrid interfaces, mobile device equipment, wireless networking, positioning systems, and context-sensing technologies. These games extend the gaming experience into the physical realm – be it the city streets, the remote wilderness, or a living room. Players equipped with mobile devices move through the world; built-in or external sensors capture information about their current context, used to deliver gaming experiences adaptable to where they are, what they do or even how they feel. The player is released from the console and experiences a game interwoven with the real world, commonly available anytime, anywhere (Benford et al., 2005).

The contribution of this paper is threefold. Firstly, a novel classification scheme is proposed offering a perception of pervasive games evolution. Secondly, we investigate in detail a number of games from several angles, so as to offer insights on the trends and challenges in pervasive gaming. Last, building upon the main findings of this investigation, we extract design principles and suggest best practices and implementation guidelines for designers and practitioners. The surveyed games are examined with respect to the following design aspects (see Fig. 1):

- *Communication* refers to wireless technologies enabling the interaction either among players or between players and some sort of game management engine.
- *Player equipment and game space visualization* criteria refer to the devices used by players and the means utilized for the visualization of the game space.
- *Information model* criteria consider the informational and architectural models adopted in these games to support the game scenarios and assist the users in satisfying their needs.
- *Localization and context-awareness* criteria deals with technologies used to track user position as well as personal, social, and environmental aspects triggering changes in the game environment, which may otherwise be static.
- *Orchestration* refers to techniques, human support (e.g., actors), and infrastructure used by developers to manage live game action behind the scenes (Benford et al., 2005).
- *Evaluation* refers to qualitative and quantitative methods utilized to measure the extent to which the game design has met its objectives with regards to several criteria. It regularly aims at extracting generic game design guidelines.

The above-listed design and evaluation aspects essentially capture the research questions mainly addressed in the pervasive games scientific literature and the practical issues investigated by prototype designers and developers. Among them, the first three design aspects reflect the technological and architectural foundations of pervasive games: namely, the wireless technologies that enable the communication between the players and the game engine, the equipment used to access in-game content, the game activity visualization means and the structuring/organization of game engines. Context-awareness represents an organic element in every application field of pervasive computing. Orchestration is a unique aspect of pervasive games which originates from the common requirement of many prototypes for dedicated infrastructure supplied to the players or deployed in the game area and the need for supporting players' coaching and in-game activities (Benford et al., 2005). Lastly, the design and execution of evaluation trials represent a key issue commonly addressed in recent pervasive games research as it allows developers to assess and measure the factors affecting the overall quality of experience for the players (Jegers 2009; Saarenpää 2008).

Our survey is based on the review and comparison of 18 pervasive games, including both research prototypes and commercial projects (13 and 5, respectively): *TimeWarp* (Wetzel et al., 2009), *Epidemic Menace II (EM II)* (Fischer et al., 2006), *Treasure* (Guo et al., 2012), *Age Invaders* (Cheok and Khoo 2006), *Urban Defender* (Urban 2011), *Hot Potato* (Chatzigiannakis et al., 2010), *Blowtooth* (Kirman et al., 2012), *Capture The Flag (CTF)* (Cheok et al., 2006), *Can You See Me Now? (CYSMN?)* (Broll et al., 2006), *Uncle Roy All Around You (URAAY)* (Benford et al., 2004), *Your Way Your Missions* (Chen et al., 2013), *FreshUp* (Zender et al., 2014), *Barbarossa* (Kasapakis et al., 2015, 2013), *Ingress* (Google, 2013), *Mogi* (Benjamin, 2007), *Parallel Kingdom Age of Emergence (P.K. AoE)* (PerBlue, 2011), *Zombies, Run!* (Start, 2013) and *Invizimals* (GameSpot, 2012).

While several other pervasive game prototypes currently exist (e.g., (2004; Chatzidimitris et al., 2014; Cheok et al., 2004; Flintham et al., 2007; Hannamari et al., 2007; Olli, 2002; Stenros et al., 2007)) we have chosen the above-mentioned projects as a compromise between having a fairly sized games' sample and achieving a balanced representation of prototypes with respect to their generation, genre, and utilized technologies. We have also mainly focused our attention on the most popular games as well as those with the highest scientific impact.

In particular, commercial products have been selected with respect to their active players and market success (Benjamin, 2007; GameSpot, 2012; Google, 2013; PerBlue, 2011; Start, 2013).[1] As for research prototypes we have excluded games released before 2002 as their technological handicap would undermine a fair comparison with their recent counterparts. The chosen games are amongst the most influential within the pervasive gaming research community (as evidenced by the number of citations they have received), while the respective articles provide a sufficiently detailed discussion to allow us to extract all the information needed to evaluate them with respect to the evaluation criteria (Benford et al., 2004, 2006; Chatzigiannakis et al., 2010; Cheok and Khoo, 2006; Cheok et al., 2006; Fischer et al., 2006; Guo et al., 2012; Urban, 2011; Wetzel et al., 2009). Last, we survey a number of very recently released prototypes to ensure up-to-date analysis and to capture technological trends (Chen et al., 2013; Kasapakis et al., 2013; Kirman et al., 2012; Zender et al., 2014).

The remainder of this paper is organized as follows: Section 2 gives an overview of research related to our survey and explains the research methodology adopted in our survey. Section 3 classifies and briefly presents the set of examined pervasive game projects, summarizing their main features. Section 4 evaluates the projects with respect to the above-listed design aspects. Section 5 indicates technologies and design decisions which have succeeded or failed with respect to user acceptance. Section 6 discusses current technological trends, suggests research opportunities and challenges for pervasive gaming research and translates our main survey findings into concrete developer guidelines. Section 7 focuses on the threats and barriers which impede the further adoption of pervasive games, while Section 8 suggests the main drivers in the transition towards the next generation of pervasive games. Lastly, Section 9 concludes our work.

## 2. Related work and research methodology

To the best of our knowledge, the study mostly relevant to our owns was published in 2005 (Magerkurth et al., 2005). Inevitably, Magerkurth et al. only offer a snapshot of the first generation of pervasive games. The authors identified several pervasive game subgenres and discussed their benefits and critical issues under the lens of their underlying technology base. Another relevant survey was published by Broll et al. in 2006 (Broll et al., 2006), focusing on the typical technological challenges tackled by pervasive game developers. Nevertheless, the authors limited their study to a narrow sample of three games. A more recent survey (Kasapakis and Gavalas, 2013), published by the authors of this paper, reviewed 10 games, the latest released in 2011. Apart from being less detailed, that survey lacks investigation of important aspects of pervasive games (e.g., orchestration, and evaluation methods) and does not report concrete design guidelines for future development. Other surveys have been limited in scope, focusing on location-based (Avouris and Yiannoutsou, 2012) or augmented reality (AR) games (Thomas, 2012): namely, on game genres largely embraced by pervasive games.

Many researchers have proposed classification schemes of pervasive games in sub-genres: smart toys, affective games, augmented tabletop games, location-aware games, proximity games, event games, cross-media games, mixed-reality (i.e., augmented reality/virtuality) games, and trans-reality games, to name only a few (Jegers, 2009; Lindley, 2005; Magerkurth et al., 2005; Montola et al., 2009, 2006; Thomas, 2012). In the alternative classification scheme proposed by Hinske et al. (2007), pervasive games are viewed as a ludic form of mixed-reality entertainment with goals, rules, competition, and attacks, based on the utilization of pervasive computing technologies.

The classification scheme adopted herein has been dictated by the increasing heterogeneity of pervasive games, with respect to the utilized communication and positioning technologies, visualization means, user equipment, sensoring infrastructure, game locality (e.g., in/outdoors), orchestration requirements, etc. Therefore, we argue that a vertical classification of pervasive games in disjointed, non-overlapping genres is particularly difficult. Pervasive games, especially those prototyped in recent years, commonly lack a single common denominator characterizing them as pervasive (Montola et al., 2006). Even more so, radical developments in mobile and pervasive computing (e.g., advanced processing, and networking and sensory capabilities of mobile devices) increasingly facilitate the integration of – until recently – distinct technologies and features (e.g., location/environmental/social/emotional contexts, variety of communication means, third party services, rich 2D/3D graphics, AR, etc.) which are now interchangeably by developers as off-the-shelf solutions. For instance, games combining location awareness with AR have become increasingly common (Fischer et al., 2006; Herbst et al., 2008; Kasapakis et al., 2013). These developments blur the boundaries among the above-mentioned sub-genres making them largely ambiguous and inseparable. In fact, several of the game prototypes reviewed in this survey may belong to in more than one of these sub-genres, practically invalidating any genre-based classification approach.

In our work we receive inspiration from the classification proposed by Hinske et al. Hinske et al., (2007), nevertheless, we argue that it is not sufficient to embrace all aspects of pervasive

[1] *Zombies Run*! has more than 600,000 players (although it is sold for $3.99), *Parallel Kingdom AOE* (PerBlue, 2011) and *Ingress* (Google, 2013) feature more than 1,000,000 players, while *Mogi* (Benjamin, 2007) has had more than 100 participants per month even though it is not promoted through popular mobile application markets.

**Table 1**
Common features found in pervasive games generations.

| Generation | Time frame | Localization | Communication | Context | Orchestration | Player Equipment |
|---|---|---|---|---|---|---|
| 1st | 2002–2009 | GPS/self reporting/no localization | WiFi/Bluetooth/Zigbee | Captured by external sensors | Heavy/light orchestration actions | Custom equipment, wearable computers, PDAs, feature phones |
| 2nd | 2009–2014 | GPS/Cell-ID | WiFi/3G/Zigbee | Captured by build-in sensors | Light/No orchestration actions | Smartphones |
| 3rd | 2014-onwards | GPS/proximity-based localization/crowdsourcing localization platforms | WiFi/WiFi Direct/4G | Captured by built-in sensors /3rd party web-services | No orchestration actions | Wearables (glasses, smart watches, health bands), smartphones |


**Fig. 3.** Tag cloud depicting most frequently used terms in 2G pervasive games.

gaming. For instance, several instances of pervasive mobile or trans-reality games[2] cannot be considered as a breed of mixed-reality games.[3] Along this line, we propose a generations-based classification method, wherein pervasive games are categorized based on their release date. This classification offers a lucid reflection of the evolution of pervasive gaming field from its early days until today, while also highlighting the trends that are more likely to predominate in the – near – future.

The review of the 18 representative prototypes does not only provide an update on the latest advances in the field of pervasive gaming. Rather, we take an approach completely different to that of existing surveys. Namely, we adopt a horizontal, design aspects-based approach which offers a comparative view of the examined projects and underlines design and technological developments. This approach eases the extraction of design principles and best practices and serves as reference point for future prototype development in both academia and industry. Finally, we provide a detailed report on the open research issues in the field of pervasive gaming.

Our survey undertakes a methodological approach comprising the following steps: (a) careful selection of a fairly large sample of pervasive game prototypes, maintaining a balance of generations, genres, and representation of commercial/research prototypes; (b) classification of the selected games in distinct generations based on their game and technological elements, offering insights on the evolutionary path of pervasive gaming; (c) systematic evaluation of the selected games with respect to a broad range of criteria which reflect the research questions pursued by prototype designers and developers; (d) identification of game design elements, principles, and practices commonly appreciated or rejected by users; (e) discussion of the main evaluation findings, highlighting game design/technology trends and open issues for future research; and (f) formulation of concrete design/implementation guidelines for designers and practitioners in the field, extracted from the identified trends as well as from the compilation of user evaluation studies.

## 3. Classification and presentation of pervasive games

As explained in Section 2, in this article we advocate a different approach, classifying pervasive games in successive generations. Those generations are marked by technology transitions closely following the general mobile/pervasive computing developments. Further to providing advanced instruments to game developers for rapid prototype implementation, technology transitions signify parallel conceptual transitions with respect to game scenarios, player-game engine interactivity, perception of technology pervasiveness, and quality of experience, hence, substantiating the proposed generation-based classification. Even though the time frames and the technological boundaries among designated generations are debatable, we argue that such a classification may serve a systematic overview of the pervasive games' landscape and offer insights on the actual evolutionary path of pervasive gaming. A careful examination of the features of the surveyed game prototypes indicates a notable shift around 2009. Therefore, we distinguish existing projects in those released from the early releases of 2002 until 2009, and those prototyped from 2009 onwards, termed as first and second generation pervasive games, respectively. Interestingly, early signs exist of another major shift towards the next (i.e. third) generation of pervasive games, which is currently underway. The features characterizing pervasive game generations are summarized in Table 1. Currently, the landscape of third generation games has not yet stabilized and no prototypes exist which could be recognized positively as 3G games. As a result, their respective features are mostly extracted from preliminary examples showcasing how emerging technologies could be utilized in the conceptual framework of next generation pervasive games; therefore, these features are somewhat indicative and speculative. The roadmap towards third generation pervasive games is discussed in Section 8.

### 3.1. First generation

The first generation of pervasive games is delimited between 2002 and 2009. 1G pervasive games mostly used GPS to obtain the location of players, although some enable self-reported positioning or lack the localization feature. WiFi, GPRS, and Bluetooth have been common communication solutions, while user/environmental context incorporated into the game rules' has been mostly obtained via external sensors. Finally, most games required

[2] Trans-reality games involve distinct but interconnected game spaces, one being the physical world and the other being an interactive virtual or mixed-reality world. This is quite different from mixed-reality games that seek to create a single game space integrating both physical and virtual elements (Lindley 2004).

[3] Mixed-reality (MR) games merge real and virtual worlds somewhere along the "virtuality continuum" in order to produce game spaces that seek to integrate virtual and physical elements within a coherently experienced perceptual game world (Thomas, 2012). The best known type of mixed reality is augmented reality, wherein the real world perceived by users is enhanced through superimposed virtual objects.

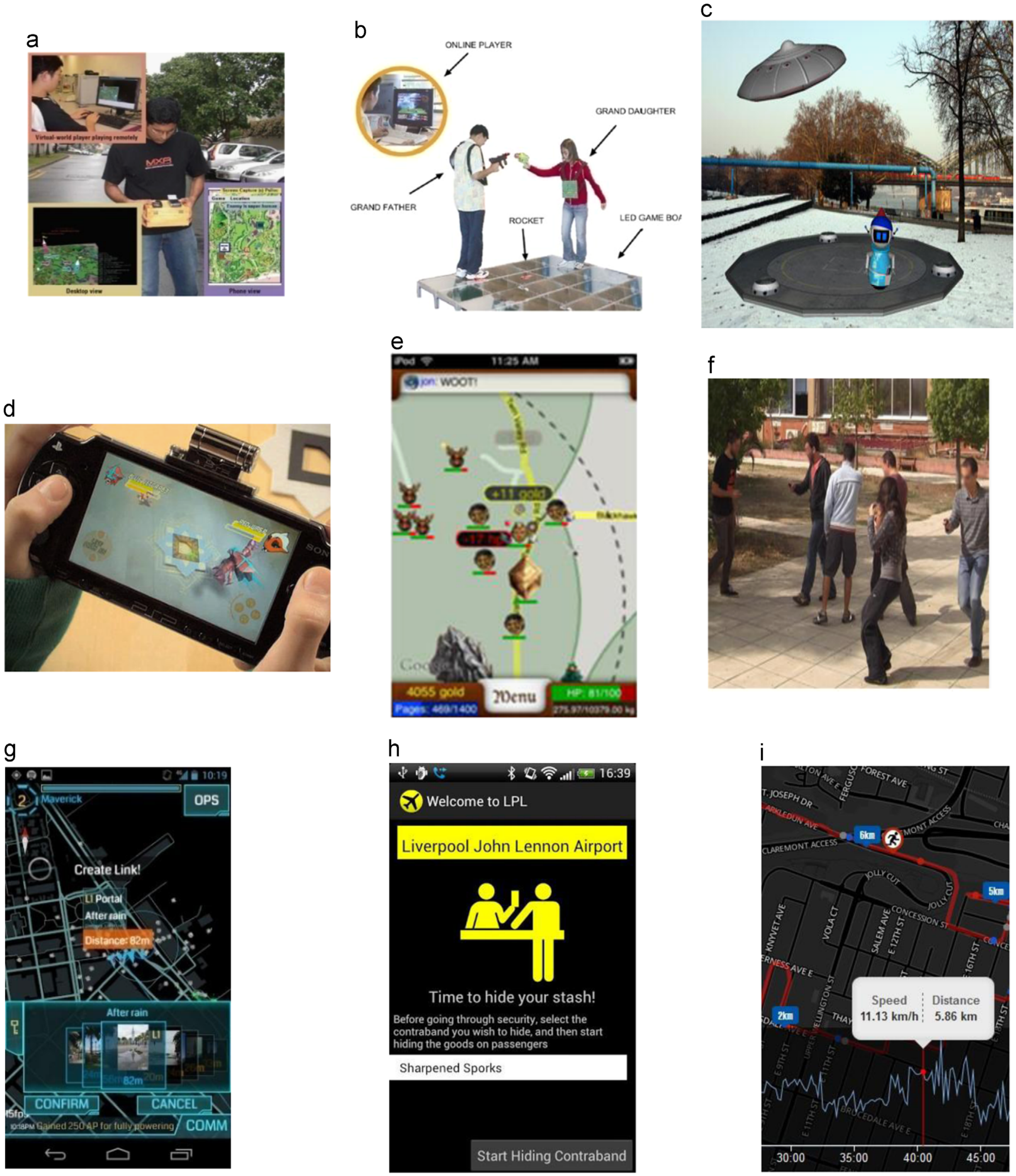


**Fig. 4.** (a) Capture the flag; (b) age invaders; (c) timewarp; (d) invizimals; (e) P.K. AoE; (f) hot potato (g) Ingress; (h) Blowtooth; and (i) Zombies Run!.

orchestration (typically, the presence of experts or actors during the game sessions) and the player equipment usually included more than one device (custom devices, wearables, external sensors, and PDAs). The tag cloud of Fig. 2 illustrates the most frequently used terms encountered in 1G pervasive games with respect to the main features tabulated in Table 1. Below, we briefly present the concept by surveying 1G pervasive game projects.

In *CYSMN?* runners run around real city streets to catch the online players that move through the virtual street representations (Broll et al., 2006). *URAAY* is a mixed-reality game that mixes online and outdoors participants, physical and virtual worlds, and programmed game-play with live performance, wherein the players search for an elusive character named Uncle Roy (Benford et al., 2004). In the Japanese game *Mogi*, the administrators place virtual treasures in the real world, collected by players at certain times and places. Benjamin (2007; Montola et al., 2009).

*EM II* is a cross media, multiplayer, social adventure game with strategy and action elements, wherein users try to eliminate a humankind-threatening virus epidemic, fighting against 3D viruses roaming around in the real world using AR technology (Fischer et al., 2006). *CTF* (see Fig. 4a) is based on the original 'Capture the Flag', a popular outdoor game. Real and virtual-world players are called 'knights' and 'guides' (Cheok et al., 2006). Any knight can occupy a castle by dropping his/her team's physical flag at a selected place, while guides use traps and potions to help knights; the game terminates when a team successfully captures its enemy's flag and carries it to its base.

*Age Invaders* (see Fig. 4b) involves two children playing with two grandparents in an interactive physical media space, while two parents can join in the game via the Internet as virtual players, thus increasing the inter-generational interaction (Cheok and Khoo 2006). *TimeWarp* (see Fig. 4c) is a mobile mixed-reality game played in the old town of Cologne by two players who try to stabilize the time-space continuum that is endangered by little robots (Wetzel et al., 2009). *Urban Defender* is a location-aware game acted in the real world using a ball as the only interface. The players throw the ball against a wall to conquer as many quarters as possible; they also try to reinforce these quarters and defend them against other players (Urban 2011).

### 3.2. Second generation

The onset of the second generation of pervasive games was around 2009. The games prototyped from that date onwards mainly use GPS for localization and WiFi/3G for communication. A major trait of these games is the use of smartphones as the sole game equipment. The built-in sensors of smartphones are frequently exploited to capture user and environmental context. Finally, 2G games are less dependent on orchestration (their scenarios rarely require the presence of actors or experts). The tag cloud of Fig. 3 illustrates the most frequently encountered terms in 2G pervasive games.

*Invizimals* (see Fig. 4d) is a commercial casual game released by Sony Computer Entertainment. Players use PlayStation Portable (PSP) handhelds and lay proprietary printed marker patterns in the real-world. These markers are detected by the PSP's camera and rendered as traps in the virtual game world such that virtual animals can be hunted and captured by the players (GameSpot, 2012). *PK AoE* (see Fig. 4e) is a GPS-based online role playing game for Google Android and iPhone devices, that uses Google Maps in the background and superimposes a whole new virtual world upon it (PerBlue, 2011). In *Hot Potato* (see Fig. 4f) players try to pass the potato to another player using a device (sensor node) through gesturing, when in proximity to the co-player. A player is disqualified when a potato 'blows' while she/he holds it (Chatzigiannakis et al., 2010).

*Treasure* is a pervasive game played within players' daily living environments. Unlike other approaches based on predefined game content and proprietary devices, *Treasure* exploits the "design-in-play" concept to enhance the variability of a game in mixed-reality environments. Dynamic and personalized role design and allocation by players is enabled in *Treasure* by exploring local smart objects as game props (Guo et al., 2012). In *Ingress* (see Fig. 4g) the primary goal of the game is to defend the takeover of humankind by an unknown "Shaper" force or, depending on the perspective, to assist in the "Enlightenment" of humankind through an alliance with the Shapers. This is accomplished through aligning with either the Resistance or the Enlightened faction and by creating "Control Fields" over geographic areas (Google, 2013).

In *Blowtooth* (see Fig. 4h) players use their mobile phones to hide virtual drugs on nearby airline passengers in real airport check-in queues. After passing through airport security, the players must find and recover their drugs from the innocent bystanders, with the latter having not realized they were ever involved in the game (Kirman et al., 2012). *Zombies, Run!* (see Fig. 4i) is a chase game and audio adventure wherein the player runs outdoors trying to complete missions and get away from zombies. Upon returning home, the player can use supplies collected outdoors to upgrade her base (Start, 2013). *Your Way Your Missions* (*YWYM*) provides a Google Maps-based tool for players to predefine routes, and utilizes a self-reporting method to obtain the planned routes of players. The incentive is to counter imprecision of positioning technologies and, hence, the inefficiency of information adaptation based on location and radius. Via such a design, *YWYM* missions are assigned to players depending on the location properties of missions and the routes scheduled by players (Chen et al., 2013).

The goal of *FreshUp* is to help freshmen at universities get accustomed to their new environment and tasks in a playful and motivating manner. The game focuses on issues like course registration, use of the cafeteria, library access, and public transport. The players win when they collect four cards that address four knowledge types: factual, orientational, actionable and practical knowledge (Zender et al., 2014).

In *Barbarossa* (Kasapakis et al., 2013), players are introduced to the game through an invitational phase using a publicly available Android application, and try to achieve a high rank to secure invitation to the second game phase. Thereafter, they have to cooperate in teams of three players and complete individual, complementary game scenarios which involve a variety of technologies like AR, QR-codes, Google Maps and Directions APIs,[4] and weather web services.[5] The quest for players is to cooperatively discover and unlock a real hidden chest locked by two combination locks.

Tables 2–6 summarize the main features of surveyed games (concept, release date, creator, whether it is played by a single or multiple players, locality, generation, genre, unique features, current status, cost, and effort). Note that most of the bibliographical sources describing the surveyed games miss information relevant to the development cost and effort, while some only refer to manpower engaged in the games' execution phase (i.e., orchestration). Notably, all surveyed commercial games (apart from *Invizimals*) are distributed via mobile application markets, like Google Play[6] and iTunes,[7] which facilitate application deployment to users' devices and ensure wide dissemination (Google, 2013; PerBlue, 2011; Start, 2013). *Zombies Run!* represents an interesting business case as it has been crowdfunded[8]; in fact, the project raised far more funds than the amount pledged by developers, showcasing the potential of the crowdfunding model for future promising pervasive games ideas.

It should be noted that *Mogi* and *Treasure* could have been defined as 2G and 1G games, respectively, based on their utilized technologies. However, the assignments shown in Table 2 were dictated by their release dates.

[4] https://developers.google.com/maps/documentation/directions/.

[5] https://weather.yahoo.com/.

[6] https://play.google.com/store.

[7] http://store.apple.com/.

[8] Crowdfunding is a novel method for funding a variety of new ventures, allowing individual founders of for-profit, cultural, or social projects to request funding from many individuals, often in return for future products or equity (Mollick 2013).

**Table 2**
Main features of the reviewed pervasive games.

| Game | Concept | Release date/ Creator | Single/ Multi Player | Game space locality | Generation | Genre | Unique features | Current status | Funding, cost & effort |
|---|---|---|---|---|---|---|---|---|---|
| **CYSMN?** (Broll et al., 2006) | Chase | 2003/Blast Theory, Mixed Reality Lab, University of Nottingham | Multiplayer | Indoors/ Outdoors (in a predefined area) | 1G | Location-aware, cross-media, event-based, mixed reality, trans-reality | | Research prototype | Supported by the Equator IRC, funded by EPSRC, AHRB, ACE and the V2 Organization; 4 professional performers used as outdoors runners. |
| **URAAY** (Benford et al., 2004) | Item hunt/ Puzzle/ LARP | 2003/Blast Theory, Mixed Reality Lab, University of Nottingham | Single Player | Indoors/ City streets | 1G | mixed reality, location-aware, cross-media, event-based, trans-reality | Encourages players to cross boundaries between physical and virtual worlds (e.g. get into a limousine with a stranger). | Research prototype | Supported by the Equator IRC, funded by EPSRC, AHRB, ACE and the V2 Organization; live actors and a limousine was used along with Uncle Roys office. |
| **Mogi** (Benjamin 2007; Montola et al., 2009) | Item hunt | 2003/ KDDI | Multi/ Single player | Indoors/ Outdoors | 1G | Location-aware, mixed reality, event-based | Players can earn real money. | Commercial product | 2$ for monthly subscription. |
| **EM II** (Fischer et al., 2006) | Item hunt/ Puzzle/ LARP | 2006/ Fraunhofer FIT, University of Tampere | Multiplayer | Indoors/ Outdoors (in a predefined area) | 1G | Location-aware, cross-media, proximity-based, event-based, mixed reality | | Research prototype | 18 researchers worked into the project; developers reported high costs to stage EM II. |
| **CTF** (Cheok et al., 2006) | Chase | 2006/National University of Singapore | Multiplayer | Indoors/ City streets | 1G | Location-aware, cross-media, proximity-based, trans-reality | | Research prototype | – |
| **Age invaders** (Cheok and Khoo, 2006) | Chase/ puzzle | 2006/Mixed Reality Lab | Multiplayer | Indoors/ Floor Board | 1G | Proximity-based | Compensation for elderly players' disadvantages. | Research prototype | – |
| **TimeWarp** (Wetzel et al., 2009) | Item hunt/ Puzzle | 2007/iPcity | Multi/ Single player | City streets | 1G | Location-aware, proximity-based, mixed reality | | Research prototype | – |
| **Urban Defender** (Urban, 2011) | Chase | 2009/Zurich University of Arts Department of Interaction Design | Multiplayer | City streets | 1G | Location-aware, smart toy | | Research prototype | – |
| **Invizimals** (GameSpot, 2012) | Action/ Adventure | 2010/Sony Computer Entertainment Europe | Multi/ Single player | Outdoors/ indoors | 2G | Mixed reality | | Commercial product | Price: ~20€ |
| **P.K. AoE** (PerBlue, 2011) | Item hunt/ puzzle/ strategy/ role playing | 2010/PerBlue | Multiplayer | Indoors/ Outdoors | 2G | Location-aware, mixed reality | Supports massive amount of players; persistent game world. | Publicly available/ Commercial product | Provided free of charge; in-game products available for sale. |
| **Hot Potato** (Chatzigiannakis et al., 2010) | Chase | 2010/University of Patras | Multiplayer | Indoors/ Outdoors | 2G | Proximity-based | Allows operation in connected/disconnected mode; persistent game world. | Research prototype | Partially supported by the European Union (IST-2005–15964-AEOLUS and ICT-2008–215270-FRONTS). |
| **Treasure** (Guo et al., 2012) | Item hunt/ Puzzle | 2011/Keio University | Multi/ Single player | Indoors | 2G | Proximity-based, mixed reality, event-based | Dynamic, personalized role design and allocation by players. | Research prototype | - |
| **Ingress** (Google, 2013) | Item hunt/ Chase | 2012/Google | Multiplayer | City streets | 2G | Location-aware, mixed reality, event-based | Establishes "portals" at Points of Interest (POIs) in proximity to the player. | Commercial product | Provided free of charge. |
| | Item hunt | 2012/Lincoln Social Computing | Single player | Indoors | 2G | Location-aware, proximity-based | Game settings are restricted in airports, before/ after security checks. | Publicly available | - |

**Table 2** (*continued*)

| Game | Concept | Release date/ Creator | Single/ Multi Player | Game space locality | Generation | Genre | Unique features | Current status | Funding, cost & effort |
|---|---|---|---|---|---|---|---|---|---|
| **Blowtooth** (Kirman et al., 2012) | | Research Centre, University of Lincoln | | | | | | | |
| **Zombies Run!** (Start, 2013) | Item hunt/ Chase | 2012/Six to start | Single player | Indoors/ City streets | 2G | Location-aware | Takes into account the players' song playlist to determine the duration of missions. | Publicly available/ Commercial product | Founded by Kickstarter[a] raising $72,627 from 3464 backers ( > 5 five times the amount pledged); price: 3.59 €; 100.000–500.000 downloads in Google Play. |
| **YWYM** (Chen et al., 2013) | Puzzle | 2013/Zhejiang University | Single Player | City streets | 2G | Location-aware, trans-reality | Missions are assigned to players based on the location properties of missions and the routes planned by players. | Research prototype | - |
| **FreshUP** (Zender et al., 2014) | Puzzle | 2013/University of Potsdam | Multiplayer | Indoors/ Outdoors | 2G | Location-aware, cross-media game, trans-reality | | Research prototype | - |
| **Barborossa** (Kasapakis et al., 2015, 2013) | Chase/Item hunt/ Puzzle/ | 2013/University of the Aegean | Multi/ Single player | Indoors/ Outdoors | 2G | Location-aware, event-based, mixed reality, trans-reality | Participants receive rank-based invitations in an invitational game mode. Separate game roles are supported with various technological and orchestrating needs. | Research prototype | Self funded project; developers reported 12 person months for implementation and 3 person months for user trials execution. |

[a] https://www.kickstarter.com/.

**Table 3**
Communication and communication model features.

| | Networking technologies | Synchronous/Asynchronous communication |
|---|---|---|
| **CYSMN?** | Wireless LAN | Synchronous |
| **URAAY** | GPRS | Asynchronous |
| **Mogi** | 3G | Asynchronous |
| **EM II** | LAN, WiFi, Bluetooth, GPRS | Asynchronous |
| **CTF** | GPRS, Bluetooth | Synchronous |
| **Age Invaders** | Bluetooth | Synchronous |
| **Time Warp** | Bluetooth | Asynchronous |
| **Urban Defender** | IEEE 802.15.4 | Asynchronous |
| **Invizimals** | WiFi (adhoc mode) | Synchronous/Asynchronous |
| **P.K. AoE** | WiFi, GPRS, 3G | Synchronous |
| **Hot Potato** | IEEE 802.15.4 | Synchronous/Asynchronous |
| **Treasure** | IEEE 802.15.4 | Synchronous/Asynchronous |
| **Ingress** | WiFi, 3G | Synchronous |
| **Blowtooth** | WiFi, 3G, Bluetooth | Synchronous |
| **Zombies Run!** | WiFi, 3G | Synchronous/Asynchronous |
| **YWYM** | WiFi, 3G | Synchronous |
| **FreshUP** | WiFi, 3G | Synchronous |
| **Barborossa** | WiFi, 3G | Synchronous/Asynchronous |

## 4. Design aspects-based evaluation of pervasive games

### 4.1. Communication

Networking technologies are fundamental for pervasive games as they enable the communication among players or between a player and a centralized game engine facility. Bluetooth has been a common networking choice among many games to enable short-range connectivity, followed by IEEE 802.15.4. In most cases, Bluetooth has been supplemented by GPRS and Wireless LANs. Other games opted to use 3G/WiFi and IEEE 802.15.4-compliant radios. Notably, developers and users reported connection and latency problems when using WLAN or GPRS technology in many game projects (Cheok et al., 2006, 2004; Kirman et al., 2012; Olli, 2002; Saarenpää, 2008). The communication model adopted (synchronous/asynchronous) mostly depends on the supported game scenario and game play style.

Evidently, correlation exists among the games' generation (i.e. shipping date) and adopted networking technologies, reflecting the evolution path of wireless technologies. Another selection criteria relates to the intention to support a small- or large-scale playscape, and indoors or outdoors coverage. The increasing availability of free WiFi connectivity and the reduced data communication costs of 3G networks, along with the high data transmission rates achieved in the emerging 4G deployments, designate those networking technologies as the most practical choices for pervasive game developers. This claim is backed by the timeline shown in Fig. 5 which clearly illustrates that short range communication, once mainly supported by Bluetooth in 1G games (with the exception of *Blowtooth*[9]), has been substituted by remote client/server communication in 2G projects. For instance, in *PK AoE* the players exchange goods via WiFi, GPRS, or 3G even when standing next to each other. This observation proves that developers are nowadays less reluctant in implementing game scenarios that require always-on connectivity. Besides, both the iOS and Android platforms support auto-WiFi/3G switching whereby the mobile data connection switches from 3G to WiFi whenever a free WLAN is in range.

[9] In *Blowtooth*, Bluetooth-enabled devices are used as content generation instruments.

**Table 4**
Context awareness aspects.

| | Location awareness | Localization | Usage of user position information | Social context awareness | Additional context-parameters |
|---|---|---|---|---|---|
| **CYSMN?** | ✓ | GPS | Real-time navigation (visualization on map), visualization of co-players positions | Other players location | – |
| **URAAY** | ✓ | Players declare their location using a map | Real-time navigation (visualization on map), transparent location-based information provision, visualization of co-players positions | Other players last known location | – |
| **Mogi** | ✓ | Cell ID | Real-time navigation (visualization on map), transparent location-based information provision in proximity of landmarks, visualization of co-players positions | Other players location and activity | Time, moon phase, real world elements |
| **EM II** | ✓ | GPS | Real-time navigation (visualization on map), transparent location-based information provision, visualization of co-players positions | Other players location and activity | Orientation, wind direction |
| **CTF** | ✓ | GPS | Real-time navigation (visualization on map), visualization of co-players positions | Other players location and activity | Human touch (pressure) |
| **Age Invaders** | ✓ | RFID | Visualization of co-players positions | Other players location and activity | – |
| **Time Warp** | ✓ | GPS, Computer Vision (CV) | Real-time navigation (visualization on map), transparent location-based information provision | Other players location and activity | Orientation |
| **Urban Defender** | ✓ | GPS | Checking the building status that the ball hits on | Other players location and activity | Acceleration |
| **Invizimals** | - | Players detecting markers | Display digital items | Other players activity | Surface color, orientation, acceleration, sound level, marker position |
| **P.K. AoE** | ✓ | GPS, WiFi cell ID | Real-time navigation (visualization on map), transparent location-based information, visualization of co-players positions | Other players location and activity | Cities founded and neighborhoods controlled by other players |
| **Hot Potato** | - | Proximity metric (IEEE 802.15.4 radio range) | Check co-player proximity to enable passing of 'hot potato' | Proximity to other players | Gesturing (acceleration) |
| **Treasure** | - | U3D | Uses the positions of smart objects rather than user location | Other players activity | Smart object location and orientation |
| **Ingress** | ✓ | GPS, WiFi cell ID | Players capture and link portals and collect energy matter | Other players location and activity | POIs nearby the player location |
| **Blowtooth** | ✓ | GPS | Check whether the user is within an airport or not | Other players activity | Nearby Bluetooth devices |
| **Zombies Run!** | ✓ | GPS | The game uses the player location to visualize the mission route | - | Speed, acceleration |
| **YWYM** | ✓ | GPS | Transparent location-based information provision | Other players activity | – |
| **FreshUP** | ✓ | GPS, WiFi cell ID | Real-time navigation (visualization on map), visualization of co-players positions | Other players activity | – |
| **Barbarossa** | ✓ | GPS, WiFI cell ID | Players must reach certain outdoors locations to complete certain tasks | Other players last known location, and activity, profile data acquired from social networks | Time, temperature, acceleration, environmental sound level, orientation, proximity to 'places' (landmarks, shops, etc), weather. |

**Table 5**
Player equipment and game space visualization features.

| | Player equipment | Game space visualization | Visual representation (maps/ graphics) |
|---|---|---|---|
| **CYSMN?** | Walkie-Talkie, PDA, PC, GPS Receiver | VR | 2D/3D |
| **URAAY** | Handheld computer, PC, Web-Camera | VR | 2D/3D |
| **Mogi** | Mobile phone, PC | VR | 2D/3D |
| **EM II** | LCD touch screen, PC, Mobile phone, PDA AR device, Bluetooth aerosol can device | AR, VR | 2D/3D |
| **CTF** | PC, smartphone, Bluetooth-based GPS receiver, Linux-based Bluetooth embedded flag | VR | 2D/3D |
| **Age Invaders** | Bluetooth toy gun, LED blocks floor, PC, shoes with embedded RFID tags | VR | 2D/3D |
| **Time Warp** | UMPC, headset, Bum bag with audio transmitter | AR, VR | 2D/3D |
| **Urban Defender** | Customized Ball | Vibration | - |
| **Invizimals** | Sony PSP | AR, VR | 2D/3D |
| **P.K. AoE** | Smartphone | VR | 2D |
| **Hot Potato** | Sensor node (SunSPOT) | - | - |
| **Treasure** | Smart objects embedded with MOTE sensors, rotatable AR projection device (Prot) | AR, VR | 2D/3D |
| **Ingress** | Smartphone | AR, VR | 2D/3D |
| **Blowtooth** | Smartphone | VR | 2D |
| **Zombies Run!** | Smartphone | VR | 2D |
| **YWYM** | Smartphone, PC | VR | 2D |
| **FreshUP** | Smartphone, PC | VR | 2D |
| **Barbarossa** | Smartphone, Sensor node (SunSPOT) | AR, VR, vibration | 2D |

**Table 6**
Information model and architectural features.

| | Game session management | Game engine model/ Organization | Content creation | Portability |
|---|---|---|---|---|
| **CYSMN?** | Stores the time elapsed from game entering time; also runners' photos and statistics | Centralized | Predefined/Adapted to location | Played at specific settings |
| **URAAY** | Stores the declared player position | Centralized | Predefined/Adapted to location | Played at specific settings |
| **Mogi** | Stores players' score and collected items, avatar name, blood type, zodiac sign, registration date, ranking, introduction line | Centralized | Predefined/Adapted to location | Played at specific settings |
| **EM II** | Stores viruses killed and total score | Centralized | Predefined/Adapted to location | Played at specific settings |
| **CTF** | – | Hybrid adhoc/ centralized | Predefined/Adapted to location | Played at specific settings |
| **Age Invaders** | – | Hybrid adhoc/ centralized | Predefined/Adapted to location | Played at specific settings |
| **Time Warp** | Stores players' score and their trajectory | Adhoc | Predefined/Adapted to location | Played at specific settings |
| **Urban Defender** | Stores into beagle board PC info about conquered buildings | Centralized | Predefined/Adapted to location | Played at specific settings |
| **Invizimals** | Stores players' score, collected Invizimals and Invizimals state | Hybrid adhoc/ centralized | Predefined/Adapted to location (use of nearby object colors and markers to generate game content) | Played anytime, anywhere |
| **P.K. AoE** | Stores information about the last player's participation, duration of play, avatar's gender, current lifetime stats in gold, flags, oil wells, and levels earned; the user can resume the game at any time. | Centralized | Predefined/Adapted to location/User generated (players can build buildings) | Played anytime, anywhere |
| **Hot Potato** | Stores a countdown counter value, devices that hold hot potatoes, number and IDs of active players | Hybrid adhoc/ centralized | Predefined | Played at specific settings |
| **Treasure** | Stores scenarios designed by players | Hybrid adhoc/ centralized | Predefined/Adapted to location/User generated (the players can adjust the role of a given set of smart objects) | Played at specific settings |
| **Ingress** | Stores players collected exotic matter and captured and linked portals | Centralized | Predefined/Adapted to location/User generated (players contribute to new portals creation subject to developers approval). | Played anytime, anywhere |
| **Blowtooth** | Stores the drugs planets/obtained by all the players playing Blowtooth | Centralized | Adapted to location/User generated (using available Bluetooth devices around the player in Airports) | Played at specific settings |
| **Zombies Run!** | Stores the gathered resources, the players base state and the mission statistics (speed, distance etc) | Hybrid adhoc/ centralized | Adapted to location | Played anytime, anywhere |
| **YWYM** | Stores missions created by the players and the players response to missions | Centralized | Predefined/Adapted to location/User generated (creation of missions for other players to complete) | Played at specific settings |
| **FreshUP** | Stores completed and obtained tasks of participating teams | Centralized | Predefined/Adapted to location | Played at specific settings |
| **Barbarossa** | Stores missions created and completed by the players, the players statistics, previous players scores | Centralized | Predefined/Adapted to location/User generated (players create missions for other players) | Played at specific settings/Played anytime, anywhere |

### 4.2. Localization and context awareness

Players' location tracking represents a major challenge in pervasive game design, as content and core game action typically depend on the absolute or relative players' positions (e.g., for real-time navigation, location-based information provisioning, co-players' positions' visualization, etc.). In fact, the location of players is captured by almost all surveyed game projects. GPS technology has been a reasonable choice for outdoor user positioning in most projects. In practice though, many users reported frustration due to GPS serious coverage and accuracy problems, especially in urban landscapes wherein the multipath effect accentuates GPS uncertainty. Over the course of pervasive games' evolution (see Fig. 6), the coverage problems of GPS motivated developers to supplement GPS with WiFi Cell ID to track users' locations. Besides, most recent game scenarios are functional even with the low-accuracy location fixes achieved by WiFi Cell ID localization. Moreover, even the most affordable phone nowadays supports both of the above localization techniques, implying that game developers can safely utilize them in their prototypes. Even so, localization uncertainty remains an issue in many game scenarios.

Interestingly, almost all the examined games utilize some sort of social context, most prominently co-players' location and activity. This is typically needed to enable social interaction and collaboration among players or to prevent encounters with enemies. Some recent prototypes also make use of players' social network profile data (Kasapakis et al., 2013), accessed via available web services.

The heterogeneity of pervasive games is also mirrored in the variety of additional contextual parameters utilized. Occasionally, the developers incorporate rather unusual context parameters (e.g., in *EM II* viruses spread according to the wind direction) to support the individual needs of gaming styles and scenarios. As for

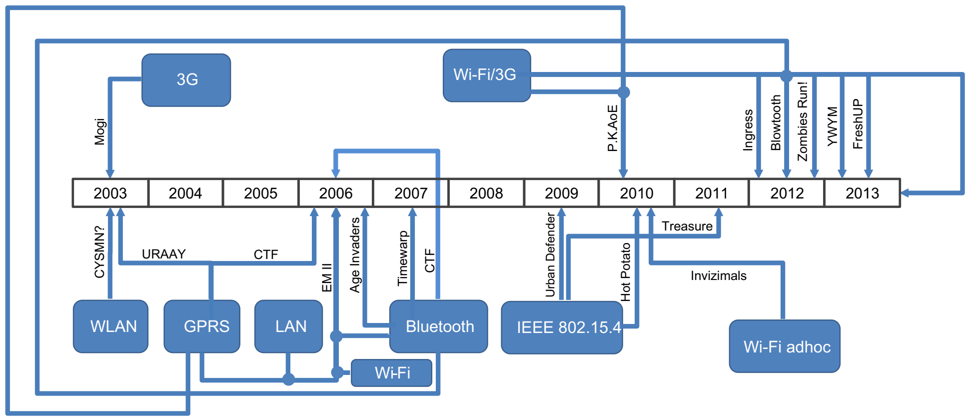


**Fig. 5.** Timeline of communication technologies utilization in pervasive games.

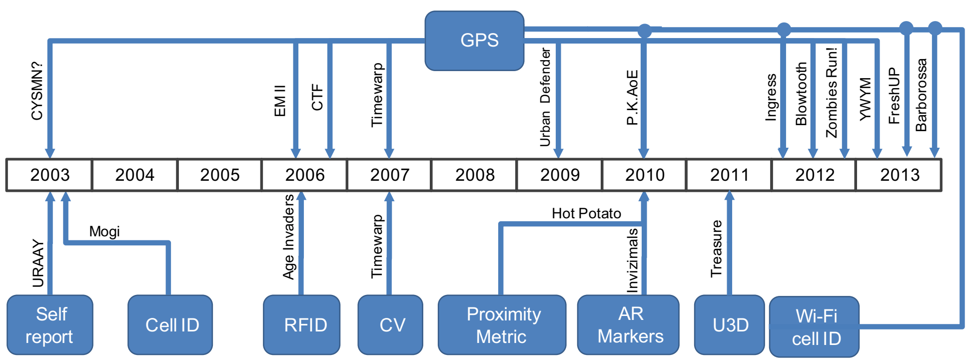


**Fig. 6.** Timeline of localization technologies utilization in pervasive games.

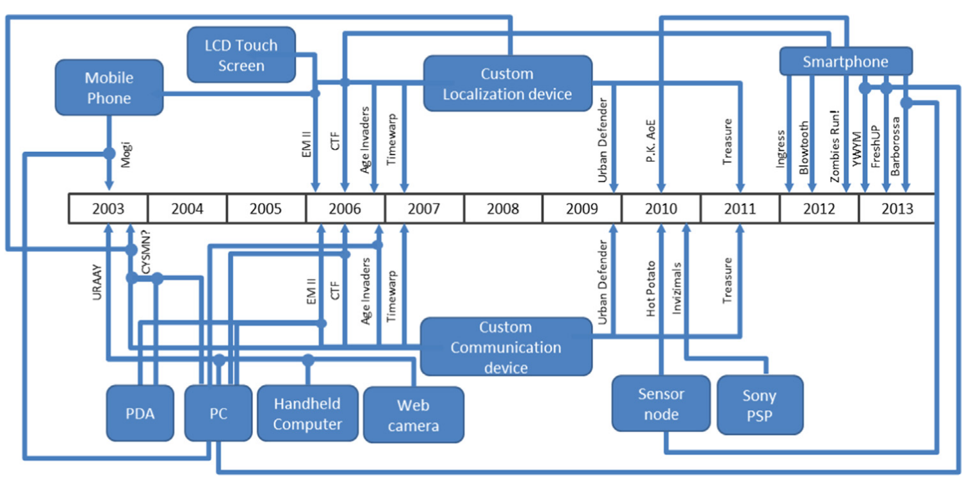


**Fig. 7.** Timeline of player equipment evolution in pervasive games.

sensory infrastructure, the transition towards 2G games has been marked by the decreased use of external sensor devices in favor of smartphones' built-in sensors. Most recent projects additionally obtain context data from web services, facilitated by the mobile platforms' support on web content manipulation (Pocatilu, 2010). For instance, in *Barbarossa* user applications obtain environmental context (temperature and nearby points of interest) from open web services.

## 4.3. *Players equipment and game space visualization*

Players of 1G pervasive games typically used more than one device as player equipment. That was inevitable as, at the time, localization, networking and visualization capabilities were provided by different instruments. In *EM II*, for example, the players used either a feature phone or a mobile AR-system to capture viruses as well as a GPS-enabled PDA to feed their position into the game engine.

The transition towards 2G games has been primarily characterized by the use of smartphones as sole player equipment (see Fig. 7). Notably, the principal role of smartphones among utilized game equipment is also a distinctive feature of commercial games. This is mainly due to the focal objective of the commercial projects towards attracting wider audiences; this, in turn, compels developers to pursue openness (anytime/anywhere playability) and compatibility with widely used devices. Namely, to implement games that do not require specialized equipment; that utilize commonly supported networking, localization, and built-in sensor capabilities; and exploit application markets to ensure wide dissemination and distribution.

Indisputably, smartphones are expected to maintain their dominant position as principal game equipment for the foreseeable future, especially as they continue to incorporate additional instruments (proximity and light sensors, NFC readers, etc.). However, their exclusiveness may be challenged by the use of wearables (e.g., smart glasses), mainly in game scenarios that will benefit from hands-free interaction.

Regarding the utilized means of game space visualization, virtual reality (VR) has been a popular mediation option, with augmented reality (AR) lately claiming an increased share. The majority of the games visualize content through 2D and 3D graphics/maps.

### 4.4. Information model and architecture

Most games exclusively maintain basic, explicitly stated profile information, like name and gender, while some provide basic personalized services based on user profile (e.g., adjustment of the game's pace based on user age or avatar selection based on user gender). Several games maintain game history records, typically fed as implicit input to the game engine; for instance, player statistics or credits earned, player trajectories, and game state information. In general, game session management is regarded as essential for pervasive games as it allows attaching video games-like features and conveniences such as player scores/rankings, allowance to pause and resume, etc.

Several games are based on a centralized model, wherein a single server facility maintains game session state information, with players' devices communicating through it in a synchronous or asynchronous manner. Others enable direct adhoc communication between players or adopt a hybrid adhoc/centralized organization model. Nonetheless, the choice of the game engine organization model is largely dictated by the game scenario to be supported, although the current technological status favours always-on connectivity, hence, centralized models.

Portability is a must-have feature for any commercial pervasive game so that it is functional anywhere, offering a universally comparable look and feel. On the other hand, the majority of examined research prototypes are bound to predefined areas. The rationale is that they are mainly implemented for research purposes, aiming at measuring the effect of diverse (hence, difficult to reproduce/relocate) game equipment and supportive infrastructure. Moreover, developers of research prototypes commonly opt to perform evaluation trials in controlled environments. Portability is also linked with game content generation, in the sense that pre-edited content (typically connected to a specific game setting) cannot be easily ported to other settings. Therefore, allowing users to undertake the role of content creators (even if such content needs to be approved by game moderators) improves the portability potential of games. Furthermore, evidence exists that user-generated content related to specific areas may be of high quality (Kasapakis et al., 2013), as it benefits from the knowledge of the local contributors, while also consolidating inclusivity, sociability, and engagement (Lehner et al., 2014).

### 4.5. Orchestration and assigned roles

Orchestration involves all the actions and techniques used by developers to manage the live game behind the scenes and ensure a game flow with minimum interruptions and errors. Orchestration may be distinguished in (a) pre-game orchestration, namely actions taken before the game session starts, such as the registration of the game area into real world coordinates or the initialization and positioning of game items (e.g., placing QR-Codes or markers at certain spots); and (b) on-game orchestration, namely actions taken during the game session, in real-time, like adding, removing, or relocating game items, modifying their state and adding or removing players or player equipment) (Benford et al., 2005).

Pre-game and on-game orchestration actions are commonly found in both 1G and 2G pervasive games, yet these two generations differ with respect to the amount of human resources engaged in on-game orchestration. In 1G games, several on-game orchestration actions are carried out by actors or experts aiming at assisting the players and briefing the game scenario. In 2G games, on-game orchestration mostly involves centralized facilities, either automated (e.g., in *Barbarossa*, the game pace is adjusted based on the player's local area temperature, taken from a weather web service) or semi-automated (e.g. in *Ingress* the creation of new portals is requested by players via the game application, with those requests being reviewed by the orchestrators team). When the games require a human presence, this is often undertaken by bystanders or developers (rather than experts or actors) thereby simplifying the orchestration process.

As shown in Tables 7–10, the registration of the game area into real world coordinates is a 'compulsory' pre-orchestration action when the game includes certain real world spots that the player should interact with during the game session. Also, most surveyed games catered for several inter-dependent player roles; in general, this is regarded as an advisable practice since social interaction among players is one of the mostly appreciated features of pervasive games (Lehner et al., 2014), although it hinders the setting up of the games, hence, their portability.

### 4.6. Evaluation

Evaluation trials are crucial in reporting technical flaws and assessing the usability, playability, and immersion aspects of pervasive game prototypes. Novel evaluation methods and criteria are lately sought after, aiming at organizing evaluation trials tailored to the unique characteristics of pervasive games (Jegers, 2009).

Among the surveyed games, the commercials products and *Urban Defender* have not been formally evaluated. The remaining games have been evaluated through at least two means of evaluation. Questionnaires (in some cases both pre-game and post-game questionnaires are distributed to participants) along with interviews and discussions with participant focus groups have been the most common evaluation methods. Several trials further included some sort of live action monitoring, such as logged data (i.e., recording of user interaction/mobility patterns), live players' observations (by humans), camera-based surveillance, and video analysis. The number of participants varied from 10 to 447. Most often, recruited participants have been students, personal contacts of the developers, university (and alike organizations) employees, or respondents to recruitment advertisements. An interesting participant recruitment method has been applied in *Barbarossa* (Kasapakis et al., 2015): user evaluators have been selected based on their ranking in an invitation game phase in which the most committed participants were invited to act as evaluators in the main phase of the game. This approach has had a positive impact on the players' experience and helped developers to secure high-quality feedback from the field trials.

The overall experience with game trials suggests that evaluation criteria should be game-dependent so as to obtain feedback relevant to the examined research questions. Moreover, the traditional questionnaire/survey-based approaches appear to produce more revealing and reliable results when combined with observation of subjects' in-game behavioral patterns[10] which allows

[10] Questionnaires and surveys are subject to validity threats because participants may forget or leave out valuable information. Further, they may fail to generate useful information as they are prone to opinion bias. Lastly, participants often answer dishonestly due to fearing judgment or being unwilling to reveal all

**Table 7**
Orchestration features.

| | Pre-game orchestration | Registration of the game area into real world coordinates | On-game orchestration | User roles |
|---|---|---|---|---|
| **CYSMN?** | Virtual representation of real world and users through maps/ 3D models; online players chosen from a website and introduced into the game. | ✓ | Technical team checking GPS and WLAN status for each runner and supporting them using walkie-talkie. | Outdoor player/ Online player |
| **URAAY** | Virtual representation of real world using 3D graphics; players taking a brief introduction about the game by an actor; players receive a handheld computer in the beginning of the game session. | ✓ | Player position and technical status tracking; improvised text messages sent to outdoors players using predefined voice clips; three actors assisting players onsite; public text chat forum available to online players. | Outdoor player/ Online player |
| **Mogi** | Administrators place virtual objects on the game world | ✓ | – | Outdoor players / Online players |
| **EM II** | Technical lead: Ensures that all equipment is prepared for dramaturgy lead on time and starts all applications when needed; team formation | ✓ | Orchestration team uses a big matrix illustrating all players and devices; an actor provides technical advice, orchestrates the game flow and ensures that players stay immersed in the storyline. | Outdoor player/ Station player |
| **CTF** | Briefly introduce the game and explain the use of equipment to participants | ✓ | – | Outdoors players (Knights)/ Station players |
| **Age Invaders** | The online user enters her name/ age to calculate age difference and predict the reaction time of the user; online player watches virtual representations of real game world. Developers explained the equipment functionality to the players. | – | – | Led block system player/ Online player |
| **Time Warp** | Virtual representation of real world and users through maps/ 3D models; | ✓ | – | Outdoor players (Communicator, Navigator) |
| **Urban Defender** | Developers pre-defined the buildings the players could capture | ✓ | – | Outdoor player |
| **Invizimals** | Players are required to place a marker to see the Invizimals | – | – | Invizimal collector/trainer |
| **P.K. AoE** | - | ✓ | – | Outdoor player |
| **Hot Potato** | - | – | A centralized facility checks the rules of the games. | Indoors/ Outdoors |
| **Treasure** | A game author has to create a scenario for others players to follow | ✓ | - | Indoors player/ Online player |
| **Ingress** | The developers use POIs of the physical world in order to create portals | ✓ | Players can submit requests for new portals creation and developers accept or decline those requests. | Outdoor player |
| **Blowtooth** | – | – | – | Indoors player |
| **Zombies Run!** | – | ✓ | – | Outdoor/Indoors player |
| **YWYM** | Players need to create a predefined route and feed it into the system. Players were trained to using mobile devices before the evaluation. | ✓ | | Outdoor player/ Online player |
| **FreshUP** | Players trained to use the mobile game equipment. The developers create a number of tasks for the players to complete. | ✓ | – | Outdoor player/ Online player |
| **Barbarossa** | Printed QR-codes placed in the physical location of clues; a real chest hidden in a secret place, obtainment of players location temperature and nearby points of interest using web-services | ✓ | Developers or bystanders enrolled as online players | Outdoor player/ Online player |

developers to cross-check and validate evaluation results. Developers are advised to employ 'discreet' observation rather than 'invasive' methods, such as live observation by humans, which have received criticism for generating more reserved players' behavior (Fischer et al., 2006).

## 5. Determinants of user acceptance

The pervasive games analysed in this survey have been thoroughly evaluated by their developers aiming at understanding user perception with respect to crucial design aspects (communication, localization, context awareness, player equipment, visualization of player location, and usage of AR). According to the evaluation results, some design methods have been well accepted by the users while others have proved ineffective and received negative user evaluations.

Games based on WiFi communication and GPS positioning often suffered disconnections, generating poor communication and GPS 'shadows' (i.e., areas where WiFi connection and GPS location fix have been impossible); this effect has been criticized for interrupting the game flow and players' immersion, hence compromising their quality of experience (Benford et al., 2004, 2006; Cheok et al., 2006; Fischer et al., 2006; Herbst et al., 2008). In response to these practical problems, several game design methods, found to be highly effective in previously evaluated prototypes, have been proposed to deal with the uncertainty raised by the use of technology in pervasive games (Benford

(*footnote continued*)
their thoughts and opinions, especially when an experimenter is present (Wehbe and Nacke, 2014).

**Table 8**
User evaluation aspects.

| | Evaluation methods | Number/background of participants | Invitation methods | Evaluation criteria | Extracted design guidelines | Major evaluation findings |
|---|---|---|---|---|---|---|
| **CYSMN?** | Prototype testing, observations, log data, interviews with participants | Unknown number (street players were professional runners) | – | Performance of utilized localization methods and wireless networking | Remove, hide, manage, reveal or exploit (as appropriate) the uncertainty emerging while using technologies. | The audio channel (real-time walkie-talkie stream from the runners) was an essential part of the experience; the social play was important; GPS and WLAN problems were reported; technologies strongly influence player experience. |
| **URAAY** | Prototype testing, observation, interviews, emails, log data | 227 street players - 447 online players | Advertising | Overall game experience | Refer to real game settings and draw on the events associated with them; implicate passersby; inject live action using actors; exploit ambiguity and boundariescrossing; encourage social game play; be realistic about positioning and networking technologies. | |
| **Mogi** | Has not been evaluated | | | | | |
| **EM II** | Prototype testing, observation, log data, pre-/post-game questionnaires, focus groups, camera-based surveillance | 29 school students/ journalists/FIT employees | E-mails | Modes of participation and social play, game story & game play, joy of use and experience design, technological issues, ethical issues, business aspects | | Players enjoyed playing with both friends and strangers; the involvement of a real story satisfied the players and met their expectations.<br>Technical errors interrupted the game flow; inaction led to stepping out of the game; AR content not visible under sunlight; problems reported on GPS usage and location fix latency; surveillance and crowded areas caused frustration to some players; many players found potential for commercial exploitation for that type of games. |
| **CTF** | Prototype testing, pre-/post-game questions to the players | 32 (NUS students and staff) | - | Robustness, intuitiveness, interactivity, excitement | | Several technical problems relevant with the use of GPS and GPRS; most players proposed the use of sound and vibration as output methods; players felt that communication was an important game aspect; physical interaction, increased interest. |
| **Age Invaders** | Prototype testing, questionnaire, interviews (only with the ten players invited to play for second time) | 10 (5 university employees & 5 high school students) | - | Concentration, challenge, player skills, control, clear goals, feedback, immersion, social interaction. | | Satisfactory overall game experience; both the elderly and young players were excited to replay the game. |
| **Time Warp** | Prototype testing, questionnaires, video analysis, interviews | 24 students/city tour guides | - | Attention, allocation, presence (spatial situation model, possible actions, temporal presence, higher cognitive involvement, suspension of disbelief, domain specific interest), social presence (of real and virtual people), usability; sense of place. | Design guidelines for AR games:<br>**Presence**: include a sufficient amount of physical actions for players, assign them critical time tasks and confront them with moral questions to increase their involvement into the game; design virtual characters with rich personality; high quality audio/dialogs can make up for medium quality graphics.<br>**Sense of place**: exploit the features of the real game space and connect it with the narrative structure of the game; include sufficient amount of virtual content.<br>**Collaboration**: if necessary, players should to be able to share devices. | The equipment caused frustration; AR content not visible under sunlight; GPS caused tracking unavailability and inaccuracy problems; players claimed to pay more attention to technology rather than the game and felt more present in the real than the game world; players did not realize difference in time periods and felt not present with other players. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | **Real world implications**: check the physical game space for its suitability and temporal availability; overly crowded areas and vehicle roads should be avoided to prevent accidents. **Technical and usability**: when utilizing GPS for localization, consider using virtual objects that can act realistically even while floating due to inaccurate positioning (like UFOs used in TimeWarp); hide occlusion among real and virtual objects; inform players about GPS signal quality or incorporate GPS shadows into the game play. | |
| **Urban Defender** | Has not been evaluated | | | | | |
| **Invizimals** | Has not been evaluated | | | | | |
| **P.K. AoE** | Google Play average rating: 4.1/5 – Total ratings: 22,355 | | | | | |
| **Hot Potato** | Prototype testing, questionnaires, log data | 23 students (6 without engineering background) | - | Input mechanisms for player interaction, coordination of player interactions, reliability and multi-games support, support for storyline-based and community-based extensions, delay-tolerant service. | | Most players reported high level fun factor for the game; most players were positive about physical interaction; neutral player response with regards to the current gesture recognition implementation; players would welcome addition of screen and vibration into the game. |
| **Treasure** | Prototype testing /focus groups | 15 Keio University students (13 non-CS students). | E-mails | Attractiveness, prospects, immersion, simplicity, variability, willingness to design. | | There were failure situations caused by technical problems; most players willing to play such games again; players able to accomplish game tasks with little or no guidance; ease in authoring the game by using the authoring kit; all participants found the smart object-based game play highly innovative; most players considered that there is room for commercial exploitation. |
| **Ingress** | Google Play average rating: 4.4/5 – Total ratings: 64,979 | | | | | |
| **Blowtooth** | Prototype testing, questionnaires | 6 (personal contacts of developers) | Personal contacts of developers | Competence, frustration, security awareness, anxiety awareness of fellow passengers. | Consider all possible game spaces, even those looking unsuitable at first; take into account the context's nature and incorporate it as part of a game structure to provide enjoyable and thought-provoking experiences for players. | Matching pervasive game content, narrative and tasks to the unique features of a challenging environment may generate enjoyable experience for players. |
| **Zombies Run!** | Google Play average rating: 4.3/5 – Total ratings: 5505 | | | | | |
| **YWYM** | Prototype testing, log data, interview, questionnaires | 23 (post-graduates from the campus of Zhejiang University) | | YWYM trial, defining routes, searching and making responses to missions, designing missions. | | Trajectory pattern mining and prediction techniques could replace route predefining and self-reporting methods to relieve the interaction overhead of users; user-mediated methods could be employed to improve the performance of route prediction, for example, providing a map-based tool for users to input the destinations of their movements. |
| **FreshUP** | Prototype testing by students, log data, focus groups | 124 (University of Potsdam freshmen) | - | Orientation, familiarization, contacts to fellow students, gaming experience. | | The game has been found helpful to University freshmen as a tool to orientate, acquire study competence and socialize with their fellow students. |
| **Barbarossa** | | 30 (participants recruited via an | Invitational game freely | Easiness, usability, game play experience. | Consider developing a, orchestration-free preliminary invitational game phase | The execution of cost-effective, open invitation game phases may serve as a |

**Table 8** (*continued*)

| Evaluation methods | Number/background of participants | Invitation methods | Evaluation criteria | Extracted design guidelines | Major evaluation findings |
|---|---|---|---|---|---|
| Prototype testing, log data, questionnaires, interviews | invitational game phase) | available from Google Play | | incorporating compatible game play buildings blocks (i.e. technologies and scenario) with those used in the main game phase. Execute the invitational game phase prior to evaluating of the main one to recruit highly qualified participants, thereby maximizing the usefulness and investment payback of field trials. | means for recruiting highly qualified subjects for user trials on pervasive game research prototypes, thereby increasing the reliability and quality of evaluation results. |

et al., 2004, 2006; Fischer et al., 2006; Herbst et al., 2008). These methods include:

- Careful deployment of the game into suitable areas (e.g., in areas that do not include buildings) to increase the accuracy of GPS and use of additional WiFi access points to prevent communication holes.
- Utilization of sensors (e.g., accelerometer) to predict/calculate the location of players so as to deal with GPS disconnections or low accuracy location fixes. Audio streams can also be used to guide the players through GPS or communication shadow areas.
- Integration of location self-reporting (instead of GPS-based positioning) and prototyping of standalone game applications to allow the game to remain functional while the players' equipment is disconnected.
- Notification of players about disconnection incidents so that they can handle them to continue playing the game or incorporation of known GPS and communication shadow areas into the game play (e.g., a player can 'hide' from other players when in GPS shadows or appear 'inaccessible' while disconnected from WiFi networks).

As for context awareness aspects, the integration of rich context (e.g. wind direction, acceleration, sound level, etc.) into the game play in addition to players' location, has been perceived positively by players (Benford et al., 2006; Chatzigiannakis et al., 2010; Fischer et al., 2006; Herbst et al., 2008). The exploitation of physical game space characteristics (e.g., airports and labs), so as to fit the game's scenario and narrative, considerably enhanced the players' overall quality of experience (Benford et al., 2004; Herbst et al., 2008; Kirman et al., 2012). Finally, many players argued that social context integration, collaboration support, and team formation contributed in improving their quality of experience (Benford et al., 2006; Cheok et al., 2006; Fischer et al., 2006).

The suitability of smartphones as main game instrument (due to integrating a variety of sensors along with a GPS receiver and supporting broadband wireless connectivity) has been validated in several user acceptance studies (Chen et al., 2013; Fischer et al., 2006; Kirman et al., 2012; Zender et al., 2014). However, the commitment to hold the device up for prolonged time sessions to capture AR content has been reported as an unwanted feature by players. A successful design workaround addressing this issue has been the scheduling of breaks within game sessions or the use of audio (rather than visual) augmentation to support the evolution of the narrative. Moreover head-mounted displays (HMDs) proved useful for AR projection, although the use of heavy HMDs occasionally caused fatigue and frustration (Wetzel et al., 2009). Another cause of frustration has been the assumption of high precision GPS location fixes, which led to misplaced floating AR objects (Herbst et al., 2008).

As regards the visualization of players' location, users mostly preferred the use of auto-updated maps with overlaid markers denoting individual players (Chen et al., 2013; Cheok et al., 2006; Zender et al., 2014). The use of an avatar to represent the player within a 3D environment associated with a real location (Benford et al., 2004; Benford et al., 2006; Cheok and Khoo, 2006) has also been appreciated. On the other hand, the use of explicit map updates (e.g., press a button to update the map) was found disturbing by most evaluators (Fischer et al., 2006).

Live orchestration (e.g., technical teams intruding in game action) has proved to cause frustration and awkwardness to players (Benford et al., 2006; Fischer et al., 2006). Reducing the reliance of game play to live orchestration actions, undertaking transparent background orchestration (Fischer et al., 2006), and offering live actor support (Benford et al., 2004) have been reported as the most successful orchestration design methods which enhanced the players' quality of experience. Lastly, relying on surveillance to support orchestration or to collect evaluation data has caused inconvenience and has been perceived as activity violationing privacy by players (Fischer et al., 2006). Table 1, below, summarizes the design aspects found to be successful or a failure, according to user acceptance studies.

## 6. Trends, developer guidelines and research challenges in pervasive gaming

The proliferation of mobile platforms, the fast evolution pace of wireless networking, and the increasing availability of sensing devices have shaped a favorable technology landscape for the adoption of pervasive gaming. The advent of pervasive mobile games (at the beginning, practically mobile versions of fully-fledged desktop video games) was the first major step towards the vision of pervasive gaming. Soon after, several games specifically designed for mobile platforms appeared (Fischer et al., 2006). Such games take advantage of the mobile features like network connectivity, portability, and inference of game context, enabled by the emergence and commercial availability of pervasive computing technologies. Coupled with AR technology, which allows the mix of physical and virtual playscape and the participation of online and 'street' players, pervasive games succeed in creating innovative and exciting game experiences. Below, we discuss the current technological trends and their implications in pervasive gaming; we also offer brief guidelines for designers and developers while suggesting promising research directions.

### *6.1. Communication issues*

Wireless communication represents a fundamental requirement for pervasive game design. Among others, latency, transfer speed, coverage, cost, and ease of deployment are the most important factors for choosing a networking technology. Of course, those need to be examined in connection with the particular game scenario and user requirements. For instance, WLANs offer low user cost, low latency, and high transfer speeds, which are necessary in fast action-paced games with rich player-to-player interaction, as it ensures smooth game play. On the other hand, WLANs cannot satisfy requirements for wide area coverage. Currently, 3G communication appears to be the obvious solution for outdoor games, although it may still result in considerable cost charges for mobile players. In the near future, the use of Mobile WiMAX and LTE standards offering superfast data rates in highly dynamic environments and promising a drop in communication charges, are expected to prevail worldwide.

When direct player-to-player communication is required, Bluetooth has been so far the most practical choice for adhoc communication, mainly due to its huge installation basis. However, it suffers from several technical restrictions (e.g. non-negligible delay for neighbour device discovery, limited communication range, etc. Vergetis et al., 2005) which make it inappropriate for highly dynamic and/or large-scale gaming environments. Emerging short-range solutions such as ZigBee overcome many of the Bluetooth restrictions and could serve as an effective substitute, especially as these standards become adopted by smartphones.[11] "WiFi direct", which enables WiFi peer-to-peer connectivity among mobile devices is also highly likely to influence future game development.[12]

### *6.2. Localization techniques*

GPS is the primary choice as a localization technique for outdoor game developers, although in some urban environments it is known to experience connectivity, latency, and accuracy problems. WiFi/3G cell ID techniques may also be considered in cases where high localization accuracy is not important, while Bluetooth (or alternative short/medium-range communication technologies) may act as a proximity measurement tool, e.g., in chasing games. In games utilizing AR content, developers may use additional localization technologies in conjunction with GPS (like DRM III or CV) to ensure improved precision so as to allow the projection of AR content at the right display position, and eliminate game flow interruptions due to GPS unavailability.

For indoor games, developers may choose among the many indoor localization systems (Varshavsky and Patel, 2010), some already available as commercial systems in the market. Although such systems may offer accurate position tracking, they typically require dedicated installations; hence, respective investments take a long time to return, while the games are difficult to relocate. RFID and NFC technologies can be used as supplementary means for in/outdoor location tracking. Although NFC-compatible smartphones have become commercially available, it is still unsafe to rely on such equipment as their market penetration remains relatively low. At the time, QR codes represent the safest option, as QR-code scanning leverages applications shipped on most smartphones and may indirectly provide positioning information[13] without the need for specialized equipment.

Current developments in localization technologies still fail to deal with positioning uncertainty, especially outdoors. Several approaches could be investigated for mitigating the effect of uncertainty (Flintham et al., 2003; Kirman et al., 2012): removing it (e.g. by carefully choosing game locations and times); revealing it (so that players are able to act accordingly); exploiting it, by deliberately incorporating uncertainty into the structure of a game (for example, enabling players to "hide in the shadows" by moving out of sensor fields' coverage); or by designing "intelligible" systems (i.e., applications generating explanations of their behavior, so as not to frustrate players or compromise their trust in the game engine.

### *6.3. Context awareness*

Most game scenarios should benefit by incorporating the location context of players. Additional context parameters (such as acceleration, orientation, proximity, gesturing, human presence, time, light intensity, sound level, wind direction, weather conditions, and moon phase) comprise alternative modes of implicit input in game projects, often producing immersive game experiences. Some of the abovementioned contextual parameters may be captured by dedicated wireless sensor network installations (Chatzigiannakis et al., 2011); the emergence of robust, programmable, low-cost 802.15.4-compliant sensor node platforms will likely influence the design decisions of pervasive game developers as those could reliably feed a multitude of environmental, social, and activity context data. Likewise, smartphones that commonly integrate GPS receivers, cameras, sensors, compasses and NFC readers are expected to play a significant role in providing

[11] Research evidence already exists for the feasibility of integrating ZigBee into mobile devices (Olteanu et al., 2013); and the first ZigBee-powered smartphone and tablet have already appeared (TazTag TPH-One and Samsung S5PV210 Cortex A8, respectively).

[12] http://developer.android.com/guide/topics/connectivity/wifip2p.html.

[13] For instance, a QR code placed at location with geo-coordinates (qr_x, qr_y) could be coded to redirect, when scanned, to a URL like http://www.mygame.com/index.php?x=qr_x&y=qr_y&time=currentRTime. That way, the geolocation of the player would be revealed along with the scanning timestamp through the HTTP GET request.

**Table 9**
Successful and failed game design aspects.

| Pervasive games aspects | Successful design techniques | Failed design techniques |
|---|---|---|
| **Communication** | Use of 3G; incorporation of communication shadows into the game scenario; careful deployment to avoid or handle communication shadows; notification of players about disconnection incidents. | Reliance exclusively on WiFi. |
| **Localization** | GPS, sensor-aided and self-reporting player positioning; explicit player repositioning and audio guidance of players; careful deployment to avoid or handle GPS shadows; incorporation of GPS shadows into the game scenario; notification of players about lack of GPS coverage. | Designing the game to function with high accuracy GPS fixes. |
| **Context awareness** | Integration of environmental context data into the game play; integration of social context; support for team formation and collaboration scenarios. | |
| **Player equipment** | Use of smartphones. | Use of heavy HMDs. |
| **Player position visualization** | Auto-updated maps visualizing player location via a marker; representation of the player in a virtual world visualizing a real location. | Explicit map updates for player position visualization. |
| **Use of AR** | Taking into account GPS inaccuracies to avoid floating objects misplacement; use of HMD for AR content projection. | Rely on the GPS high accuracy location fixes; requiring the player to hold the device up for a long time. |
| **Orchestration** | Live action actor orchestration; transparent background orchestration. | Intrusive on game orchestration by technical teams; surveillance of players' activity. |

contextual input in future game developments. Context parameters may also be provided by publicly available third party web services (e.g., mapping services, weather status and forecast, public transportation schedules, social media feeds, etc.) thereby expanding the context capturing capabilities of smartphones.

So far, social context is only exploited for detecting co-players' presence and activity, or feeding a player's profile with demographic data obtained from their social network profile. The massive amounts of information piled in popular social network platforms along with the APIs available to developers to exploit these data create expectations for designing and prototyping games which leverage the social circles of players, their elicited preferences (e.g., through processing 'likes' or activity feeds), or even their temper (e.g., detected by natural language processing of uploaded messages). The potential of socially-aware pervasive games is substantiated by recent evidence that sociability is an important factor of pervasive games as players seem to enjoy the ability to socialize inside the boundaries of the game world (Lehner et al., 2014). Along this line, social media APIs could be used to facilitate player recruitment and team establishment either through exploring the social neighbourhood of other game participants or through mining social graphs to discover individuals with similar game interests (Kourtellis, 2012). Inversely, pervasive games could allow players to publish their in-game progress via online social media channels.[14] Another opportunity stems from a feature commonly encountered in pervasive games: the way they obfuscate the social boundary of play, where the activity of playing is often blurred with the player's ordinary life (Montola and Waern 2006). To this end, pervasive games could be designed to help players translate their in-game networks directly into real world peer groups (this idea has been demonstrated in the social networking game *Snag'em* (Cateté et al.) which supports the establishment of social connections among conference attendees).

### 6.4. Player equipment, position visualization, and use of AR

The variety of equipment carried by players has considerably decreased since 1G pervasive games. This trend is mostly driven by the evolution of mobile devices' hardware, which tends to incorporate numerous sensors able to capture context data that previously required independent devices to acquire. Besides, the combination of integrated sensors with the built-in camera in most smartphones, provides an excellent solution for developing mobile AR apps. The popularity of commercial products like *Ingress* (Google, 2013) and *PK AoE* (PerBlue, 2011) substantiates the claim that mobile devices with sensors capabilities become a driver for developers to achieve wider adoption of pervasive games. Alongside these developments, future research could investigate the use of haptics[15] as player equipment in pervasive games. With haptic technology, the players could potentially feel the vibrating force or resistance when hitting a ball or "shooting" a gun (Faust and Yoo, 2006). The inclusion of textile feedback conveys touch confirmation in the interaction of players with virtual objects, and injects a sense of realism by fully engaging the user's senses (Saddik, 2007). Relevant empirical studies (Strachan and Murray-Smith, 2009) revealed that haptics consistent with actions displayed on-screen increase immersion and improve enjoyment.

Most games use 2D maps for position visualization, while additional visual information may be conveyed through 2D/3D graphics. The use of 3D maps/graphics is expected to prevail, due to the increased rendering capability of devices and support by both the Android and iOS platforms (Gavalas and Economou, 2011); alongside these developments, high-level Javascript APIs have recently appeared which support web-based interactive 3D graphics.[16] Google Maps currently dominate among map representation tools due to specialized API support on all major mobile platforms. However, restrictions on the use or availability of map information (e.g., a 25,000 map loads per day/developer limit currently holds for Google Maps API) is likely to create room for open map platforms based on crowdsourced data (e.g., OpenStreetMap [17]), especially when considering games that make heavy use of map services (Chatzidimitris et al., 2014).

Simulation modalities (including VR and AR) represent a key feature in many games scenarios to expand game experiences. Furthermore, screen sizes of modern handhelds grow, while their graphics rendering capability improves, thereby facilitating high-

[14] Early evidence of this exists with *World of Warcraft* which supports sharing screenshots and displaying recent achievements on Twitter (https://us.battle.net/support/en/article/world-of-warcraft-twitter-integration). Likewise the Google Play Game Services (https://developer.android.com/google/play-services/) offer a cloud platform where players' scores are stored, also offering binding to Google+ accounts and forming leaderboards.

[15] Haptics or haptic technology, is a tactile feedback technology that recreates the sense of touch by applying mechanical stimulation (forces, vibrations, or motions) to the user.

[16] http://threejs.org/.

[17] http://www.openstreetmap.org/.

**Table 10**
Synopsis of technological trends, their implications in pervasive gaming, developer guidelines, research opportunities and challenges.

| | Current status in pervasive gaming | Technology trends | Implications/trends in pervasive gaming | Developer guidelines and research opportunities | Open issues and research challenges in pervasive gaming |
|---|---|---|---|---|---|
| **Communication** | Widespread use of WiFi and 3G for player-to-game engine communication; Bluetooth for player-to-player communication. | Deployment of Mobile WiMAX and LTE infrastructures; WiFi Direct support in recent Android and iOS releases; signs of growing ZigBee support by smartphones/tablets. | Use of Mobile WiMAX and LTE for player-to-game engine communication; WiFi Direct for player-to-player communication. | Implement auto switching from 3G/4G to WiFi whenever a free WLAN is within range; game scenarios should provide for network 'coverage holes'. | Implementation and assessment of game features that benefit from high-speed wireless data communication rates (e.g. multimedia streaming). |
| **Localization** | GPS/WiFi cell id for outdoors localization; marker-based indoors localization. | Appearance of crowdsourcing localization projects; commercialization of indoor localization systems; proliferation of NFC-compliant phones. | GPS/WiFi cell id for outdoors localization remains prevalent; indirect NFC or QR codes-based in/outdoors positioning. | Use supplementary localization in conjunction with GPS for mobile AR games; utilize short/medium wireless networking as proximity metric among players; avoid reliance to any indirect positioning method other than QR codes to secure wider players audience; take localization imprecision into account. | Turning localization uncertainty to a game feature (e.g., enable players to hide in "GPS shadows". |
| **Context awareness** | Location-aware gaming; regular utilization of additional contextual information (speed, orientation, acceleration, etc) | Availability of low-cost 802.15.4-compliant sensory platforms; fabrication of multiple built-in sensors in widespread mobile devices; availability of ultrafast/inexpensive wireless communications; proliferation of publicly available web services offering contextual information; increased penetration of social networking. | Rapid development of context-aware games using smartphones as sole gaming instrument; increased use of 3rd parties' web services. | Incorporate data gathered in social networking platforms in game scenarios; allow players publishing their in-game progress in online social media channels; develop games which may translate in-game networks into real world peer groups; exploit the characteristics of the game space in the game's scenario and narrative. | Accurate elicitation of player preferences and mood from social network activity; accurate and reliable inference of game context. |
| **Player equipment** | Increased use of smartphones as sole game equipment. | Wider adoption of wearable systems like smart watches and glasses. | Wearable devices foreseen to dominate player equipment in the emerging 3rd generation of pervasive games. | Exploit the unique assets and value-added properties of wearable devices in order to offer unobtrusive game play and allow users to digest cues from the physical scape; utilize light-weight HMDs. | Investigation of human factors associated with novel interaction styles and usability of wearables; consideration of haptic technology usage in game equipment. Resource (energy) management. |
| **Use of graphics and position visualization** | Mostly use of 2D graphics; Google maps-based position visualization. | Increased processing power (hence, rendering capability) of mobile devices; availability of high-level APIs supporting web-based interactive 3D graphics; wider adoption of crowdsourced mapping services. | Increased use of 3D graphics; growing share of open mapping services. | Avoid overuse of 3D graphics in order not to entirely shift focus from physical to virtual elements; utilize interactive open map platforms in games making heavy use of mapping services. | Incorporation of 3D mapping features (e.g., 3D buildings, and street views provided by the Google Maps platform) in game interaction. |
| **Augmented reality** | AR games become increasingly common. | Increased screen sizes and improved graphics rendering capability in modern handhelds and game consoles. | Development of high quality 2D and 3D AR content even as a side-feature of pervasive games. | Carefully test AR content rendering on targeted end user devices; prevent user information overload and overreliance on AR content such that important cues from the environment are missed; prevent system delays by predicting and preloading future AR views; take into account GPS inaccuracy. | Accurate localization to ensure the projection of AR content at the right display position in sensor-based AR; investigation of player perception/immersion for alternative (to visual) augmentation modalities, such as audio and vibration. |
| **Game engine organization** | Explicitly stated profile information; use of centralized | Increased availability of wireless networks favoring always-on connectivity; evolution of cloud | Increased reliance on centralized game engines for synchronous | Employ distributed adhoc game engine architecture to support game scenarios that feature highly | Implementation of distributed games session management techniques; develop cloud- |

**Table 10** (*continued*)

| | Current status in pervasive gaming | Technology trends | Implications/trends in pervasive gaming | Developer guidelines and research opportunities | Open issues and research challenges in pervasive gaming |
|---|---|---|---|---|---|
| | facilities mainly for game session management. | computing; WiFi Direct support in recent Android and iOS releases. | communication and delegation of heavy processing jobs. | localized game play during encounters on the street; employ hybrid architectural models to allow secret interactions among players. | based game engines to support real-time high-quality video streaming and/or send-to-sync messages. |
| **Orchestration** | The majority of research prototypes require some sort of pre-game and/or on-game orchestration. | Availability of web services offering access to information about local points of interest and/or geo-tagged photos. | Trend towards lighter orchestration requirements. | Avoid reliance on dedicated infrastructure deployed on the field (e.g. deployed sensors, markers, QR codes, etc); motivate players' enrollment in on-game orchestration; design uncomplicated scenarios and apply simple game rules; utilize live actor support. | Automated monitoring of players compliance to game rules; automated registration of the game area into real world coordinates utilizing publicly available mapping services and web services. |
| **Portability** | Portability mainly addressed in commercial games; portability rarely a design objective in research prototypes (content bound to predefined areas, requirement for specialized equipment and/or supportive infrastructure). | Proliferation of mobile devices with multiple built-in sensors. | Surfacing of pervasive games incorporating user-generated content. | Design location-independent scenarios; avoid employing multiple inter-dependent player roles requiring medium/long-term engagement; rely on widespread devices as sole game equipment; incentivize the generation of high-quality content by players through some sort of awards. | Assessment of user-generated content quality (e.g., through co-players evaluation) to allow game function without content moderators; automated content generation utilizing publicly available web services; implementation of player matching techniques in support of multiplayer game scenarios. |
| **Evaluation methods** | Questionnaires, interviews, logged data, live players observation | Ability to log application usage data in various ways; availability of affordable wearable, mobile biosensors. | Shift of developers' interest from investigating technical issues to assessing usability and game perception aspects; quantitative data contrasted against qualitative data to extract safer conclusions. | Recruit enough qualified participants (via application stores) to receive unbiased feedback; organize preliminary/invitational game phases to raise game awareness. | Accurate sentiment analysis; cross-checking of recorded sentiment against other types of logged data and compiled participant answers to questionnaires; extension of existing heuristic evaluations to capture the unique properties of pervasive games. |

quality 3D graphics augmentation. Most popular and recent mobile platforms (including PSP) fulfill the hardware and software requirements for supporting satisfactory AR content, acting as a driver for developers to incorporate AR in pervasive games. Although numerous showcases of employing visual augmentation in games already exist (Thomas, 2012) the use of alternative mediation modalities (like audio or vibration) has not yet attracted equal attention. The employment of such modalities as a supplement to, or even a substitution for, visual augmentation is particularly promising as they have been found not only to enhance immersion but also to mitigate attention distraction while playing the game (Paterson et al., 2010).

### 6.5. Game engine organization, orchestration and portability

As for the game engine model, client–server architectures currently represent the prevalent organization model. As wireless (WiFi and 3G/4G) connectivity becomes increasingly pervasive, fast and cost-effective and as cloud computing evolves providing access to enormous computing power, client–server organization is expected to be adopted unreservedly not only for game session management but to support communication among players and deliver rich multimedia content. In fact, cloud support has become a reality for the video game industry in recent years,[18] representing an alternative method for distributing and playing computer games. In a cloud gaming system, the game engine is hosted on powerful cloud servers, while gamers interact via networked thin clients. Cloud-based gaming represents a particularly promising opportunity for mobile and pervasive games as it suggests a neat solution for handling the resource constraints and fragmentation challenges inherent in mobile devices. Such schemes may offer game developers more control over the content, while allowing players to gain access to complex game libraries and powerful rendering machines via any client device. Services common in cloud-based systems, such as real-time high-quality video streaming, could be especially useful in pervasive games that incorporate short-term multimedia-rich interactive sessions. However, the latency effect should be carefully considered to address the requirement for high responsiveness and prevent degradation of user experience (Claypool and Finkel, 2014). A parallel development is marked by cloud-based tools like Google Cloud Messaging for Android,[19] which could be utilized to dispatch send-to-sync messages (i.e., 'tickles' that invite mobile applications to sync data from the server), thereby mitigating the requirement for always-on connectivity of mobile clients. However, the mobile ad hoc model (Kortuem et al., 2001) is also likely to spread among future pervasive games as it could apply to a variety of game scenarios that feature highly localized and adhoc game play during encounters on the streets. As Bluetooth is a short-range technology with a relatively low transfer rate and long network setup time, the use of WiFi direct-compliant equipment is expected to become increasingly common. An alternative option is to design hybrid models in which publicly visible and legitimate actions take place at central servers, yet allowing secret or private interactions occurring in peer-to-peer mode (Benford et al., 2005).

Games' pre-orchestration (e.g., registration of the game world into real world coordinates, placement of game items, team formation, etc.) may be crucial in several instances. Many game scenarios benefit from interweaving aspects of the physical environment, otherwise the scenario may appear irrelevant or out-of-context to the players. For instance, creating missions incorporating nearby buildings, squares, or landmarks using open APIs (e.g., Google Places), enabling location-based web searches, and predicting the uncertainty that may emerge while using these services and then dealing with it (Benford et al., 2006). On-game orchestration actions should also be carefully provided for, in order to enhance players' engagement and ensure adherence to the game rules. Today, methods are being searched for to automate games' orchestration and reduce the active and physical involvement of orchestrators and moderators, as they will facilitate game deployment.

Portability, namely the adaptability of a playscape to any environment and the game's availability at anytime, appear to be must-have features for commercially successful pervasive games (GameSpot, 2012; Google, 2013; PerBlue, 2011; Start, 2013). Further to automating orchestration, the provision of instruments to allow authoring user-generated content may significantly increase a game's portability besides increasing its fun factor. Offering incentives to the players (through some sort of in-game awards) may be an effective tool to ensure high-quality content generation. Furthermore, letting users define the spatial–temporal game staging settings, may be used as a tool to lower the effect of imprecision and uncertainty with respect to positioning and communication in pervasive games, as the players themselves develop the ideal conditions to launch and play the game sessions (Flintham et al., 2003). To cope with 'cold start'-like problems (i.e., enable satisfactory game experiences in areas where not much content has been generated) or even to pursue automated/semi-automated content generation, developers could consider designing game scenarios that incorporate crowdsourced content from online archives (e.g., geo-tagged photos from Flickr and Instagram, or points of interest from OpenStreetMaps).

### 6.6. Evaluation methods, and recruitment of evaluators

The evaluation of usability, quality of experience and immersion in the context of pervasive games represents a challenging subject which calls for an interdisciplinary approach that crosses the boundaries of biological, behavioral and social sciences (Hinske et al., 2007; Jegers, 2007). Presumably, sentiment analysis (i.e., detection of players' attitude towards specific game aspects) may be a useful complement aside to 'traditional' evaluation methods in order to reach safer conclusions with respect to the examined evaluation metrics. Although not yet practiced in user evaluation trials, the advent of affordable and wearable mobile biosensors measuring and processing electroencephalogram (EEG[20]) activity now offers a cost-effective solution for automated sentiment analysis. It is foreseen that EEG monitoring may provide invaluable insights for perceived usability (e.g., indicating frustration due to difficulty of pursuing a game's action) and immersion (e.g., to capture suspense, relief, joy, concentration/distraction, etc.) game aspects (Nacke et al., 2009; Wehbe and Nacke, 2014).

As regards the formalization of evaluation methods, heuristic evaluation[21] has been a usability inspection method commonly practiced by usability experts. As heuristics are cheap, fast, and easy to use, several lists of heuristics have been proposed for developers to use while evaluating games (Desurvire et al., 2004; Federoff, 2002; Saarenpää, 2008; Sweetser and Wyeth, 2005). Researchers also evolved classic games' heuristics lists towards

[18] Cloud-based gaming platforms already exist, such as the open-source GamingAnywhere platform (http://gaminganywhere.org/).

[19] Google Cloud Messaging (GCM) for Android is a service that allows developers to send data from their server to Android-powered devices (even to specific users) and receive back messages from the devices over the same connection (https://developer.android.com/google/gcm/).

[20] EEG biosensors record brain waves, usually described in terms of frequency bands, which allow inferences to be made about mental idleness, cognitive processing, emotions, and sensations of players.

[21] Heuristics typically refer to recognized aspects and requirements that the game (or software) should meet or avoid in order to be of high quality.

evaluating mobile games (Korhonen and Koivisto, 2006); however, those are hardly applicable to pervasive games, mainly due to their strong connection with the physical environment and human activity (Jegers, 2008; Saarenpää, 2008).Therefore, an open research issue is to adapt and extend the scope of existing heuristic lists so as to capture the particular characteristics of pervasive games (a synthesis of heuristics tailored to mobile games and physical outdoor games may be promising) (Fullerton et al., 2004).

Another important yet commonly neglected game evaluation issue relates to the recruitment of qualified evaluators. Developers typically rely on advertisements, employees of their own organizations, and personal contacts for evaluating their games (Jones and Marsden, 2006; Saarenpää, 2008). Existing participant-recruitment methodologies are disputable, as studies revealed that the explicit invitation of evaluators into game trials, may affect participants' behavior and bias evaluation results (Brown et al., 2011). We argue that the developers may exploit the available application markets (e.g., Google Play and App Store) in order to exercise a sort of 'game experience crowdsourcing'; that is, to recruit large numbers of participants possibly already familiar with pervasive games and receive useful feedback, either user-supplied comments or automatically logged usage data (e.g., using Google Analytics). Such 'external' evaluators are likely to be less biased and express their opinions more freely, thereby considerably improving the reliability and quality of evaluation results. Furthermore, the fact that pervasive games are commonly played together by several players enrolled in inter-dependent roles over prolonged game sessions highlights the need to recruit highly motivated players, committed to undertake their game roles. Along this line, the execution of -publicly announced 'invitational' phases may be used to raise game awareness, and indicate the most competent and committed players to participate in the 'official' game trials (Kasapakis et al., 2015).

## 7. Risks, threats, and barriers for pervasive games

Notwithstanding their affordances in creating engaging game experiences and their increasing popularity, pervasive games face several serious threats and barriers that impede their further adoption:

*Safety*. Player safety issues may arise in pervasive game play due to time-constrained competition or player immersion. Players may neglect standard safety precautions (e.g., run in front of oncoming traffic or enter clearly marked construction zones) in order to score more points or because they are focusing their attention on their handheld's display (Ballagas and Kuntze Walz, 2008; Benford et al., 2005). Removing time constraints (so that players do not feel rushed), setting up the game space in pedestrian-only areas, using wearable devices rather than handhelds, and displaying safety-warning statements could be exercised as safety precaution measures, depending on the game scenario at hand.

*Awkwardness*. Many studies indicate that players feel uneasy while playing pervasive games that take place out of their culturally established place (Montola, 2011). Uneasiness has been reported in games that require obvious gestures (Ballagas and Kuntze Walz, 2008), role-playing, equipment (Herbst et al., 2008), sound effects (Ballagas and Kuntze Walz, 2008), or acting in a "ridiculous" manner (Fischer et al., 2006). Visible play with devices and gestures causes awkwardness especially when it is clearly observable but also inexplicable for the spectator (Montola, 2007).

*Privacy*. Privacy is an important consideration in pervasive gaming, although not as important as in other application areas of pervasive computing, as players are supposedly aware that their game activity and behavior is monitored and utilized within the game's logic. However, Markus (Montola, 2005) argues that when a game is played constantly, privacy considerations become an issue. Privacy issues are subject to trade-offs: to be aware of another players state you need to 'tell' something about yourself; to access personalized services you need to disclose personal profile information, and so on. Olli (2002) suggested that games can offer a functional testing ground for potential users of other kinds of location-based services: "in a setting with commonly accepted rules, people can experiment what it feels like when other people are able to locate you".

*Team establishment*. Pervasive game scenarios often involve multiple characters who act interdependent roles (Cheok et al., 2006; Fischer et al., 2006; Kasapakis et al., 2013). Namely, players undertaking those roles are typically required to co-exist in either time or space for the whole duration or a part of the game session. In such cases, the dynamic establishment of user groups (teams) among players sharing similar interests or behavior could possibly be considered necessary. Such grouping could take into account the actions/behaviors of peer players (i.e., use collaborative filtering techniques (Herlocker et al., 2000)), or even the current game context (e.g., use context-aware collaborative filtering methods (Gavalas and Kenteris, 2011)).

## 8. The roadmap towards 3G pervasive games

As explained in Section 3, we argue that a major transformation of the pervasive games' landscape is in progress, advocating the establishment of a third generation of pervasive games in the near future. Technological developments in the fields of wireless networking and embedded systems/wearable computing act as the main drivers in the transition towards 3G pervasive games.

Wearable computing revolutionizes the ways in which computers are perceived, through interweaving computing power within everyday artifacts, being embedded in clothing (e.g., shoes) or creating form factors that can be used like clothing (e.g., watches, glasses) (Starner, 1996). Wearable devices are capable of providing data like linear/gravitational acceleration, angular velocity, compass heading, pressure, and temperature with an update rate high enough to be useful, yet cheap and easy to acquire (Gouthaman, 2014).

Notably, wearable computers have been an emblem of 1G pervasive gaming as well. In 1G, wearables have been mainly used to complement networking, sensory, or visual capabilities impossible (at the time) to consolidate in a single device. The use of wearables in 3G games is conceptually and functionally different, as they are enrolled to enable alternative means of interaction and generate immersive experiences, alongside offering added value services.

Early signs exist today that showcase the exploitation of emerging technologies (likely to be widespread in the future) in gaming. Glass Mini Games[22] exemplify how wearable devices like Google Glass[23] may be potentially used in pervasive games. In Glass Mini Games, players can try to maintain their balance or shoot objects flying around them using the Glass sensors to target them and the voice directions to shoot. The provision of such capabilities together with the built-in GPS can possibly generate highly immersive pervasive game experiences in the near future. Other smart wearable devices like fitness trackers (Miller, 2013) and smart watches (Gouthaman, 2014) are anticipated to be viewed as player equipment in future pervasive games projects

[22] https://developers.google.com/glass/samples/mini-games.
[23] https://www.google.com/glass/.

as there are already applications whose features could be easily migrated to pervasive gaming. For instance, the Lifelog Android application[24] utilizes the wearable Sonys Smartband to keep track of a player's movement and physical activity, aspects already integrated in several pervasive game scenarios.

As for communication, the next generation of pervasive games is expected to exploit WiFi direct-compatible mobiles to enable direct player-to-player communication, when needed, without the strict range limitations of Bluetooth. Further, the wider coverage of the ultra-broadband 4G networks with their decreased access costs makes it possible to promote the use of web services (alongside built-in sensors) for prompt and seamless context provisioning.

GPS is expected to continue as the preferred technology for user location tracking. WiFi and Cell-ID are also expected to continue as GPS complements or even function independently, especially as crowdsourcing projects like the Mozilla Location Service[25] gain ground. Further, 3G pervasive games are expected to be functional mostly without orchestration actions, as preliminary showcases tend to function with no orchestration requirements.

Notably, the developers of future pervasive game prototypes will need to address the resource management problem. This mainly concerns battery consumption due to the simultaneous utilization of the resource-hungry GPS receiver and sensors in smartphones and wearables. That requirement reduces the uptime of game sessions and often compromises the user experience (Ballagas and Kuntze Walz, 2008; Fujiki et al., 2008). Although the factors contributing to energy spending have been thoroughly investigated in both smartphones (Metri et al., 2012) and wearables (Williamson et al., 2015), relevant issues in the specific context of pervasive games have not yet been studied. Pending developments in mobile devices energy management, developers could either investigate the feasibility of dynamic offloading computational intensive tasks to cloud infrastructures (Huang et al., 2012) or bypassing the problem by improving players' energy awareness or turning energy scarcity into a game feature (e.g. motivate 'hiding' by deactivating GPS or 'increasing difficulty level' to earn extra points by turning off the screen).

## 9. Conclusions

This article presents an in-depth survey of the rapidly evolving field of pervasive games, based on 18 prominent research and commercial prototypes. We have adopted a classification scheme describing three distinct generations based on the design and technological elements of the selected games, offering insights on the evolutionary path of pervasive gaming. Our generation-based classification is based on the recognition that genre-based separation criteria become increasingly ambiguous, as most pervasive game prototypes nowadays fit into more than one sub-genre. The selected games have been evaluated with respect to a broad range of design aspects. Game design elements, principles, and practices which have succeeded or failed with respect to user acceptance studies have been identified. Furthermore, we highlighted game design/technology trends and formulated concrete design/implementation guidelines for designers and practitioners in the field.

We argue that the above-described methodological approach enables a novel outlook of pervasive gaming that may assist future developers (both in research and industry) in appreciating the evolution of pervasive gaming from its origins to the present, and understanding the main drivers towards next-generation pervasive games. Our approach also provides a report of best practices and current trends which are translated into a set of unified design guidelines, thereby facilitating the development process for successful future prototypes. Finally, the systematic evaluation of the reviewed prototypes has revealed several research challenges that suggest promising directions for future pervasive games research.

[24] http://www.sonymobile.com/gb/apps-services/lifelog/.

[25] The Mozilla Location Service (https://location.services.mozilla.com/) is an open service which lets devices determine their location based on network infrastructure like WiFi access points and cell towers.

## References


Avouris NM, Yiannoutsou N. A review of mobile location-based games for learning across physical and virtual spaces. J Univers Comput Sci 2012;18:2120–42.

Ballagas R, Kuntze A, Walz SP. Gaming tourism: Lessons from evaluating REXplorer, a pervasive game for tourists. In: Proceedings of the 6th international conference on pervasive computing (PERVASIVE 2008); 2008. p. 244—61.

Benford S, Rowland D, Flintham M, Hull R, Reid J, Morrison J, et al.. "Savannah": designing a location based game simulating lion behavior. In: Proceedings of the international conference on advances in computer entertainment technology (ACE'2004); 2004.

Benford S, Flintham M, Drozd A, Anastasi R, Rowland D, Tandavanitj N, et al. Uncle Roy all around you: implicating the city in a location-based performance. ACM Adv Comput Entertain 2004.

Benford S, Magerkurth C, Ljungstrand P. Bridging the physical and digital in pervasive gaming. Commun ACM 2005;48:54–7.

Benford S, Crabtree A, Flintham M, Drozd A, Anastasi R, Paxton M. Can you see me now? ACM Trans Comput–Hum Interact 2006;13.

Benjamin J. Japanese pervasive game: mogi position & emotion in a pervasive world. In: Proceedings of the Beijing pervasive game symposium and workshop; 2007.

Broll W, Ohlenburg J, Lindt I, Herbst I, Braun AK. Meeting technology challenges of pervasive augmented reality games. In: Proceedings of 5th ACM SIGCOMM workshop on network and system support for games (NetGames'06); 2006. p. 28–39.

Brown B, Reeves S, Sherwood S. Into the wild: challenges and opportunities for field trial methods. In: Proceedings of the SIGCHI conference on human factors in computing systems, ACM; 2011. p. 1657–66.

Cateté V, Hicks D, Lynch C, Barnes T. Snag'em: graph data mining for a social networking game. In: workshop on graph-based educational data mining. p. 10.

Chatzidimitris T, Gavalas D, Kasapakis V. PacMap: transferring PacMan to the physical realm. In: Proceedings of the international conference on pervasive games (PERGAMES'14); 2014.

I. Chatzigiannakis, G. Mylonas, O. Akribopoulos, M. Logaras, P. Kokkinos, P. Spirakis, The hot potato case: challenges in multiplayer pervasive games based on AdHoc mobile sensor networks and the experimental evaluation of a prototype game, CoRR abs/1002, vol. 1099; 2010.

Chatzigiannakis I, Mylonas G, Kokkinos P, Akribopoulos O, Logaras M, Mavrommati I. Implementing multiplayer pervasive installations based on mobile sensing devices: field experience and user evaluation from a public showcase. J Syst Softw 2011;84:1989–2004.

Chen L, Chen G, Benford S. Your way your missions: a location-aware pervasive game exploiting the routes of players. Int J Hum–Comput Interact 2013;29:110–28.

Cheok AD, Khoo ET. Age invaders: inter-generational mixed reality family game. Int J Virtual Real 2006;5:45–50.

Cheok AD, Goh KH, Liu W, Farbiz F, Fong SW. Human Pacman: a mobile, wide-area entertainment system based on physical, social, and ubiquitous computing. Pers Ubiquitous Comput 2004;8:71–81.

Cheok AD, Sreekumar A, Lei C, Thang LM. Capture the flag: mixed-reality social gaming with smart phones. IEEE Pervasive Comput 2006;5:62–3.

Claypool M, Finkel D. The effects of latency on player performance in cloud-based games. In: Proceedings of the 2014 IEEE 13th annual workshop on network and systems support for games (NetGames'14); 2014. p. 1–6.

Desurvire H, Caplan M, Toth JA. Using heuristics to evaluate the playability of games. CHI '04 extended abstracts on human factors in computing systems, ACM; 2004. p. 1509–12.

Faust M, Yoo Y-H. Haptic feedback in pervasive games. In: Proceedings of the third international workshop on pervasive gaming applications; 2006. p. 1–8.

Federoff M. Heuristics and usability guidelines for the creation and evaluation of fun in video games. M.Sc. thesis. University of Indiana. 2002.

Fischer J, Lindt I, Stenros J. Final crossmedia report (part II) – epidemic menace II evaluation report, integrated project on pervasive gaming; 2006.

Flintham M, Benford S, Anastasi R, Hemmings T, Crabtree A, Greenhalgh C, et al. Where on-line meets on the streets: experiences with mobile mixed reality games. In: Proceedings of the SIGCHI conference on human factors in computing systems; 2003. p. 569–76.

Flintham M, Giannachi G, Benford S, Adams M. Day of the figurines: supporting episodic storytelling on mobile phones. In: Proceedings of the 4th international conference on Virtual storytelling: using virtual reality technologies for storytelling. Springer-Verlag; 2007. p. 167–175.

Fujiki Y, Kazakos K, Puri C, Buddharaju P, Pavlidis I, Levine J. NEAT-o-Games: blending physical activity and fun in the daily routine. Comput Entertain (CIE) 2008;6:21.

Fullerton T, Swain C, Hoffman S. Game design workshop: designing. Prototyping, and playtesting games. CRC Press; 2004.

GameSpot, Invizimals Review – GameSpot.com; 2012.

Gavalas D, Economou D. Development platforms for mobile applications: status and trends. IEEE Softw 2011;28:77–86.

Gavalas D, Kenteris M. A pervasive web-based recommendation system for mobile tourist guides. Personal and ubiquitous computing, 15; 759–70.

Google, Ingress Google; 2013.

Gouthaman S. Gesture detection system using smart watch based motion sensors. In: Proceedings of the 2014 international conference on circuits, systems, communication and information technology applications (CSCITA'14); 2014. p. 311–6.

Guo B, Fujimura R, Zhang D, Imai M. Design-in-play: improving the variability of indoor pervasive games. Multimed Tools Appl 2012;59:259–77.

Hannamari S, Kuittinen J, Montola M. Insectopia evaluation report. Integrated project on pervasive gaming; 2007.

Herbst I, Braun A-K, McCall R, Broll W. TimeWarp: interactive time travel with a mobile mixed reality game. In: Proceedings of the 10th international conference on human computer interaction with mobile devices and services. ACM; 2008.

Herlocker JL, Konstan JA, Riedl J. Explaining collaborative filtering recommendations. In: Proceedings of the ACM conference on computer supported cooperative work; 2000.

Hinske S, Lampe M, Magerkurth C, Röcker C. Classifying pervasive games: on pervasive computing and mixed reality. Concepts and technologies for pervasive games—a reader for pervasive gaming research, 1; 20.

Huang D, Wang P, Niyato D. A dynamic offloading algorithm for mobile computing. IEEE Trans Wirel Commun 2012;11:1991–5.

Jegers K. Pervasive game flow understanding player enjoyment in pervasive gaming. Comput Entertain 2007;5.

Jegers K. Investigating the applicability of usability and playability heuristics for evaluation of pervasive games. In: Proceedings of the 2008 3rd international conference on internet and web applications and services (ICIW'2015); 2008. p. 656–61.

Jegers K. Pervasive gameflow: identifying and exploring the mechanisms of player enjoyment in pervasive games. Ph.D. thesis. Umea University; 2009.

Jones M, Marsden G. Mobile interaction design. John Wiley & Sons; 2006.

Kasapakis V, Gavalas D. Design aspects and context awareness in pervasive games, creating personal, social, and urban awareness through pervasive computing. IGI Glob 2013:131–56.

Kasapakis V, Gavalas D, Bubaris N. Addressing openness and portability in outdoor pervasive role-playing games. In: Proceedings of the 2013 3rd international conference on communications and information technology (ICCIT'13); 2013. p. 93–7.

Kasapakis V, Gavalas D, Bubaris N. Pervasive games field trials recruitment of eligible participants through preliminary game phases. Pers Ubiquitous Comput 2015. http://dx.doi.org/10.1007/s00779-015-0846-z (online).

Kirman B, Linehan C, Lawson S. Blowtooth: a provocative pervasive game for smuggling virtual drugs through real airport security. Pers Ubiquitous Comput 2012;16 755–767.

Korhonen H, Koivisto EMI. Playability heuristics for mobile games. In: Proceedings of the 8th conference on human–computer interaction with mobile devices and services (Mobile HCI 2006); 2006. p. 9–16.

Kortuem G, Schneider J, Preuitt D, Thompson TGC, Fickas S, Segall Z. When peer-to-peer comes face-to-face: collaborative peer-to-peer computing in mobile Ad-Hoc networks. In: Proceedings of the 1st international conference on peer-to-peer computing (P2P'2001); 2001. p. 75–91.

Kourtellis N. On the design of socially-aware distributed systems. Ph.D. thesis. University of South Florida; 2012.

Lehner U, Baldauf M, Eranti V, Reitberger W, Fröhlich P. Civic engagement meets pervasive gaming: towards long-term mobile participation. CHI'14 extended abstracts on human factors in computing systems. ACM; 2014. p. 1483–8.

Lindley CA. Trans-reality gaming. In: Proceedings of the 2nd annual international workshop in computer game design and technology; 2004.

Lindley CA. Game space design foundations for trans-reality games. In: Proceedings of the 2005 ACM SIGCHI international conference on advances in computer entertainment technology (ACE'2005); 2005. p. 397–404.

Magerkurth C, Cheok AD, Mandryk RL, Nilsen T. Pervasive games: bringing computer entertainment back to the real world. Comput Entertain 2005;3:1–19.

Metri G, Agrawal A, Peri R, Weisong S. What is eating up battery life on my SmartPhone: a case study. In: Proceedings of the 2012 international conference on energy aware computing; 2012. p. 1–6.

Miller A. Fitness trackers. The ACM magazine for students, 20; 24–6.

Mollick ER. The dynamics of crowdfunding: determinants of success and failure. J Bus Ventur 2013;29:1–16.

Montola M. Exploring the edge of the magic circle: defining pervasive games. In: Proceedings of digital arts and culture (DAC'2005); 2005.

Montola M. Tangible pleasures of pervasive role-playing. In: Proceedings of DiGRA Situated Play conference; 2007. p. 178–85.

Montola M. A ludological view on the pervasive mixed-reality game research paradigm. Pers Ubiquitous Comput 2011;15:3–12.

Montola M, Waern A. Participant roles in socially expanded games. In: Proceedings of the 3rd international workshop on pervasive gaming applications, pervasive conference (PerGames'06). Citeseer; 2006. p. 165–173.

Montola M, Waern A, Nieuwdorp E. Domain of pervasive gaming. IPerG deliverable, D5; 3B.

Montola M, Stenros J, Wærn A. Pervasive games: theory and design. CRC Press; 2009.

Nacke LE, Drachen A, Kuikkaniemi K, Niesenhaus J, Korhonen HJ, Hoogen VDWM, et al. Playability and player experience research. In: Proceedings of the 2009 DiGRA international conference (DiGRA'09); 2009.

Olli S. All the world's a Botfighter stage: notes on location-based multi-user gaming. In: Proceedings of the computer games and digital cultures conference; 2002. p. 35–44.

Olteanu AC, Oprina GD, Tapus N, Zeisberg S. Enabling mobile devices for home automation using Zigbee. In: Proceedings of the 2013 19th international conference on control systems and computer science (CSCS'13); 2013. p. 189–95.

Paterson N, Naliuka K, Jensen SK, Carrigy T, Haahr M, Conway F. Design, implementation and evaluation of audio for a location aware augmented reality game. In: Proceedings of the 3rd international conference on fun and games; 2010. p. 149–56.

PerBlue. Parallel Kingdom. 〈http://www.perblue.com/〉; 2011.

Pocatilu P. Developing mobile learning applications for android using web services. Inform Econ 2010;14:106–15.

Saarenpää H. Data gathering methods for evaluating playability of pervasive mobile games. M.Sc. thesis. University of Tampere; 2008.

Saddik E. The potential of haptics technologies. IEEE Instrum Meas Mag 2007;10:10–7.

Starner T. Human-powered wearable computing. IBM Syst J 1996;35:618–29.

S.T. Start. Zombies. Run!. 〈https://www.zombiesrungame.com/〉; 2013.

Stenros J, Montola M, Waern A, Jonsson S. Momentum evaluation report. IPerG deliverable, D11; 7.

Strachan S, Murray-Smith R. Bearing-based selection in mobile spatial interaction. Pers Ubiquitous Comput 2009;13:265–80.

Sweetser P, Wyeth P. GameFlow: a model for evaluating player enjoyment in games. ACM Comput Entertain 2005;3.

Thomas BH. A survey of visual, mixed, and augmented reality gaming. ACM Comput Entertain 2012;10:1–33.

IAD. Urban Defender. 〈http://popupcity.net/urban-defender/〉; 2011.

Varshavsky A, Patel S. Location in ubiquitous computing. In: Krumm J, editor. Ubiquitous computing fundamentals. CRC Press; 2010. p. 285–319.

Vergetis E, Guerin R, Sarkar S, Rank J. Can bluetooth succeed as a large-scale ad hoc networking technology? IEEE J Sel Areas Commun 2005;23:644–56.

Wehbe R, Nacke LE. Games user research using EEG techniques. CHI PLAY 2014 games user research workshop and analytics; 2014.

Wetzel W, Blum L, McCall R, Oppermann L, Broeke TS, Szalavári Z. Final prototype of timewarp application. IPCity; 2009.

Williamson J, Liu Q, Lu F, Mohrman W, Li K, Dick R, et al. Data sensing and analysis: challenges for wearables. In: Proceedings of the 2015 IEEE 20th Asia and South Pacific design automation conference (ASP-DAC); 2015. p. 136–41.

Zender R, Metzler R, Lucke U. FreshUP – a pervasive educational game for freshmen. Pervasive Mob Comput 2014;14:47–56.