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ORIGINAL ARTICLE

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Human Pacman: a mobile, wide-area entertainment system based on physical, social, and ubiquitous computing

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Abstract Human Pacman is a novel interactive entertainment system that ventures to embed the natural physical world seamlessly with a fantasy virtual playground by capitalizing on mobile computing, wireless LAN, ubiquitous computing, and motion-tracking technologies. Our human Pacman research is a physical role-playing augmented-reality computer fantasy together with real human–social and mobile gaming. It emphasizes collaboration and competition between players in a wide outdoor physical area which allows natural wide-area human–physical movements. Pacmen and Ghosts are now real human players in the real world, experiencing mixed computer graphics fantasy–reality provided by using the wearable computers. Virtual cookies and actual tangible physical objects are incorporated into the game play to provide novel experiences of seamless transitions between real and virtual worlds. We believe human Pacman is pioneering a new form of gaming that anchors on physicality, mobility, social interaction, and ubiquitous computing.

Keywords Collaboration · Physical interaction · Social computing · Wearable computer · Tangible interaction · Ubiquitous computing

1 Introduction

In recent years, the world has seen the proliferation of highly portable devices, such as personal digital assistants (PDAs), laptops, and cellular telephones. Trends in computing environment development also suggest that users are gradually being freed from the constraints of stationary desktop computing with the explosive expansion in mobile computing and networking infrastructure. With this technological progress in mind, we have developed *human Pacman*, a genre of computer entertainment that is based on real-world-physical, social, and wide-area mobile-interactive entertainment. The novelty of this computer game has the following aspects: first, the players physically and immersively role-play the characters of the Pacman and the Ghosts, as if a fantasy computer digital world has merged with the real physical world. Second, users can move about freely in the real world over wide area indoor and outdoor spaces whilst maintaining seamless networked social contact with human players in both the real and virtual world. Third, human Pacman also explores novel tangible aspects of human physical movement and perception, both in the player's environment and in the interaction with the digital world. In other words, objects in the real world are embedded and take on a real-time link and meaning with objects in the virtual world. For example, to devour the virtual "enemy", the player has to tap on the real physical enemy's shoulder; to obtain a virtual "magic" cookie, the player has to physically pick up a real physical treasure box with an embedded Bluetooth device attached.

Human Pacman ventures to elevate the sense of thrill and suspended disbelief of the players in this untypical computer game. Each of the novel interactions mentioned is summarized in Table 1. We will proceed by firstly giving the research background for the human Pacman system and the previous works that have motivated us. Then, we will give details on the gaming experience of playing human Pacman, as well as clarifying the design of the actual game play. Finally, we will give details and experimental results of a user study performed on the system.

2 Background

Today's mainstream entertainment revolves around interactivity. People today enjoy entertainment that they

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Table 1 Detailed descriptions of the features of human Pacman

Feature	Details
Physical gaming	Players are physically role-playing the characters of Pacman and Ghosts; with wearable computers donned, they use free bodily movements as part of interaction between each person, between the real and virtual world, and among objects in the real wide-area landscapes and virtual environments
Social gaming	Players interact both directly with other players when they are in physical proximity, or indirectly via the wireless LAN network by real-time messaging. There is a coherent networked social contact among players in both the real and virtual worlds, as well as throughout their boundaries. People from all around the world can also participate in the human Pacman experience by viewing and collaborating in real time over the internet with the physical human Pacmen and Ghosts who are immersed in the physical-real-world game
Mobile gaming	Players are free to move about in the indoor\outdoor space without being constrained to the 2D\3D screen of desktop computers
Ubiquitous computing	Everyday objects throughout the environment seamlessly have a real-time fantasy digital world link and meaning. There is automatic communication between wearable computers and Bluetooth devices embedded in physical objects used in game play
Tangible interaction	Throughout the game, people interact in a graspable and tangible manner. For example, players need to physically pick up objects to collect them digitally, or to tap on the shoulder of other players to devour them
Outdoor wide-area gaming arena	Large outdoor areas can be set up for the game whereby players carry out their respective missions for the role they play. This could even be linked throughout cities

can control, and experience, in which they are fully involved [1]. In fact, not only do they want such entertainment, they also want to enjoy it together with family and friends. As shown in [2], one of the top reasons why people like to play games is that it is usually a social activity people can enjoy with others. Social gaming has gained popularity since the introduction of networked games [2]. Networked games overcame the barrier of distance, enabling real people to play against each other over large areas. After all, there is no opponent like a live opponent, since no current computer model will rival the richness of human interaction [3]. Nevertheless, even in networked computer games, social interaction between players is limited since natural interactions, such as behavioral engagement and cognitive states, are lost. Thus, by bringing players into physical proximity for interaction, human Pacman brings networked social computer gaming to a new ground because humans enjoy being physically together, and socially interacting with each other [4]. Essentially, human Pacman brings the exciting interactive aspects of networked gaming, and merges it with the real physical world, to allow a seamless real-time networked social contact between humans in both the real and virtual worlds simultaneously.

Human Pacman also has aspects derived from pioneering work that has been developed in ubiquitous gaming. Multi-player mobile gaming is demonstrated in Pirates! [5]. Pirates! implements the game on PDAs with proximity-sensing technology to incorporate a player's contextual information (such as physical co-location of players and objects in the world) into the game's context as important elements of the game's mechanics. However, visual and sound effects of game play are limited by the relatively low computing power of PDAs. Augmented Reality (AR) and Virtual Reality (VR) cannot be implemented, therefore, immersive experience is rather limited due to the flat 2-D display used on PDAs. The E3 project [6] examines the essential elements of free play, and multi-user social interaction. It focuses on human-to-physical interaction and human-to-human interaction. However, it does not explore a large-scale configuration where users walk around. In the CityWide Performance project [7], mobile players use handheld PDAs with global positioning systems (GPS) and wireless communications to access a virtual world when moving through the physical world. These mobile players compete and collaborate with online players in a networked game. Similar to Pirates!, visuals are limited to a 2-D display on the handheld computer, and the tracking resolution of players is rather large.

In the pre-computer age, games were designed and played out in the physical world with the use of real-world properties, such as physical objects, our sense of space, and spatial relations. Nowadays, computer games focus the user's attention mainly on the computer screen or a 2-D/3-D virtual environment, thereby, constraining physical interactions. However, there seems to be a growing interest in physical gaming and entertainment, even in industry. Commercial arcade games have recently seen a growing trend of games that require human–physical movement as part of interaction. For example, dancing games such as Dance Dance Revolution and ParaParaParadise [8] are based on players dancing in time with a musical dance tune and moving graphical objects (see Fig. 1). However, these systems still force the person to stand in more or less the same spot, and focus on a computer screen in front of them. Nevertheless, the underpinning philosophy is similar. One of the goals for human Pacman is to bring physical gaming into computer entertainment.

Even though human Pacman uses AR techniques as part of its interface, it is only for providing a comprehensive user interface for the players. There have been previous works which focused on using AR in entertainment. AR2 Hockey [9] is a system that allows two users to hit a virtual puck on a real table, as seen through a head-mounted display (HMD). AquaGauntlet [10] is a multi-player game where players fight with strange invaders coming from the virtual world, through

Fig. 1 A player of the ParaParaParadise arcade game

some egg-shaped objects, into the physical space. These games are played in a small and restricted area, with limited movement, and little interaction with physical space. There is no exploration of the physical environment that the player is in. In [11], Starner created a new mobile experience by introducing AR to wearable computing. An important mobile AR game is ARQuake [12], which is an AR extension of the popular computer game, Quake. Using a wearable computer equipped with GPS, ARQuake can be played indoors and outdoors. However, it is a single-player game with practically no social interaction.

3 System design and game play

Human Pacman features a centralized client–server architecture that is made up of four main entities, namely, a central server, client wearable computers, helper laptops, and Bluetooth-embedded objects. An overview of the system is shown in Fig. 2. Wireless LAN serves as a communication highway between the wearable computers, the helper computers (laptops), and the server desktop computer.

The physical location and players' status updates are sent from the client wearable computers to the server every 10–21 ms, depending on the processing load on the

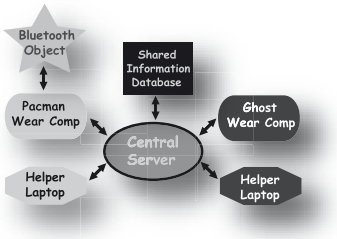

Fig. 2 Top-level system design overview of human Pacman

client. The server maintains up-to-the-minute player information (location, status, etc.), and presides over any communication between the Bluetooth objects and the wearable computers. The software flow of the server code is given in Fig. 3. Since the wearable computers were developed in the lab for this research, we proceed to discuss its detailed configuration, as summarized in Fig. 4.

At the heart of the whole system is a Desknote A980 system with a 3 GHz processor and an NVidia GeForce4 video card. Twiddler2 acts as a handheld keyboard and mouse input device for the system. The video input of the surroundings is obtained from a Firefly digital firewire camera. The Cy-Visor video see-through HMD displays the processed video. Data from the InertiaCube2 (which has been fastened onto the HMD) is obtained and used to track the user's head motion with a dynamic accuracy of 3°. Data obtained from Point Research's DRM-III module helps in determining the position of the user through the direct use of its GPS data, or indirect estimation with the dead-reckoning method using its step-counting data, which has an accuracy of 2–5% of the total distance traveled. Bluetooth communication is made with the TDK Bluetooth USB Adaptor. A touch-sensor circuit designed and built in our laboratory using capacitive touch sensors, QT160, is used to sense the touching of the backpack by the enemy player, or the touching of Bluetooth-embedded objects by Pacmen.

With the software architecture mentioned as the backbone of the game engine and the hardware as enabling tools, we proceed to describe the game play of human Pacman[1]. The main concepts of the game are first given in terms of team collaboration, ultimate game objectives, and the essential nature of the game's playground, named Pac-World. Then, we move on to present the details on the players' roles as Pacman, Ghost, and Helper, respectively. We end this section by giving examples of several actual game play situations.

3.1 Main concepts: team collaboration, ultimate game objectives and the nature of Pac-World

The players are assigned to two opposing teams, namely the Pacman team and the Ghost team. The former

[1]Videos introducing human Pacman are available online at http://mixedreality.nus.edu.sg/research-HP-videos.htm .

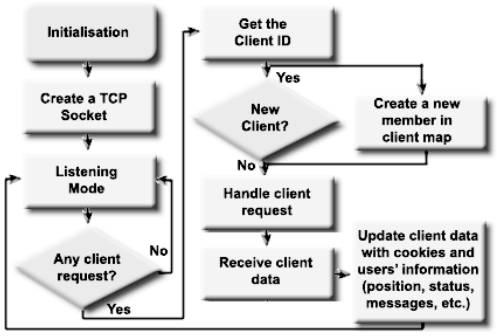

Fig. 3 Flowchart of server code

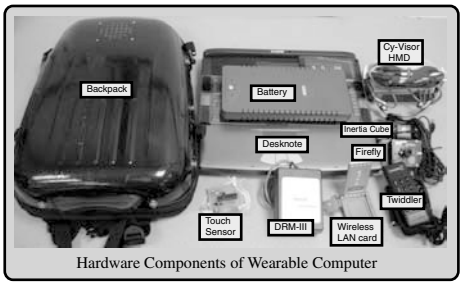

Fig. 4 Detailed configuration of the wearable computer system

consists of two Pacmen and two Helpers; correspondingly, the latter consists of two Ghosts and two Helpers. Each Pacman or Ghost is in coalition with one Helper, promoting collaboration and interaction between the users. Since a Helper player is essentially participating in the game play remotely by using a computer terminal over a wireless LAN, human Pacman can effectively be expanded to include online players anywhere on Earth who can view and collaborate, via the Internet, with real human Pacmen and Ghosts who are immersed in the physical playground.

Ever since its introduction by Namco to Japanese arcade fans in 1979, Pacman has gone through numerous stages of development. Yet, the ultimate goal of the game remains fundamentally unchanged. We have designed human Pacman to be in close resemblance to the original Pacman in terms of game objectives so that the players' learning curves are very much leveled to the point where they can pick up the game in very little time and enjoy the associated familiarity. Basically, the goal of the Pacman team is to collect all virtual plain cookies and hidden special cookies in Pac-World whilst avoiding the Ghosts. On the other hand, the aim of the Ghost team is to devour all Pacmen in Pac-World. To add to the excitement of the game play, after ''eating'' a special cookie, a Pacman gains Ghost-devouring capability and, henceforth, can attack her enemy for a limited period of time.

Pac-World is a fantasy world existing simultaneously in physical reality, in AR and VR modes. Pacmen and Ghosts, who are walking around in the real world with their networked wearable computers and HMD, view

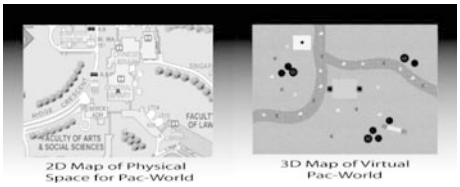

Fig. 5 Two-dimensional map of game area and its corresponding 3-D map of Pac-World

the world in AR mode. Helpers, on the other hand, can view it in VR mode since they are stationed in front of networked computers. Most importantly, there is a direct and real-time link between the wide-area physical world and the virtual Pac-World at all times, thus, providing the users with a ubiquitous and seamless merging of the fantasy digital world and the realistic physical world. As seen in Fig. 5, where the 2-D map of the selected game play area on our university campus and the 3-D map of Pac-World are shown side-by-side, we have converted the real world to a fantasy virtual playground by ingraining the latter with direct physical correspondences. This is done with the help of the dead-reckoning module (DRM-III) and inertia sensors (InertiaCube2).

The real-time position of each mobile user is sent periodically to the server through the wireless LAN. Upon receiving the position data, the server sends an update to each wearable computer detailing the position of the other mobile players, as well as the positions of all ''non-eaten'' plain cookies.

3.2 Pacman, Ghost, and Helper

Pacman has to physically move within the game area to collect all virtual plain cookies overlaid in the real world, as seen through her HMD (see Fig. 6). In addition, she has to find and collect special cookies in the virtual Pac-World. These are directly linked and represented by Bluetooth-embedded objects, shown in Fig. 7. This creates a sense of presence and immersion within the virtual Pac-World, as well as a feeling of active participation in the real world.

The Ghost can devour a Pacman by tapping on a capacitive sensor attached to a Pacman's shoulder. Likewise, a Ghost can be devoured by Pacmen endowed with Ghost-devouring powers. Such tangible physical interaction between humans, commonly found in traditional games such as hide-and-seek and the classic ''catching'' game, is now revived in this computer gaming arena.

Each Pacman and Ghost will be assigned a partner Helper who acts as an intelligence, advisor, and coordinator in her quest to achieve her goal. To enhance the gaming experience for both Pacmen and Ghosts, these players in the physical world with wearable computers are not able to see enemy mobile units (the positions of the enemies are not shown on the virtual map, and there

Fig. 6 First-person view of human Pacman

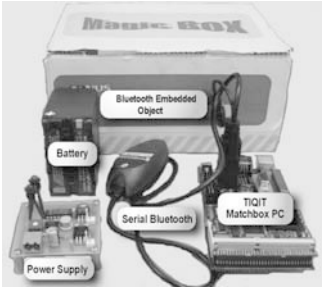

Fig. 7 Bluetooth-embedded object

is no AR labelling on them) and hidden special cookies. The Helper, who is in VR mode and sees all, guides her partner by messaging her with important information, as shown in Fig. 8. This promotes collaboration and interaction between players through the internet.

3.3 Actual game play

Collection of plain cookies Pacman collects a cookie by walking through it. Such a physical action is reflected visually in Pac-World through the disappearance of the cookie in both the AR and VR mode. In Fig. 9, the top images show the HMD view of the Pacman player as she collects a cookie. When she walks through the cookie, the cookie disappears. This collection is also reflected in real time in the virtual Pac-World (seen by the Helpers) and the Pac-World map (seen by both Pacmen and Ghosts) through the disappearance of the cookie in the corresponding location.

Ghosts cannot collect cookies. Although a Ghost is not able to see the enemy Pacman on the map, the disappearance of cookies in her map can give her a hint as to where to find a Pacman. Therefore, a Pacman has to be careful as her physical interaction with the real world (i.e., movement) can be digitally reflected in the virtual world, and be made used of by a Ghost. Novelty is again seen in such an intimate relationship between interaction in the physical world and its effect in the fantasy virtual world. Neither physical distance nor mobility could restrict each player from seeing this real-time effect as all players, including the Ghosts, can see an update of the virtual map in real time.

Fig. 8 Close collaboration between Pacman and her Helper

Fig. 9 Pacman collecting cookies

Collection of special cookies Pacman collects a special cookie by touching real Bluetooth-embedded objects placed in different parts of the game area. In Fig. 10, a sequence of pictures shows a Pacman collecting a special cookie. When the Pacman is within range of the Bluetooth object (a distance of about 10 m), communication takes place between the wearable computer and the Bluetooth device. The wearable computer sends the unique address of the Bluetooth device to the server. Upon receiving it, the server will then decide if the player is eligible to collect the special cookie that is associated with the physical Bluetooth object. If the player is not eligible (e.g., she has already collected it previously), she will not be alerted to the object. Otherwise, an alert message will be shown in the player's HMD display.

The player has to hunt for the Bluetooth-embedded object in the surrounding physical area upon receiving the alert message, thus, adding elements of fun and adventure to the game play. Having found the object, the collection is done simply by physically holding the object in her hands. Once haptic data is collected by the touch sensor, the Bluetooth device embedded in the object will send an alert message to the wearable computer, which will in turn be relayed to the server.

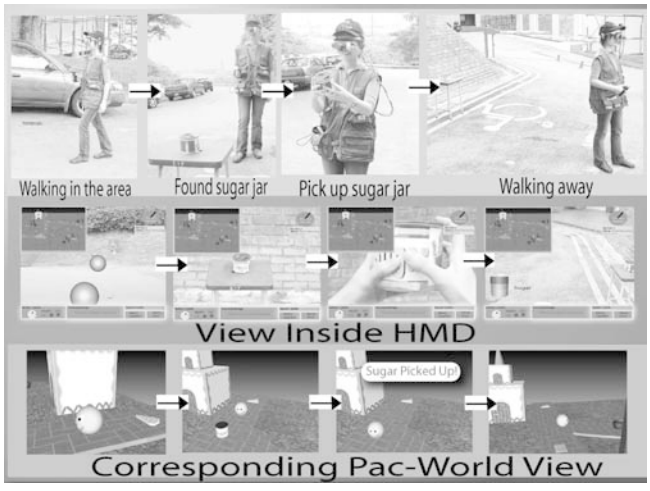

Fig. 10 Sequence of pictures showing the collection of a special cookie

The server performs a legitimacy check on the player's action and then proceeds to update its database as well as informing the wearable computer. The collection of the special cookie exemplifies a natural tangible interaction involving physically interacting with this object through human touch. Pacman is able to hold a real object naturally in her hands as should be in real-life treasure finding. Such a tangible action provides the player with a sense of touch in the fantasy domain of the game play. The collected special cookie will be kept in a virtual inventory list. As seen in the figure, collection is shown by an addition of an icon to the inventory list after the special cookie has been collected. Pacman need not lug the physical object with her as she has collected the special cookie virtually.

Collaboration between players There is an essential element of collaboration in the game play between a Pacman or Ghost with her Helper, and between any allied Pacman.

(I) Pacman or Ghost and Helper collaboration. The Helper is in a good position to assist her partner as she has a complete view of Pac-World all of the time, including the positions of all players and special cookies. Furthermore, as Helpers within the same team are physically close, they are able to collaborate between themselves and work out a strategy to achieve the team's goal. The advantage of this setup is that social interaction and collaboration is significant between Helpers, as well as between the Helper and her partner.

(ii) Pacman and Pacman collaboration. Pacman players collaborate through the transferring of special cookies between them. However, so as not to disadvantage Ghosts, Pacmen are only allowed the transfer via Bluetooth. This enforces a proximity requirement for this exchange. For example, Pacman A can initiate a request for the list of unused special cookies that Pacman B has. Upon approval, A can request the transfer of a special cookie from B, subjected to approval by B. Transfer of the special cookie is important as a Pacman may not be able to comb the whole game area for the special cookie. Strategy and team work could be implemented, with coordination from the Helpers, to distribute special cookies between the Pacmen.

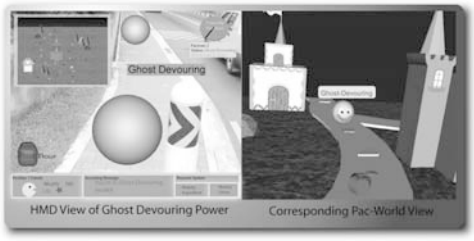

Fig. 11 HMD display and the corresponding VR mode view

Fig. 12 Ghost catching a Pacman

Use of special cookies All special cookies can only be used once. When a Pacman consumes a special cookie, she will see an alert message in her HMD, informing her of the 1 min Ghost-devouring power she has acquired. In real time, a label describing her acquired power will also be placed on top of her Pacman avatar in the VR mode. This serves to inform all Helpers, including those from the Ghost team, of her ability. This is illustrated in Fig. 11.

Devouring enemy players To devour a Pacman, a Ghost must physically touch Pacman's shoulders (see Fig. 12) to trigger the touch sensor located there. The same applies when a Pacman with Ghost-devouring capability devours a Ghost. When a Pacman or Ghost is devoured, she loses one life point of her two life points. Devouring involves tangible physical touch contact between two players. As close proximity is involved, other forms of human interaction come into play. The act of devouring makes the game more tangible and fun by involving more types of natural physical movement. When a Pacman player is the prey, her agility determines the "life-and-death" of her virtual Pacman role. Hence, not only is tangibility brought to play in this fantasy world, but also other human perceptions and instincts. Thus, this computer game provides the benefits of natural wide-area free bodily movements as part of humanistic interaction between each person.

Ending the game The game ends when either team meets its goal or when a time limit of 15 min (chosen arbitrarily) has been reached.

4 User study

To gain useful feedback from the end user, we conducted an experimental user study survey on the human Pacman system. Our aim is to find out from the actual users, their experience of the positive and negative aspects, interaction, and level of enjoyment in playing the human Pacman game. In these tests, the focus had been placed on the different novel experiences offered by the game. Our study involved 23 subjects between the age of 21 and 33, of which eight were females and 15 were males. Amongst these people, 39% indicated their level of expertise in computers as advanced, 43% as intermediate, and the rest as beginners.

The experiment setup consisted of four parts. First, the subject was asked to play traditional arcade Pacman games on a desktop computer for 5 min. Then, a 3-min human Pacman video was shown to give him or her a better understanding of the game. This was followed by a 15-min trial where the subject tried the roles of Pacman, Ghost, and Pacman's Helper for 5-min each, alongside other subjects taking a different role. An expert user acted as the Ghost's Helper. Finally, the subject had to fill in a questionnaire and provide comments on the system.

Questions and aims Table 2 shows the list of questions that were asked in the survey. Following each question is the reason for asking this question in the user study. Except for questions (I), (iv), (xi), and (xvi), multiple choices are given for all other questions.

Figure 13 gives the user study results of all of the multiple-choice questions listed earlier. The options for each question and the percentage of users who chose each option are given in the figures.

4.1 Discussion

In this section, the response to the multiple-choice questions will be discussed. All of the data have been analyzed using statistical methods. However, due to lack of space, only the data obtained from (I), (iv), and (xi) will be analyzed in detail in this paper. Insights provided by users' comments from question (xvi) are also used in the analysis.

Questions (i), (x), (xii), and (xiii) examine how well received human Pacman is by its users, and how it compares with respect to other types of games in terms of user preference. As seen from the respective findings given in Fig. 13, most of the users are enthusiastic about human Pacman. However, it is noted that, when compared with the traditional "Catch Me" game, 34.8% of the users gave a neutral stand in their preference. Results from (I) gives an average rating of 5.85 (with a variance of 1.46) indicating that human Pacman is much more favored than normal Pacman in terms of entertainment value. Statistical analysis with *a t*-test confirms the significance of our inference ($p = 6.72 \times 10^{-7}$).

The element of physicality may have been the pushing factor for the preference shown towards human Pacman over arcade Pacman and conventional computer games. However, this is not so much of a benefit over the traditional "Catch Me" game (which, by itself, is a game that involves a high level of physical participation). A number of users commented that they liked the idea of "physical involvement" and "physical movement" in human Pacman. Some said that such movement is a good form of exercise. Note that 60.9% of the users still prefer human Pacman over the traditional "Catch Me" game. This indicates that the element of physical involvement in human Pacman is not its sole attraction. The immersive experience in the role-playing of Pacman could be another element that users enjoyed over arcade Pacman and conventional computer games. Findings from question (iv) gives the average level of excitement rated by the subjects to be 6.0 (with a variance of 0.182) for the first-person experience in Pac-World and 3.33 (with a variance of 0.97) for the third-person experience in arcade Pacman, indicating a higher level of excitement in the former. A non-parametric two-condition Wilcoxon statistical test confirms the significant difference in the feeling of excitement by the players at a level of $p = 4.88 \times 10^{-4}$.

As reflected by many users, the backpack holding the wearable computer system is bulky and heavy, and the HMD is cumbersome to wear. As seen from the results obtained for question (ii), 73.9% of the users found the wearable computer to be uncomfortable. This could be the deterring factor for 77% of those who indicated that they liked playing human Pacman, but would refrain from playing it frequently. The absence of equipment weighing down the user could also make the traditional "Catch Me" game more attractive as one is unencumbered physically.

Despite not being a normal day-to-day experience, collection of virtual cookies by walking through them is deemed to be intuitive by 87% of the users (as seen in Fig. 13(iii)). The rest found the experience to be acceptable, though not intuitive. Findings for question (v) show that 78.3% found that the use of virtual cookies enhances the game, whereas 17.4% feel that the cookies are acceptable as virtual objects, but it fail to enhance the game.

A shift in alignment of virtual cookies from its supposed absolute position in real space (caused by sensing drifts), mentioned by some users, could be the reason why virtual cookies seem lacking to some users in being realistic and, thus, its inability to enhance the game. As the views of virtual cookies are calculated with respect to the user's location, any discrepancies in her exact position may lead to the "shifting" of the absolute position of the virtual cookies in real space. Since the system uses a DRM-III module and the dead-reckoning method to

Table 2 Questions in the user study

Question	Reason for asking
I. How do you rank human Pacman compared with the normal Pacman game in terms of entertainment value? Please rate between 1 (normal Pacman more entertaining) to 7 (human Pacman more entertaining).	As the idea of human Pacman originates from the previous arcade Pacman, the fundamental concept of game play is similar. The question aims to find out if any value has been added to the old Pacman game in the new system
ii. How comfortable do you feel when you are using human Pacman system?	The wearable computer system is still rather bulky and heavy compared to mobile devices such as phones, Game Boys, and PDAs. We want to find out if, and by how much, it affects the level of comfort of the user when user dons it
iii. How intuitive do you think it is to collect cookies by physically walking through them?	In everyday life, collection of an item is seldom, if ever, made by walking through it. We seek to understand if the user finds it intuitive to collect virtual cookies by walking through them, just as it is done in the original Pacman game
iv. Please rate, from 1 (lowest) to 7 (highest), the level of excitement of playing as a Pacman in Pac-World (first-person experience), in comparison with the arcade Pacman that you can play using joystick/keyboard (third-person experience)?	We want to find out if the immersive experience of human Pacman makes the game more exciting. Arcade Pacman is used as the baseline for comparison as it is fundamentally similar in game play
v. What do you think of displaying "cookies" as virtual objects augmented inside the real world?	From this question, we want to find out how realistic is the experience of collecting virtual cookies using AR
vi. Does the physical collection of a real object (special cookies) enhance the gaming experiences?	The collection of special cookies is a tangible interaction with a physical object that translates into a digital meaning (i.e., update of Pacman's inventory list). We want to find out if such graspable interaction enhances the game for the user
vii. How do you feel about the collaboration of the Pacman and the Helper in the human Pacman game?	The Helper role is added to bring in an element of collaborative experience between the human players. However, it makes the game more sophisticated. The question aims to find out if such collaboration makes the game more exciting, or does it makes the game overly complex
viii. Does the VR mode give you a good idea about the game environment?	It is important for the Helper to understand the situation her partner is in so as to dispense the appropriate advice. The ability to comprehend the game environment from the VR mode ("Gods view") is essential in helping her access the situation. Thus, we wanted to see if this is confirmed in the user's opinion
ix. What do you think of the "capturing" event implemented in our system (touching the Pacman by the Ghost)?	The "capturing" event is a reflection of the naturalistic and physical approach human Pacman took towards tangible interaction. We seek to find out if user enjoyed this feature
x. Did you like playing the human Pacman game?	Having reflected on the game by answering the previous questions, the user is quizzed on the overall level of interest she has on human Pacman
xi. Please rate, from 1 (lowest) to 7 (highest), the feeling of "social interaction" in being the Ghost, the Pacman, and the Helper.	We want to find out the level of social interaction experienced by the user in each role
xii. How do you compare this game with other computer games?	As human Pacman aims to extend and differ itself from conventional the human–computer interface used in normal computer games, this question investigates how well has human Pacman achieved its aim
xiii. How do you compare human Pacman with the traditional "Catch Me" game?	This question looks at how human Pacman compares with simple, non-computer-based games. The traditional "Catch Me" game is used as a basis for comparison due to its similarity with the "capturing" event in human Pacman. We want to see if adding the fantasy element has any benefit in the user's enjoyment over a normal catch game
xiv. If there is such a game in an amusement park, how much are you willing to pay to play the game?	Currently, acquiring the whole human Pacman system requires a high overhead, so a commercially viable version of the system could only be sustained by being based on a pay-per-use basis, which is the norm in amusement parks. This question investigates the amount of revenue per person the system could bring in if implemented commercially. The question is asked to see if there is a link between such research systems, and potential commercial use
xv. How often do you play computer games?	This question finds out how frequently the user play computer games. This enables us to find out if her love for conventional computer games would influence her desire to play human Pacman
xvi. Please give us some comments on how we can improve the system and what the current drawbacks of the system are	We seek users' comments on our system to further improve it in areas we may have neglected

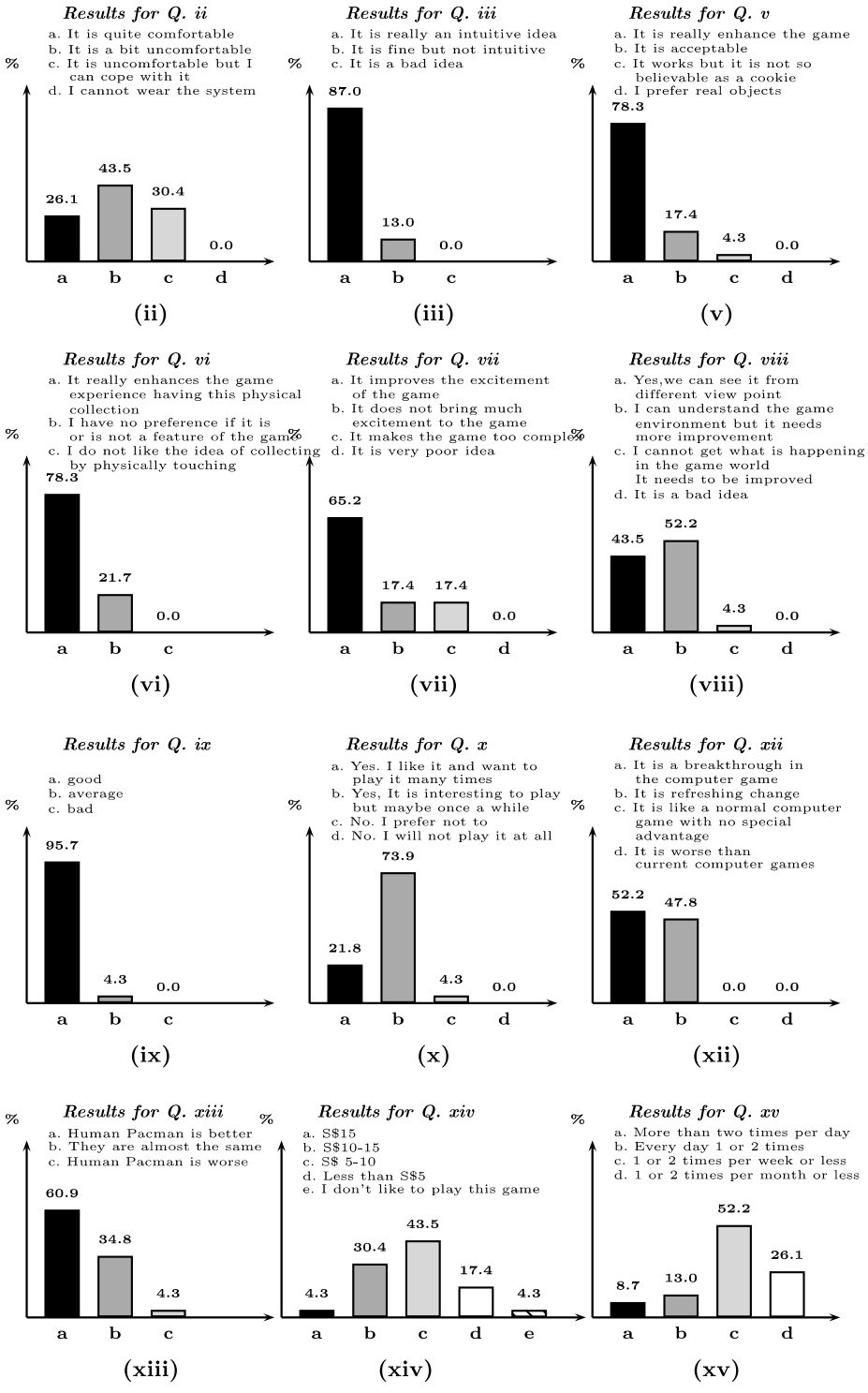

Fig. 13 Graphs of the results for all multiple-choice questions (not including (I), (iv), (xi), and (xvi) which, due to lack of space, are described in the text only)

estimate the displacement of the user, an inaccurate estimation of her stride (which varies with the individual) or the wrong count for the number of steps taken will introduce errors into the estimate. The location of the user thus computed is an estimate and may not reflect her true position in the physical space. Some users have reflected that the DRM-III module failed to sense all of the footsteps taken by the user.

Users also found the visual cue of the cookie collection (i.e., cookies disappearing from the AR world when collected) to be weak and insufficient in providing a "better feel" of collection. A number of users suggested using sound, for example a "beep", to indicate the collection of each virtual cookie. A lack of realistic affordance of virtual cookies makes reliance on other cues, to indicate collection, more important.

On the issue of the tangible interaction element in human Pacman, 78.3% (as seen in Fig. 13(vi)) found that the graspable interaction offered by the collection of real objects enhances the game. The other 21.7% gave a neutral response towards having this collection as part of the game. Almost all of the users indicated in question (ix) that they liked the "capturing" event. Despite both events being naturalistic interactions with the physical world, users seemed to like the "capturing" event more. This suggests the physical human-to-human interaction in the process of "capturing" makes the event more enjoyable.

In response to question (vii), 34.8% of the users did not find that the Helper role makes the game more exciting. In fact, 17.4% found that it makes the game too complex. Results obtained for question (xi) shows that the feeling of having social interaction has rated means of 5.67, 5.41, and 4.17 with variances of 0.97, 1.17, and 0.88 in playing as Pacman, Ghost, and Helper, respectively. The non-parametric Wilcoxon test shows insignificant difference in the level of social interaction between the Pacman and the Ghost ($p = 0.5$), while the difference between being the Ghost and the Helper is significant, with $p = 0.0039$. The Helper role is perceived to have a lesser social interaction compared to the other roles. As the study does not involve a trial of the role of the Helper in a full-scale-length game, the users may not have been able to fully comprehend the essence of the Helper role.

As reflected by the response for question (viii), almost all of the users are able to comprehend the game environment from the VR mode. It is noted that more than half of the users feel that more improvement still needs to be made for the VR mode. Users would like to see better 3D graphics and more variety of virtual objects in the VR world. Perhaps the lack of a visually appealing 3D interface compared to that found in commercial computer games makes the Helper role less attractive (our 3D models are non-commercial and designed in the laboratory by students).

Based on the results from question (xiv), the average amount that users are willing to spend to play human Pacman in amusement parks is SGD$8.15, with a variance of 16.5. This is in the typical price range of amusement rides available locally. It is noted that the 17.4% who would pay less than SGD$5 to play human Pacman also indicated in question (xv) that they seldom play computer games. Perhaps they do not enjoy playing games and are, therefore, less willing to spend on it.

4.2 Summary of findings and future work

We believe that the findings indicate that users like the idea of human Pacman as a whole. This is seen from their attitude towards playing the game, their willingness to pay to play the game, and their preference of human Pacman over other types of games. It is promising that the users were positive about the physical interaction aspects of the game, such as the first-person point-of-view and the tangible interactive elements. However, it is clear that improvements can be made to reduce the size and weight of the wearable computer.

On the individual elements of human Pacman, the collection of virtual cookies is well accepted, though improvements can be made to make the whole experience of moving towards virtual cookies and collecting it more realistic. Sound could be added as a cue to the collection. More accurate and precise tracking devices could also be developed to minimize error in location tracking, which was a factor of disapproval from the users.

Though both the "capturing" event and collection of physical objects add value to the game, it is found that the former is preferred. This could be because, during the "capturing" of Pacman, physical human-to-human interaction is involved, along with other forms of human interaction that comes into play (e.g., shrieking). The study also shows that the immersive experience is valued by users. Users like to be "physically involved" in this first-person gaming experience. This positive reception is important to note, as the tangible and physical aspects introduced into human Pacman are one of its major thesis.

As for the issue of having the Helper role in human Pacman, a less than enthusiastic response is obtained from a large portion of users, with half of these users feeling that it makes the game too complex. A more in-depth study will, in future, be made on why such sentiment is prevalent. A preliminary suggestion is the lack of a full-length trial of the game in the experiment for the user to fully appreciate the important role played by the Helper. Improvements in the aesthetical value of the VR mode may also make the Helper role more enticing.

Despite encouraging responses from the users, the human Pacman system is still unsuitable for commercial production for the following reasons:

- The cost of each set of wearable computer system is very high as they are lab prototypes
- The bulkiness and heaviness of the prototype wearable computer and HMD restricts the user to only walking, though the short response time of the system software does totally allow for quick movement, such as running
- An accurate and sensitive positioning system is needed to enhance the realism of the game
- The robustness of the system needs improvement

5 Conclusion

The continual propagation of digital communication and entertainment in recent years has forced many changes in societal psyche and lifestyle, that is, how we think, work, and play. With physical and mobile gaming gaining popularity, traditional paradigms of entertain-

ment will irrevocably shake one from the stale television set inertia. We believe that human Pacman heralds the conjuration and growth of a new genre of computer game that is built on mobility, physical actions, and the real world as a playground. Reality, in this case, is becoming more exotic than fantasy because of the mixed reality element in the game play. On the other hand, emphasis on physical actions might even bring forth the evolvement of professional physical gaming as a competitive sport of the future, for example "Pacman International League".

The element of social gaming in human Pacman symbolizes the nascence of humanity in future digital entertainment. People are looking forwards to widening their circle of friends and colleagues through social collaboration in game play. A new form of interactive entertainment has evolved.

Another important area of impact is the field of education. The technology presented in human Pacman can be exported to applications in educational training that stress "learn by experience". Students are immersed in the real site of action, and are given instructions visually through head-mounted displays or verbally through speakers or earphones. This technology serves as a powerful instrument of cognition since it can enhance both experimenting and reflective thoughts through mixed reality and interactive experience.

In conclusion, we believe human Pacman is a novel system in the new hybrid field of physical, social, and mobile gaming that is built on ubiquitous computing and networking technology. The players are able to experience seamless links between the real and virtual worlds and, therefore, a higher than ever level of sensory gratification is obtained.

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