

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.

Keywords: pervasive computing; gaming; context-awareness; localization; information model; orchestration; game space visualization.

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 [53]. 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 [3].

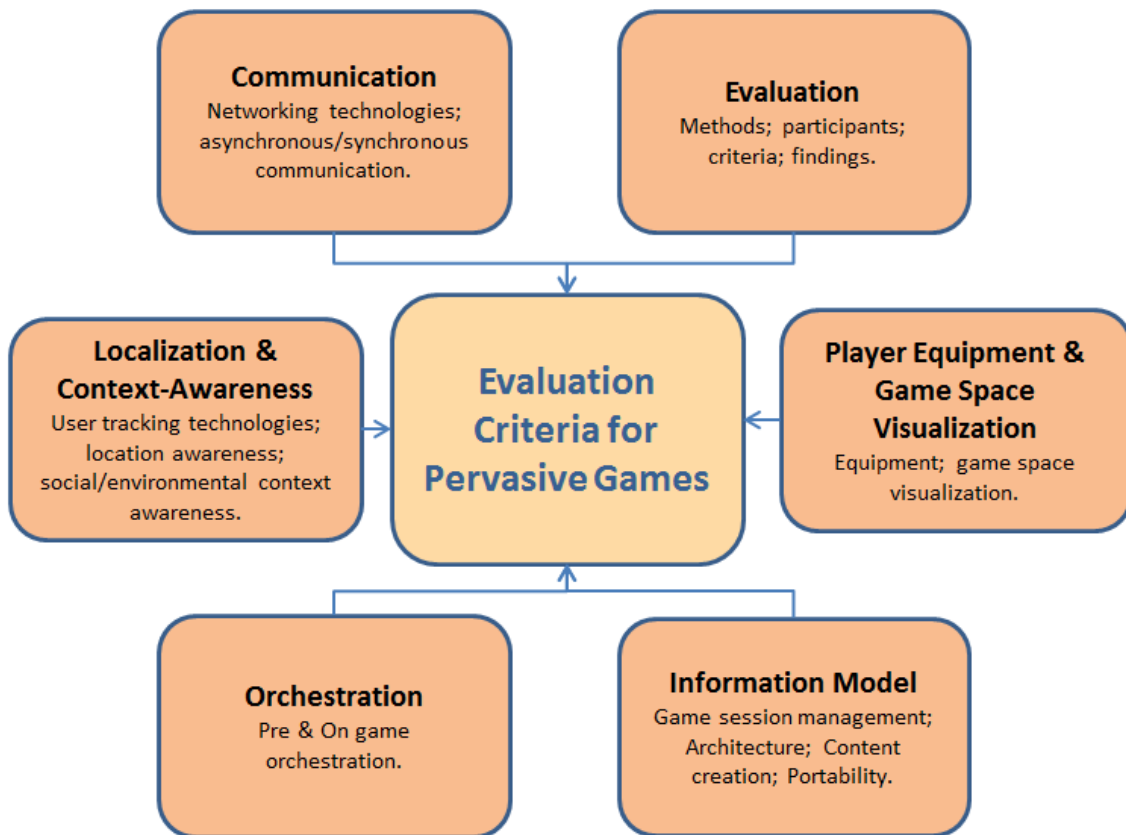


Figure 1. Design and evaluation aspects of pervasive games.

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 Figure 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 [3].

- *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 [3]. 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 [39, 69].

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* [80], *Epidemic Menace II (EM II)* [22], *Treasure* [32], *Age Invaders* [15], *Urban Defender* [38], *Hot Potato* [12], *Blowtooth* [46], *Capture The Flag (CTF)* [16], *Can You See Me Now? (CYSMN?)* [8], *Uncle Roy All Around You (URAAAY)* [4], *Your Way Your Missions* [14], *FreshUp* [82], *Barbarossa* [44, 45], *Ingress* [30], *Mogi* [7], *Parallel Kingdom Age of Emergence (P.K. AoE)* [67], *Zombies, Run!* [72] and *Invizimals* [27].

While several other pervasive game prototypes currently exist (e.g., [6, 11, 17, 23, 33, 64, 73]) 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 [7, 27, 30, 67, 72]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 [4, 5, 12, 15, 16, 22, 32, 38, 80]. Last, we survey a number of very recently released prototypes to ensure up-to-date analysis and to capture technological trends [14, 45, 46, 82].

¹ *Zombies Run!* [72] has more than 600,000 players (although it is sold for \$3.99), *Parallel Kingdom AOE* [67] and *Ingress* [30] feature more than 1,000,000 players, while *Mogi* [7] has had more than 100 participants per month even though it is not promoted through popular mobile application markets.

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 own was published in 2005 [53]. 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 [8], 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 [43], 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 [1] or augmented reality (AR) games [76]: 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 [39, 51, 53, 57, 58, 76]. In the alternative classification scheme proposed by Hinske et al. [36], 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, sensing 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 [58]. 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 [22, 34, 45]. These developments blur the

boundaries among the abovementioned 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. [36], nevertheless, we argue that it is not sufficient to embrace all aspects of pervasive gaming. For instance, several instances of pervasive mobile or trans-reality games² cannot be considered as a breed of mixed-reality games³. 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; (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

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 [52].

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 [76]. The best known type of mixed reality is augmented reality, wherein the real world perceived by users is enhanced through superimposed virtual objects.

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.

Generation	Time frame	Localization	Communication	Context	Orchestration	Player Equipment
1 st	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
2 nd	2009-2014	GPS/Cell-ID	WiFi/3G/Zigbee	Captured by build-in sensors	Light/No orchestration actions	Smartphones
3 rd	2014-onwards	GPS/proximity-based localization/crowdsourcing localization platforms	WiFi/WiFi Direct/4G	Captured by built-in sensors / 3 rd party web-services	No orchestration actions	Wearables (glasses, smart watches, health bands), smartphones

Table 1. Common features found in pervasive games generations.

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 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 Figure 3 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.

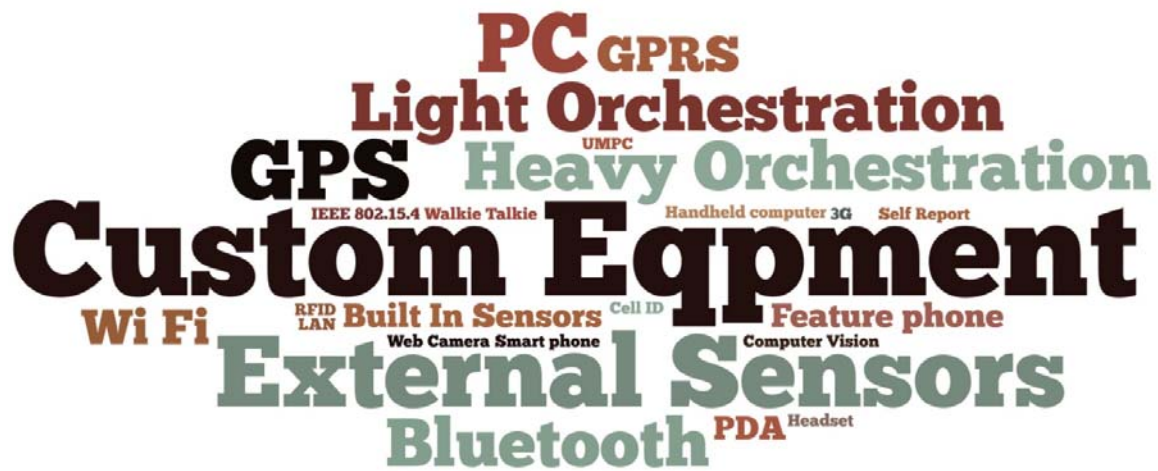


Figure 2. Tag cloud depicting most frequently used terms in 1G pervasive games.

In *CYSMN?* runners run around real city streets to catch the online players that move through the virtual street representations [8]. *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 [4]. In the Japanese game *Mogi*, the administrators place virtual treasures in the real world, collected by players at certain times and places. [7, 57].

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 [22]. *CTF* (see Figure 4a) is based on the original 'Capture the Flag', a popular outdoor game. Real and virtual-world players are called 'knights' and 'guides' [16]. 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 Figure 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 [15]. *TimeWarp* (see Figure 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 [80]. *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 [38].

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 Figure 3 illustrates the most frequently encountered terms in 2G pervasive games.



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

Invizimals (see Figure 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 [27]. *PK AoE* (see Figure 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 [67]. In *Hot Potato* (see Figure 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 s/he holds it [12].

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 [32]. In *Ingress* (see Figure 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 [30].

In *Blowtooth* (see Figure 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 [46]. *Zombies, Run!* (see Figure 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 [72]. *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 [14].

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 [82].

In *Barbarossa* [45], 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, APIs⁴, and weather web services⁵. The quest for players is to cooperatively discover and unlock a real hidden chest locked by two combination locks.



(a)



(b)



(c)



(d)



(e)



(f)

⁴ <https://developers.google.com/maps/documentation/directions/>

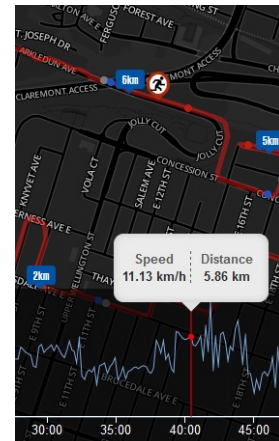
⁵ <https://weather.yahoo.com/>



(g)



(h)



(i)

Figure 4. (a) Capture The Flag; (b) Age Invaders; (c) Timewarp; (d) Invizimals; (e) P.K. AoE; (f) Hot Potato (g) Ingress; (h) Blowtooth; (i) Zombies Run!.

Table 2 summarizes 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 Play⁶ and iTunes⁷, which facilitate application deployment to users' devices and ensure wide dissemination [30, 67, 72]. *Zombies Run!* represents an interesting business case as it has been crowdfunded⁸; 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.

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 [56].

Game	Concept	Release date/Creator	Single/Multi Player	Game space locality	Generation	Genre	Unique features	Current status	Funding, cost & effort
CYSMN? [8]	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.
URAAAY [4]	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 [7, 57]	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 [22]	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 [16]	Chase	2006/National University of Singapore	Multiplayer	Indoors/City streets	1G	Location-aware, cross-media, proximity-based, trans-reality		Research prototype	-
Age invaders [15]	Chase/puzzle	2006/Mixed Reality Lab	Multiplayer	Indoors/ Floor Board	1G	Proximity-based	Compensation for elderly players' disadvantages.	Research prototype	-
TimeWarp [80]	Item hunt/ Puzzle	2007/iPcity	Multi/Single player	City streets	1G	Location-aware, proximity-based, mixed reality		Research prototype	-
Urban Defender [38]	Chase	2009/Zurich University of Arts Department of Interaction Design	Multiplayer	City streets	1G	Location-aware, smart toy		Research prototype	-
Invizimals [27]	Action/ Adventure	2010/ Sony Computer Entertainment Europe	Multi/Single player	Outdoors/ indoors	2G	Mixed reality		Commercial product	Price: ~ 20 €
P.K. AoE [67]	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 [12]	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-FRONTIS).
Treasure [32]	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 [30]	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.
Blowtooth [46]	Item hunt	2012/Lincoln Social Computing Research Centre, University of Lincoln	Single player	Indoors	2G	Location-aware, proximity-based	Game settings are restricted in airports, before/after security checks.	Publicly available	-
Zombies Run! [72]	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 ⁹ raising \$72,627 from 3464 backers (>5 five times the amount pledged); price: 3.59 €; 100.000 – 500.000 downloads in Google Play.
YWYM [14]	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 [82]	Puzzle	2013/University of Potsdam	Multiplayer	Indoors/ Outdoors	2G	Location-aware, cross-media game, trans-reality		Research prototype	-
Barborossa [44, 45]	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.

Table 2. Main features of the reviewed pervasive games.

⁹ <https://www.kickstarter.com/>

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. 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 [16, 17, 46, 64, 69]. The communication model adopted (synchronous/asynchronous) mostly depends on the supported game scenario and game play style.

	Networking technologies	Synchronous / Asynchronous communication
CYSMN?	Wireless LAN	Synchronous
URAAAY	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 (ad hoc 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

Table 3. Communication and communication model features.

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 Figure 5 which clearly illustrates that short range

communication, once mainly supported by Bluetooth in 1G games (with the exception of *Blowtooth*¹⁰), 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.

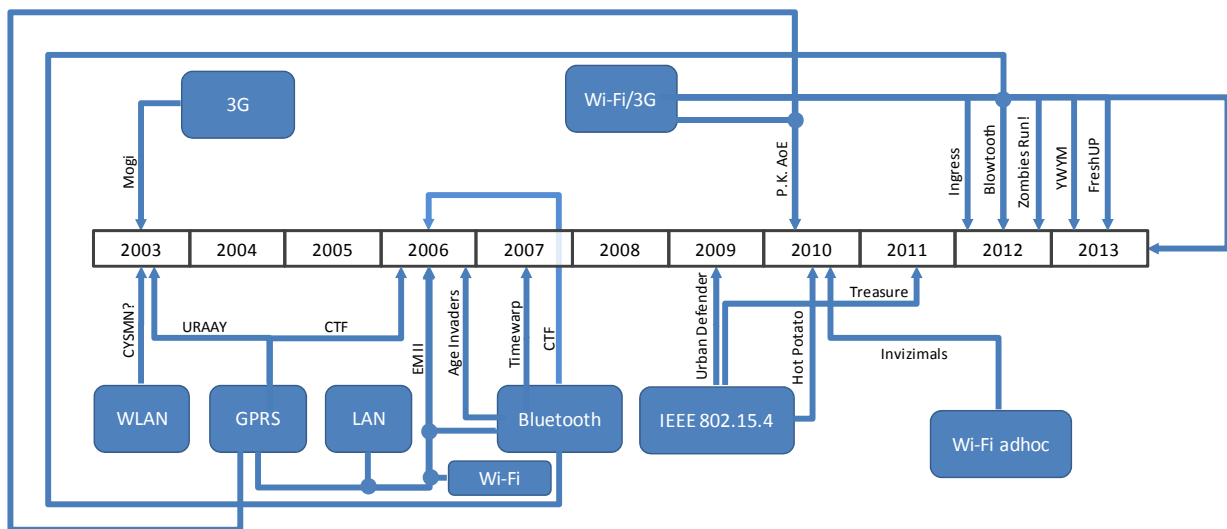


Figure 5. Timeline of communication technologies utilization in pervasive games.

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 Figure 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.

¹⁰ In *Blowtooth*, Bluetooth-enabled devices are used as content generation instruments.

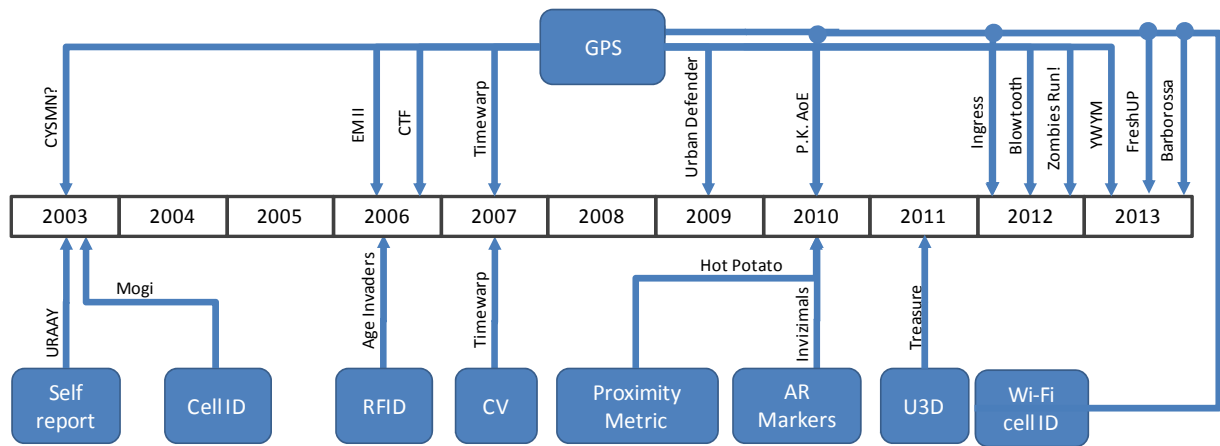


Figure 6. Timeline of localization technologies utilization in pervasive games.

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 [45], 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 sensory infrastructure, the transition towards 2G games has been marked by the decreased use of external sensor devices in favour 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 [68]. For instance, in *Barbarossa* user applications obtain environmental context (temperature and nearby points of interest) from open web services.

	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	-
URAAAY	✓	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	Other players location and activity	Orientation, wind direction

			information provision, visualization of co-players positions		
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 4. Context awareness aspects.

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 Figure 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.

	Player equipment	Game space visualization	Visual representation (maps/graphics)
CYSMN?	Walkie-Talkie, PDA, PC, GPS Receiver	VR	2D/3D
URAAAY	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 5. Player equipment and game space visualization features.

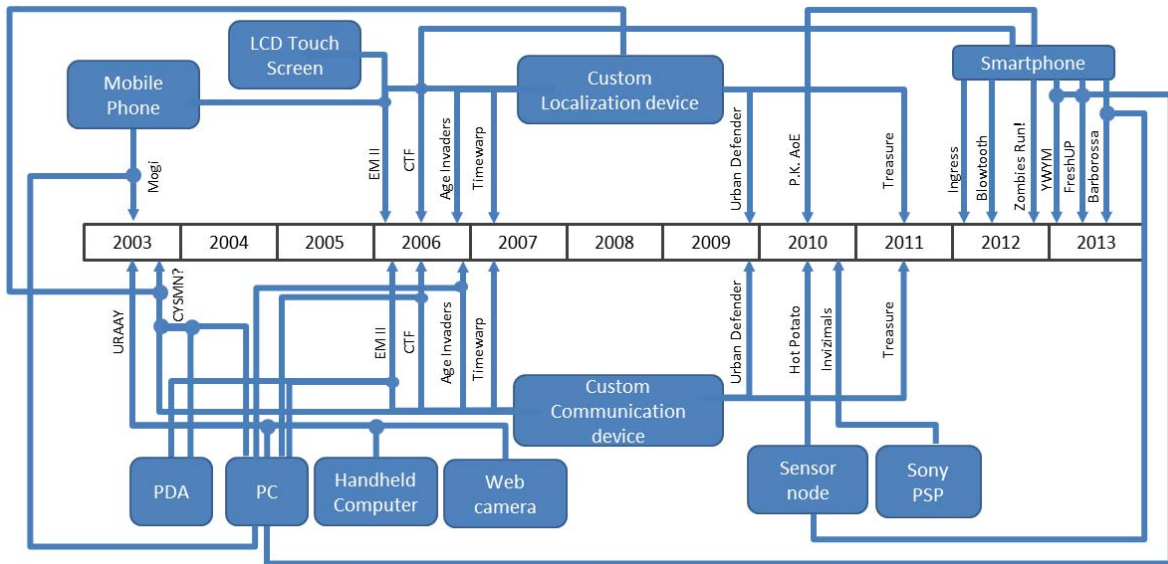


Figure 7. Timeline of player equipment evolution in pervasive games.

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 [45], as it benefits from the knowledge of the local contributors, while also consolidating inclusivity, sociability, and engagement [50].

	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
URAAAY	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	Hybrid adhoc/centralized	Adapted to location	Played anytime, anywhere

	statistics (speed, distance etc)			
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

Table 6. Information model and architectural features.

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) [3].

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 Table 7, 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 [50], although it hinders the setting up of the games, hence, their portability.

	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	✓	Technical team checking GPS and WLAN status for each runner and supporting them using walkie-talkie.	Outdoor player/Online player

	and introduced into the game.			
URAAAY	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

Table 7. Orchestration features.

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 [39].

Among the surveyed games, the commercial 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* [44]: 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 behavioural patterns¹¹ which allows 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' behaviour [22].

¹¹ 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 their thoughts and opinions, especially when an experimenter is present [79].

	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.
URAAAY	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 boundaries crossing; 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. 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),	Design guidelines for AR games: 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	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

				social presence (of real and virtual people), usability; sense of place.	quality audio/dialogs can make up for medium quality graphics. 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. Collaboration: if necessary, players should be able to share devices. 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.	with other players.
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	Matching pervasive game content, narrative and tasks to the unique features of a challenging environment may generate enjoyable experience for players.

					thought-provoking experiences for players.	
Zombies Run!	Google Play average rating: 4.3/5 – Total ratings : 5,505					
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	Prototype testing, log data, questionnaires, interviews	30 (participants recruited via an invitational game phase)	Invitational game freely available from Google Play	Easiness, usability, game play experience.	Consider developing a, orchestration-free preliminary invitational game phase 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.	The execution of cost-effective, open invitation game phases may serve as a means for recruiting highly qualified subjects for user trials on pervasive game research prototypes, thereby increasing the reliability and quality of evaluation results.

Table 8. User evaluation aspects.

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 [4, 5, 16, 22, 34]. 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 [4, 5, 22, 34]. 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 [5, 12, 22, 34]. 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 [4, 34, 46]. Finally, many players argued that social context integration, collaboration support, and team formation contributed in improving their quality of experience [5, 16, 22].

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 [14, 22, 46, 82]. 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 [80]. Another cause of frustration has been the assumption of high precision GPS location fixes, which led to misplaced floating AR objects [34].

As regards the visualization of players' location, users mostly preferred the use of auto-updated maps with overlaid markers denoting individual players [14, 16, 82]. The use of an avatar to represent the player within a 3D environment associated with a real location [4, 5, 15] 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 [22].

Live orchestration (e.g., technical teams intruding in game action) has proved to cause frustration and awkwardness to players [5, 22]. Reducing the reliance of game play to live orchestration actions, undertaking transparent background orchestration [22], and offering live actor support [4] 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 violating privacy by players [22]. Table 1, below, summarizes the design aspects found to be successful or a failure, according to user acceptance studies.

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.

Table 9. Successful and failed game design aspects.

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 favourable 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 [22]. 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. [78]) 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 smartphones¹². "WiFi direct", which enables WiFi peer-to-peer connectivity among mobile devices is also highly likely to influence future game development¹³.

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 [77], some already available as commercial systems in the market. Although such systems may offer accurate

¹²Research evidence already exists for the feasibility of integrating ZigBee into mobile devices [65]; and the first ZigBee-powered smartphone and tablet have already appeared (TazTag TPH-One and Samsung S5PV210 Cortex A8, respectively).

¹³ <http://developer.android.com/guide/topics/connectivity/wifip2p.html>

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 information¹⁴ 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 [24, 46]: 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 behaviour, 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 [13]; 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 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 [50]. Along this line, social media APIs could be used to facilitate player recruitment and

¹⁴ 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.

team establishment either through exploring the social neighbourhood of other game participants or through mining social graphs to discover individuals with similar game interests [49]. Inversely, pervasive games could allow players to publish their in-game progress via online social media channels¹⁵. 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 [62]. 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* [10] 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* [30] and *PK AoE* [67] 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 haptics¹⁶ 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 [20]. 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 [70]. Relevant empirical studies [74] 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 [28]; alongside these developments, high-level Javascript APIs have recently appeared which support web-based interactive 3D graphics¹⁷. 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., OpenStreetMap¹⁸), especially when considering games that make heavy use of map services [11].

¹⁵ 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.

¹⁶ 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.

¹⁷ <http://threejs.org/>

¹⁸ <http://www.openstreetmap.org/>

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-quality 3D graphics augmentation. Most popular and recent mobile platforms (including PSP) fulfil 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 [76] 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 [66].

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 years¹⁹, 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 [18]. A parallel development is marked by cloud-based tools like Google Cloud Messaging for Android²⁰, 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 [48] 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 [3].

¹⁹ Cloud-based gaming platforms already exist, such as the open-source GamingAnywhere platform (<http://gaminganywhere.org/>)

²⁰ 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/>).

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 [5]. 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 [27, 30, 67, 72]. 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 [24]. 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, behavioural and social sciences [36, 41]. 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 (EEG²¹) 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 [63, 79].

²¹ 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.

As regards the formalization of evaluation methods, heuristic evaluation²² 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 [19, 21, 69, 75]. Researchers also evolved classic games' heuristics lists towards evaluating mobile games [47]; however, those are hardly applicable to pervasive games, mainly due to their strong connection with the physical environment and human activity [40, 69]. 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) [26].

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 [42, 69]. Existing participant-recruitment methodologies are disputable, as studies revealed that the explicit invitation of evaluators into game trials, may affect participants' behaviour and bias evaluation results [9]. 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 [44].

²² Heuristics typically refer to recognized aspects and requirements that the game (or software) should meet or avoid in order to be of high quality.

	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 3 rd 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 3 rd 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	Accurate localization to ensure the projection of AR content at the right display position in sensor-based AR; investigation of player

				from the environment are missed; prevent system delays by predicting and preloading future AR views; take into account GPS inaccuracy.	perception/immersion for alternative (to visual) augmentation modalities, such as audio and vibration.
Game engine organization	Explicitly stated profile information; use of centralized facilities mainly for game session management.	Increased availability of wireless networks favoring always-on connectivity; evolution of cloud computing; WiFi Direct support in recent Android and iOS releases.	Increased reliance on centralized game engines for synchronous communication and delegation of heavy processing jobs.	Employ distributed adhoc game engine architecture to support game scenarios that feature highly localized game play during encounters on the street; employ hybrid architectural models to allow secret interactions among players.	Implementation of distributed games session management techniques; develop cloud-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.

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

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 [2, 3]. 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 [59]. Uneasiness has been reported in games that require obvious gestures [2], role-playing, equipment [34], sound effects [2], or acting in a "ridiculous" manner [22]. Visible play with devices and gestures causes awkwardness especially when it is clearly observable but also inexplicable for the spectator [60].

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 behaviour is monitored and utilized within the game's logic. However, Markus [61] 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 player's state you need to 'tell' something about yourself; to access personalized services you need to disclose personal profile information, and so on. Olli [64] 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 [16, 22, 45]. 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 behaviour could possibly be considered necessary. Such grouping could take into account the actions/behaviours of peer players (i.e., use collaborative filtering techniques [35]), or even the current game context (e.g., use context-aware collaborative filtering methods [29]).

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) [71]. 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 [31].

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 Games²³ exemplify how wearable devices like Google Glass²⁴ 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 [55] and smart watches [31] are anticipated to be viewed as player equipment in future pervasive games projects as there are already applications whose features could be easily migrated to pervasive gaming. For instance, the Lifelog Android application²⁵ utilizes the wearable Sony's 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 Service²⁶ 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

²³ <https://developers.google.com/glass/samples/mini-games>

²⁴ <https://www.google.com/glass/>

²⁵ <http://www.sonymobile.com/gb/apps-services/lifelog/>

²⁶ 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.

the uptime of game sessions and often compromises the user experience [2, 25]. Although the factors contributing to energy spending have been thoroughly investigated in both smartphones [54] and wearables [81], 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 [37] 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.

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