Pac-Many: Movement Behavior when Playing Collaborative and Competitive Games on Large Displays

Sven Mayer[1], Lars Lischke[1], Jens Emil Grønbæk[2], Zhanna Sarsenbayeva[3], Jonas Vogelsang[1], Paweł W. Woźniak[1], Niels Henze[1], Giulio Jacucci[4]

[1]University of Stuttgart, Stuttgart, Germany, {firstname.lastname}@vis.uni-stuttgart.de

[2]Aarhus University, Aarhus, Denmark, jensemil@cs.au.dk

[3]The University of Melbourne, Melbourne, Australia, zsarsenbayev@student.unimelb.edu.au

[4]University of Helsinki, Helsinki, Finland, giulio.jacucci@helsinki.fi

ABSTRACT

Previous work has shown that large high resolution displays (LHRDs) can enhance collaboration between users. As LHRDs allow free movement in front of the screen, an understanding of movement behavior is required to build successful interfaces for these devices. This paper presents Pac-Many; a multiplayer version of the classical computer game Pac-Man to study group dynamics when using LHRDs. We utilized smartphones as game controllers to enable free movement while playing the game. In a lab study, using a $4m \times 1m$ LHRD, 24 participants (12 pairs) played Pac-Many in collaborative and competitive conditions. The results show that players in the collaborative condition divided screen space evenly. In contrast, competing players stood closer together to avoid benefits for the other player. We discuss how the nature of the task is important when designing and analyzing collaborative interfaces for LHRDs. Our work shows how to account for the spatial aspects of interaction with LHRDs to build immersive experiences.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; K.8.0. Personal Computing: Games

Author Keywords

Large high resolution displays, multiplayer, co-located, gaming, large tiled display, collaborative.

INTRODUCTION

With advances in computing power and display technology, large high resolution displays (LHRDs) and multidisplay environments have become affordable for manifold tasks. These displays support exploring all kinds of visual data [6, 26]. Furthermore, they enhance sense-making [3] and allow users to sort information faster than on smaller displays [29]. LHRDs provide the capability to be used by multiple users at once. This enables users to get more engaged in collaborative tasks, since all users observe the same perspective on the task and are able to discuss different views without the overhead of communicating new view points. Yet, as many tasks require users to switch between individual and group work, LHRDs must allow to support these transitions for effective management of space. For example, users observe or explore different subsets of a data set and discuss the connections between these subsets together. As games for LHRDs have recently been developed, understanding spatial dynamics in front of the screen emerges as a key consideration for building immersive game experiences. When working or playing on one LHRD, users have to negotiate for display space, while in collaborative periods they might share areas. Hence, user interfaces (UIs) for LHRDs should support both individual and collaborative working periods. So far analysis of multiuser behavior around LHRDs has been limited, therefore, we see a need for a fundamental understanding of user behavior in both periods.

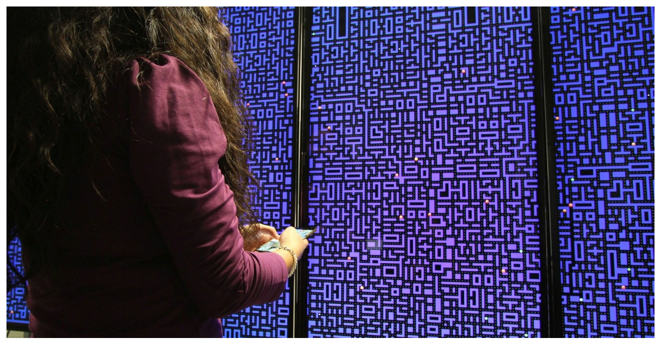

Figure 1. One player while interacting with the Pac-Many game.

To that end, we analyze behavior, movement and proxemics of pairs using an LHRD in *collaborative* and *competitive* conditions. Because of the high engagement in games, we designed Pac-Many, a multiplayer LHRD computer game, inspired by Pac-Man®. We used this game on a $4.02m \times 1.13m$ LHRD. We asked 24 participants (12 pairs) to play in collaborative and competitive game conditions. The results show different behavior and proximity patterns for the two conditions as pairs, spread in front of the screen in collaborative games, focused on the center of the screen in competitive games.

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The contribution of this paper is three-fold: (1) the design of Pac-Many, a multiplayer LHRD game; (2) an analysis of the movement patterns that revealed even distribution in space in collaborative and close disposition in competitive situations in front of an LHRD and (3) insights on enabling effective screen space management for collaborative applications on LHRDs.

RELATED WORK

This work is inspired by previous work on LHRD interaction, in particular; collaboration in front of LHRDs, territoriality, and games as research apparatus.

Benefits of LHRDs

Previous research has identified manifold benefits of larger display space and LHRDs. Ball et al. showed that users perform visual analytic tasks better when the display allows performing physical navigation [5, 7]. Rädle et al. [37] compared navigation techniques on a LHRD. Rädle et al. [37] confirmed Ball et al.'s [7] results, that users perform better when they can move in front of the display, instead of sitting in front of the LHRD. Furthermore, more complex tasks involving different kinds of data, like sense making, can benefit from LHRDs [2]. When users have to classify and sort information they benefit from the overview and the high level of details displayed on LHRDs [29]. Recently, von Zadow et al. [46] proposed focusing on playful interaction on LHRDs and designing games for such displays. Yet little is known about the interaction requirements for such games. Moreover, games can inform more generally on behavior on LHRDs, uncovering differences between competitive and collaborative situations.

Collaborative Work with Public Displays

Research has built an understanding of pair and group behavior around public displays [4, 36, 47]. Azad et al. [4] explored group behavior and formation in front of public displays. The authors analyzed group behavior in the wild as well as in the lab. Azad et al. [4] identified individual and public territories on displays. Further, Peltonen et al. [36] showed that public displays can foster social interaction between people. Wallace et al. [47] investigate collaborative touch screen interaction on an LHRD in a lab study in which pairs had to solve a jigsaw puzzle. Lastly Jacucci et al. [21] found that functionality is discovered gradually through collaborative learning in a public display scenario and further found that often the first contact with the LHRD is challenging for users. While these works explored different collaborative tasks, human-computer interaction (HCI) is yet to address how to build engaging playful experiences with LHRDs and leverage effective proximity-based interactions analogously to tabletop interfaces, e.g. [48].

Group interaction around tabletops has been explored in detail [23, 32, 38]. Scott et al. [38] identified personal territories for individual work, shared areas for collaboration and space for storing content when groups work on a tabletop. Marshall et al. [32] designed a tabletop for a tourist office and observed users in the wild. This in the wild study showed that interacting in another user's territory often leads to unsolvable conflicts. Klinkhammer et al. [23] indicated the personal territory to avoid conflicts. Tang et al. [39] analyzed group dynamics while interacting with an interactive tabletop. The results show that pairs stand closer together when cooperating. More recently, the focus has been shifting to pair and group behavior around vertical LHRDs in non-public settings [1, 22, 28]. Birnholtz et al. [10] showed that the input technique influences the collaboration. Based on an abstract classification task Liu et al. [28] analyzed five collaboration strategies with pairs of users. In a study participants used a motion-tracked controller to control the cursor. In contrast, Jakobsen and Hornbæk [22] used a data exploration task, involving different document types on a multitouch wall to analyze pair collaboration. The examples cited above all explored work-related tasks. This paper extends related work by developing a multiuser game. It focuses on uncovering differences in competitive versus collaborative situations that can inform both work and learning settings.

LHRDs Games

Besides collaboration, games for LHRDs are moving to the focus of research. Machaj et al. [30] presented PyBomber, a multiplayer game for LHRDs inspired by Bomberman. The game was designed for a 96-megapixel display and controlled with Nintendo Wii controllers. In a lab study, the authors investigated the effect of team size. The results of the study indicate less social interaction per person when playing with more players. Von Zadow et al. [46] proposed a multiplayer game for touch display walls. Toprak et al. [40] designed a game for wall-sized displays to motivate players to engage physically. Furthermore, previous research has explored games on public displays. O'Hara et al. [34] analyzed player behavior playing games on a public display. Grubert et al. [15] used the bring your own device approach in a public game to understand how people use magic lenses with public displays. These works show that large displays can offer a playful experience yet they do not address the question of how to instrument interfaces for an optimal screen sharing experience. Furthermore, past work indicates that further exploration of bodily play [25] and remote control [27] is required to build a better understanding of users can effectively interact with LHRDs.

Figure 2. A player pair standing in font of the LHRD engaging in Pac-Many while wearing the *mocap beanie hats* for position tracking.

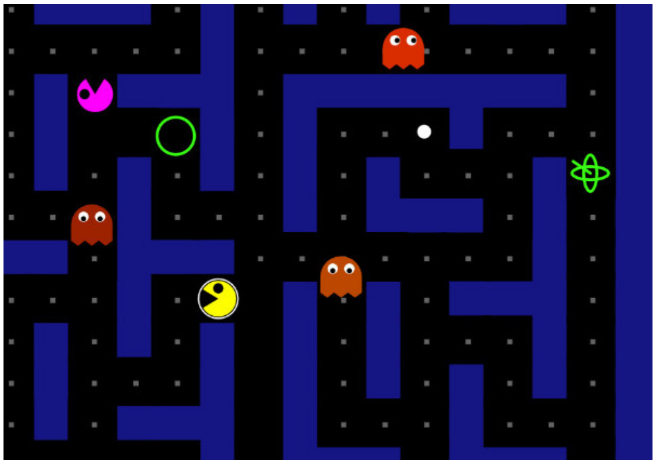
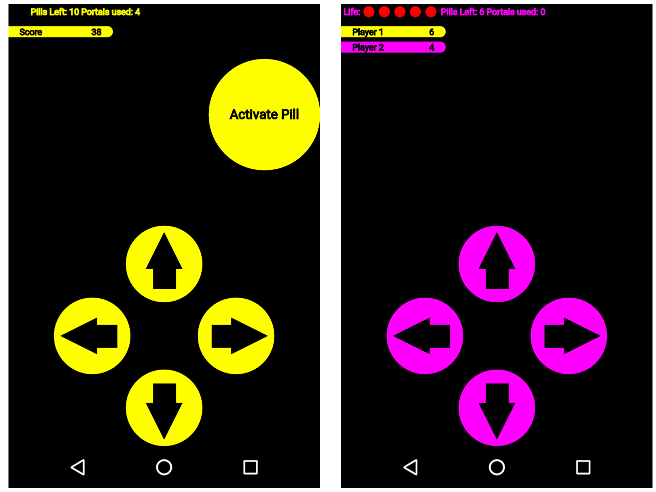


Figure 3. A visualisation of all game elements: the maze walls in a dark blue, the Pac-Men for the two players in magenta and yellow (the white circle around the yellow player indicates an active *Power Pellet*), three *ghosts* in shades of red, a blinking *Power Pellet*, a active *Pac-Portal* with the direction indicator, and a timed out *Pac-Portal* indicated by an empty green circle.



(a) Collaborative controller (b) Competitive controller

Figure 4. Two screenshots of the controller used for our study on a Nexus 5X. (a) shows the controller in the *collaborative* condition with a *Power Pellets*. (b) shows the controller in the *competitive* condition where each player has an overview over the independent game stats.

Territoriality and Proxemics

Hall [16] identified four distances for social interaction: intimate distance, personal distance, social distance and public distance. Further, Mueller et al. [33] extended these zones to scenarios where participants are out of sight but still in range to exchange radio signals. Research has utilized these distances for interaction with smart systems [9, 14, 31, 42]. Ballendat et al. [9] utilized them for interacting with a multimedia room. Marquardt et al. [31] implemented a toolkit enabling building proxemic interaction. Vogel and Balakrishnan [42] designed different interaction distances for interacting with public displays. It is, however, unknown how these findings translate to LHRDs.

Games as Research Apparatus

Von Ahn [43, 45] proposed using games to solve real world problems by having people engage in the games. In 2004 Von Ahn and Dabbish [44] labeled images using a two player game to solve an open problem using antilogarithms. Later Law and von Ahn [24] used a similar approach to label audio files. Vepsäläinen et al. [41] investigated ways to use public displays as a gaming canvas which enables solving real world problems on the go e.g. while waiting for a bus. On the other hand, previous work also proposes using games to understand how people interact with technology [17, 18, 19]. Henze et al. [18] used smartphone games to analyze touch behavior. Furthermore, games enabled a detailed understanding of typing behavior [19]. The utilization of games to explore user behavior is beneficial because participants easily engage in a game task. Consequently, our work uses a game to explore the spatial behavior when interacting with an LHRD.

PAC-MANY

Inspired by the original Pac-Man game from 1980 we propose Pac-Many, a multiplayer version designed for LHRDs. Similar to the single player version in Pac-Many players navigate their Pac-Man through a maze of *Pac-Dots*, *ghosts*, and *Power Pellets*. While the original maze is 28 tiles wide and 36 tiles tall, this is not sufficient to cover an LHRD. This needs to be adjusted to the display specifications to make use of the high resolution and the size of the display. In the following, we describe the game design and all game elements which are also shown in Figure 3.

To interact with the maze presented on the LHRD each player has a controller. As a controller, we propose using smartphones to facilitate the "bring your own device" approach [8]. The smartphones display a *D-pad* (short for digital pad); a four-way directional control with one button for each direction, similar to almost every game console controller, see Figure 4. The four buttons are then mapped to the movement directions of the Pac-Man.

Each player gets assigned a unique color. To identify which Pac-Man is mapped to which controller each Pac-Man is colored in the player's color. The buttons on the controller are also the same color, for the first identification and memorability, see Figure 4. All *ghosts* are colored in shades of red. Further whenever one player collects a *Power Pellet* an extra button appears on the controller which triggers the extra ability to be immune against *ghosts* for 5 *secs*.

We invented *Pac-Portals* to overcome large distances in the maze. *Pac-Portals* teleport player to another specific portal; a green line indicating the direction of the paired portal. *Pac-Portals* are bi-directional however after usage they are deactivated for 5 *secs*. We placed 6 pairs of bi-directional portals. The portals were equally distributed over the maze, and the distance between paired portals was at least one sixth of the screen width. All game elements are visualized in Figure 3.

The goal of the original Pac-Man was to collect all *Pac-Dots* with one game point each, and this can still be a game goal. However, with the large maze on LHRDs, the *Pac-Dot* count can easily be over 25,000. This can result in a very long playing time to achieve the goal. To keep the time to finish the game reasonable we propose a new game goal: to collect only a certain number of *Pac-Dots* and *Power Pellets* and use some of the *Pac-Portals*.

We further introduced two game modes to use the newly introduced multiplayer game Pac-Many: a collaborative and a competitive game mode. In the collaborative mode multiple players play as a collective to achieve the game goal. In the competitive game mode, the players compete with each other.

The Pac-Many source code is available under the MIT license[1] on GitHub[2].

GAME STUDY

The main goal of our study is to understand the group spatial dynamics, especially movement and proxemics, in a shared LHRD scenario. Therefore, we used Pac-Many, a multiplayer version of the classical computer game Pac-Man. We choose to use a version of Pac-Man as possible novelty bias is low and the game can as described be scaled to a large display. Further, due to the simplicity of the original Pac-Man introducing a multiplayer mode combined with collaborative and competitive modes can be achieved without complicating the game. We analyze how *collaborative* and *competitive* game conditions would affect movement and proximity patterns of the players. We used a display size which cannot, according to Lischke et al. [26] be comfortably viewed from one position. Hence, participants were required to perform physical movements to win the game.

Study Design

Our study used a within-groups repeated measures design. We used CONDITION with two levels, namely *collaborative* and *competitive*, as the independent variable (IV). During the study participants were asked to play Pac-Many. In the *collaborative* CONDITION players played together to accomplish the game goal, fight the ghosts, and thus gain one shared point count. In the *competitive* CONDITION the players played against each other with independent point counts. The order of the CONDITION was counterbalanced across all participant pairs. During the study, we constantly tracked the participant's physical positions and the screen position. We further asked participants to fill out the Social Presence Gaming Questionnaire (SPGQ) module [13] of the Game Experience Questionnaire (GEQ) [20] after each CONDITION. We further chose to record audio and video during the study as this could provide a more objective account of the movements than interviews, which are known to offer a subjective experience [12].

Apparatus

The hardware setup consisted of two smartphones, one motion tracking system, and six monitors. As smartphones, we used two Nexus 5X running Android OS (v. 7.0 Nougat). As tracking system, we used OptiTrack, a marker based motion capture system. The tracking system delivered the absolute position of the markers attached to the participant at $30\,FPS$. We calibrated the system as suggested by the manufacturer resulting in millimeter accuracy. Each participant got a hat with markers for position and orientation tracking, see Figure 2.

Six monitors were mounted next to each other in portrait orientation (see Figure 2). During the study, we used six $67.3\,cm \times 113.1\,cm$ 50" 4K Panasonic TX-50AXW804 monitors, which resulted in one $4.04\,m \times 1.13\,m$ display. The display, therefore, had a resolution of $12,960\,px \times 3,840\,px$ with a pixel density of $88\,PPI$.

We implemented the proposed multiplayer game Pac-Many as a Node.js application. The screen and the controllers connected to the application using socket.io for communication between the devices. The maze used in the study was 491 tiles wide and 144 tiles tall. The map size and ratio were needed to fill the full screen and to fit multiple players, resulting in a tile size of $7\,mm \times 7\,mm$. The enlarged maze resulted in 36,838 *Pac-Dots*. To cover the enlarged map evenly, we decided to add more *Power Pellets* (24) and more *ghosts* (100). In our study, we used only magenta and yellow as colors for Pac-Man for the two players. To lower the influence of ghosts on the movement patterns, ghosts' movements were randomized.

In the *collaborative* game condition, the team needed to collect 400 *Pac-Dots*, all 24 *Power Pellets*, use the *Pac-Portals* 12 times, and had 10 lives. To win the *competitive* game one player needed to accomplish half of the collaborative goal (200 *Pac-Dots*, all 12 *Power Pellets*, 6 *Pac-Portals*, and 5 lives).

Procedure

The participants were guided through the whole study by two researchers. When both participants arrived at our study room, we welcomed them and asked them to fill in a consent form as well as a questionnaire about their demographics. We then explained the procedure of the study. We first equipped them with *mo-cap beanie hats* which were used for the position tracking, see Figure 2. Afterward, we gave each participant a smartphone to interact with the game and time to get familiar with the controller and the game play. We then let participants play each condition for $20\,min$. After participants completed one CONDITION, we asked them to complete the questionnaires. Before the games started, the players had $15\,sec$ to locate their Pac-Man.

Participants

We recruited 24 participants (8 female) through our university's mailing list. The participants were aged from 20 to 36 years ($M = 24.6$, $SD = 3.88$). All of them had either no visual impairment or corrected to normal vision by wearing contact lenses. Four of the pairs knew each other beforehand. We provided a remuneration of EUR5.

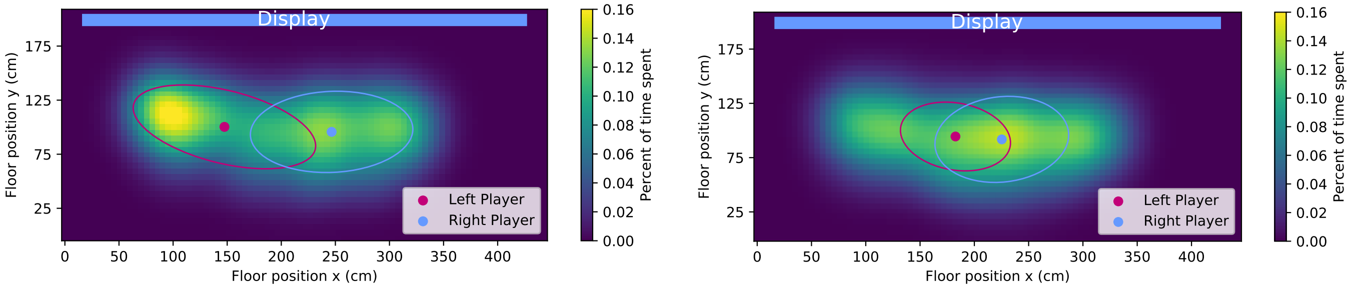
RESULTS

In total, we recorded $8\,h : 05\,min$ of game time in which participants played 65 games with an average game time of $7\,min : 28\,sec$. Each pair played on average $40\,min : 26\,sec$.

Engagement

We conducted Wilcoxon signed-rank test for all three dimensions of the Social Presence Gaming Questionnaire (SPGQ)

[1] opensource.org/licenses/MIT, last accessed: 2018-01-02
[2] github.com/interactionlab/pacmany



(a) Collaborative condition

(b) Competitive condition

Figure 5. The figures show the floor visualization in the *collaborative* and *competitive* CONDITION. We classified left and right player as the players which were more then 50 % of the time on the respective side of the display; the corresponding ellipses representing four times the *SD* oriented according to the distribution.

of the Game Experience Questionnaire (GEQ) to anayze the effect of CONDITION, see Figure 6. Our analysis revealed a significant effect of CONDITION on *Psychological Involvement Empathy* ($Z = 2.711$, $p = .007$) with *collaborative* $M = 2.49, SD = .66$ and *competitive* $M = 1.56, SD = .59$. Further, our analysis revealed a significant effect of CONDITION on *Behavioral Involvement* ($Z = 2.135$, $p = .0327$) with *collaborative* $M = 1.86$, $SD = .88$ and *competitive* $M = .89, SD = .55$. However, there was no significant effect of CONDITION on *Psychological Involvement Negative Feelings* ($Z = 1.683$, $p = .092$) with *collaborative* $M = .89, SD = .33$ and *competitive* $M = 1.33, SD = .77$.

Movements

All floor movements for both players are visualized for the *collaborative* condition in Figure 5a and the *competitive* condition in Figure 5b. We classified left and right player as the players who were more than 50 % of the time on the respective side of the display, see Figure 5.

Player-Player Distance

As Figure 5 indicated a difference in distance between players (player-player distance) we conducted a paired-sample t-test to compare player-player distance in the *collaborative* condition and the *competitive* condition. There was a significant difference between the *collaborative* ($M = 128.2\,cm$, $SD = 26.5$) and the *competitive* condition ($M = 100.3\,cm$, $SD = 16.$); $t_{11} = 4.357$, $p = .002$, see Figures 5 and 8.

As we had pairs in our study who knew each other we investigated if this had an effect on the player-player distance. Therefore, we conducted Wilcoxon signed-rank test with the mean player-player distance to anayze the possible effect of *known to each other* on the player-player distance. Our analysis revealed no significant effect of *known to each other* on *player-player distance* ($Z = .594$, $p = .552$) with *known* $M = 108.1\,cm$, $SD = 23.4$ and *not known* $M = 117.4\,cm$, $SD = 17.1$.

We further classified the player-player distance into the four interpersonal distance zones by Hall [16]: intimate, personal, social, and public zones, see Figure 8. We found that only 5.3 % of all movements in the *collaborative* condition fell into the intimate zones in contrast to 9.9 % in the *competitive* condition. Movements in the range between $46\,cm$ and $122\,cm$, the personal zone, occurred 37.6 % of the time in the *collaborative* condition and 59.6 % in the *competitive* condition. Participants had a distance within the social zone for 57. % of the time in the *collaborative* condition and 30.5 % in the *competitive* condition. None of the pairs ever had a distance within the public zone.

Since we found a significant effect of CONDITION on the player-player distance, we conducted 3 t-tests to investigate if the three zones by Hall [16] were used differently. There was a significant difference in the time spent with one zone for all three zones: intimate ($t_{11} = -3.358$, $p = .007$), personal ($t_{11} = -4.012$, $p = .003$), and social ($t_{11} = 4.621$, $p < .001$).

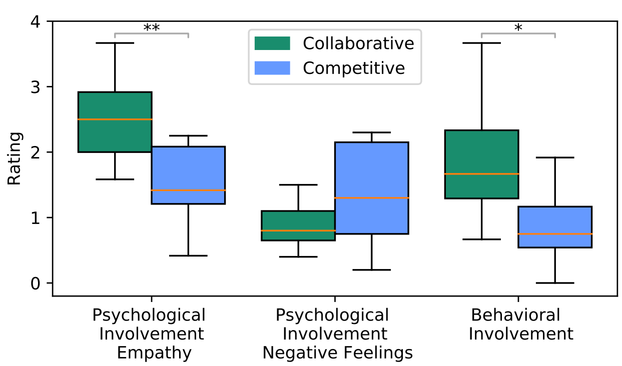


Figure 6. The Social Presence Gaming Questionnaire (SPGQ) results for the *collaborative* and *competitive* condition ($^{**}: p < .01$ and $^{*}: p < .05$).

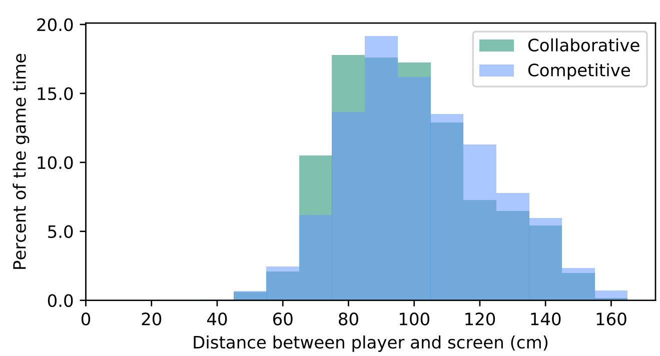


Figure 7. The graph shows the histogram of distance between the player and the display (player-display).

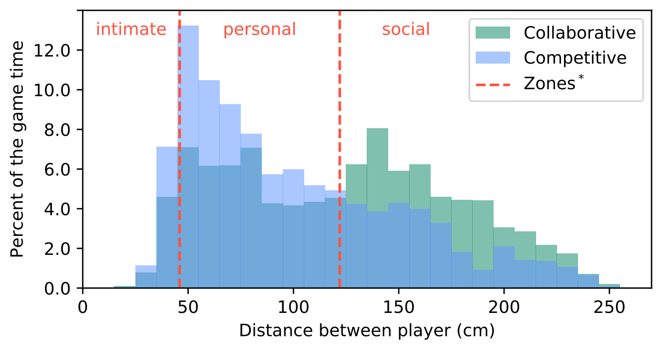


Figure 8. The graph shows the histogram of distance between players (player-player). * **interpersonal distances of man by Hall [16].**

Player-Display Distance

A paired-sample t-test was conducted to compare distance between the player and the display (player-display) in *collaborative* and *competitive* conditions. There was no significant difference between the *collaborative* ($M = 96.1\,cm$, $SD = 16.5$) and the *competitive* conditions ($M = 101.4\,cm$, $SD = 14.1$); $t_{11} = -1.614$, $p = .135$, see Figures 5 and 7.

Distanced Walked

A paired-sample t-test was conducted to compare walked distance per player in *collaborative* and *competitive* conditions. There was a significant difference between the *collaborative* ($M = 23.4\,m$, $SD = 11.6$) and the *competitive* condition ($M = 33.8\,m$, $SD = 9.1$); $t_{11} = -2.572$, $p = .003$.

Crossovers

A paired-sample t-test was conducted to compare crossovers in front of the screen in *collaborative* and *competitive* conditions. There was a significant difference between the *collaborative* ($M = 6.9$, $SD = 5.6$) and the *competitive* condition ($M = 14.6$, $SD = 12.$); $t_{11} = -2.454$, $p = .033$.

Head Movements

We further analyzed the head movements of the players. Since our first analyses revealed that the distance between the players in the two conditions was significantly different, we further investigated if head movements to the left/right (yaw) differed between CONDITIONS. Therefore we conducted a paired-sample t-test to compare the variance of yaw head movement per player in the CONDITIONS. There was a significant difference between the *collaborative* ($M = 13.9°$, $SD = 3.4$) and the *competitive* conditions ($M = 16.4°$, $SD = 5.3$); $t_{23} = -2.131$, $p = .044$.

DISCUSSION

Our work showed that whether users compete or collaborate on an LHRD significantly affects how they move in front of the screen. When designing games for LHRDs, this may create opportunities and challenges. Game designers can use our work to exploit spatial dynamics and reward players for effective collaboration, based on how they manage screen space. On the other hand, designers should be wary to place game content in ways that could cause occlusions and crossovers, thus possibly negatively affecting immersion. Our observations in the competitive conditions show that users are likely to invent strategies to hinder the other player's movement. This could be used as a playful game mechanic in competitive games e.g. to implement interruptible actions [11].

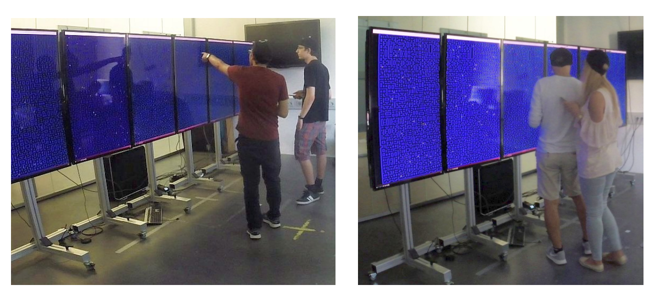
Perceived Engagement

Our results show clearly that the participants perceived the two conditions differently and, consequently, behaved differently during the two CONDITIONS. The results of the SPGQ show that participants felt more empathy and involvement in the *collaborative* condition. In contrast, participants reported having more negative feelings in the *competitive* condition. Overall, the results of the SPGQ revealed a deeper social engagement in the *collaborative* condition, than in the *competitive* condition. This indicates that the players discovered the advantage of playing together in the *collaborative* condition, while they competed against each other in the *competitive* condition.

Player-Player Distance

An analysis of the movement patterns revealed the behavioral differences. In the *collaborative* condition players shared the space in front of the display homogeneously. Furthermore, the lower number of crossovers in the *collaborative* condition indicates that pairs separate the screen into personal areas. In combination with the shorter covered distance, we can conclude that a player focuses more on one area in the *collaborative* condition, instead of playing on the whole display. Thereby, the players avoid relocating themselves in front of the display and reduce the physical demand. This approach of separating the screen space homogeneously is described in game theory as "Socially Optimal Solution" [35].

In the *competitive* condition, in contrast, the larger number of crossovers, the longest walked distance, and more head movement indicate that the players are trying to observe the whole display space over the whole match. Hence, this condition is physically more demanding than the *collaborative* condition. By having a shorter distance to the other player, each player tried to prevent benefits for the competitor. In game theory, this phenomenon is described as "Nash Equilibrium" [35]. Thereby, they do not use the display space as efficiently as in the *collaborative* condition.



(a) Helping (b) Blocking

Figure 9. On rare locations we observed helping and blocking behavior to gain benefits for the team or over the competitor.

Player-Display Distance

The distance between the players and the display (player-display distance) did not vary significantly between the two conditions. There could be a trend to stand closer to the display in the *collaborative* condition and further from the display in the *competitive* condition. This would allow the player to focus precisely on details in a smaller area in the *collaborative* condition. In the *competitive* condition the overview is more important, to restrict the competitor from collecting the game benefits. Hence, players tend to observe the display from a wider angle. However, the size of each game element is relatively small (approx. $7\,mm \times 7\,mm$). This small size underlines the benefit of an LHRD. On the other hand, it limits the viewing distance for a player to see all details.

Territoriality and Proxemics

We further categorized the player-player distance with the four distance zones by Hall [16]. We found that the time spent within each of the areas was different for all zones between the *collaborative* condition and the *competitive* condition. The difference in personal and social zones can be explained again through game theory since in our case the distance for "Nash Equilibrium" situations is within the personal zone, and the distance falls into the "Socially Optimal Solution" situations. Therefore, we consulted the video footage to understand the situations when pairs entered the intimate zone. We found crossings often shortened the distance into the intimate zone, and occurred more often in the *competitive* condition. However, we occasionally found that players came closer to the display to block the competitor's view. In blocking situations, the blocked person came closer than $46\,cm$ to see the screen (see Figure 7), and to get their own Pac-Man in sight again by looking around the blocking person, see Figure 9b. In contrast to the blocking behavior which only occurred in the *competitive* condition, we observed a helping behavior in the collaborative condition. Here one player often came close to the screen to point out locations of important game elements e.g the location of a *Pac-Dot*, see Figure 9a.

CONCLUSION

In this paper, we presented Pac-Many, a multiplayer game for LHRDs inspired by the classical computer game Pac-Man. Furthermore, we presented a lab study comparing the players' behavior in a collaborative and a competitive playing mode. The results show that the players were socially engaged in the collaborative condition and shared tasks in the game. Thereby the players minimized the physical effort and moved less in front of the display. In contrast, the competitive condition triggered physical action of the players.

The implementation of Pac-Many allows an arbitrary number of players to join a game. Furthermore, the game maze can be displayed on multiple distributed displays simultaneously. This allows us, in future work, to analyze the behavior of more than two players in front of one display. Furthermore, we will compare playing Pac-Many remotely to collocated play.

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REFERENCES

1. Ragaad AlTarawneh, Razan N. Jaber, Shah Rukh Humayoun, and Achim Ebert. 2015. Collaborative Position Patterns for Pairs Working with Shared Tiled-Wall Display Using Mobile Devices. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces (ITS '15)*. ACM, New York, NY, USA, 259–264. DOI: http://dx.doi.org/10.1145/2817721.2823490
2. Christopher Andrews, Alex Endert, and Chris North. 2010. Space to Think: Large High-resolution Displays for Sensemaking. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 55–64. DOI: http://dx.doi.org/10.1145/1753326.1753336
3. Christopher Andrews and Chris North. 2013. The Impact of Physical Navigation on Spatial Organization for Sensemaking. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (Dec 2013), 2207–2216. DOI: http://dx.doi.org/10.1109/TVCG.2013.205
4. Alec Azad, Jaime Ruiz, Daniel Vogel, Mark Hancock, and Edward Lank. 2012. Territoriality and Behaviour on and Around Large Vertical Publicly-shared Displays. In *Proceedings of the Designing Interactive Systems Conference (DIS '12)*. ACM, New York, NY, USA, 468–477. DOI: http://dx.doi.org/10.1145/2317956.2318025
5. Robert Ball and Chris North. 2005. Effects of Tiled High-resolution Display on Basic Visualization and Navigation Tasks. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*. ACM, New York, NY, USA, 1196–1199. DOI: http://dx.doi.org/10.1145/1056808.1056875
6. Robert Ball and Chris North. 2007. Realizing embodied interaction for visual analytics through large displays. *Computers & Graphics* 31, 3 (2007), 380 – 400. DOI: http://dx.doi.org/10.1016/j.cag.2007.01.029
7. Robert Ball, Chris North, and Doug A. Bowman. 2007. Move to Improve: Promoting Physical Navigation to Increase User Performance with Large Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 191–200. DOI: http://dx.doi.org/10.1145/1240624.1240656
8. Rafael Ballagas, Michael Rohs, Jennifer G. Sheridan, and Jan Borchers. 2004. Byod: Bring your own device. In *In Proceedings of the Workshop on Ubiquitous Display Environments at Ubicomp*.

9. Till Ballendat, Nicolai Marquardt, and Saul Greenberg. 2010. Proxemic Interaction: Designing for a Proximity and Orientation-aware Environment. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, NY, USA, 121–130. DOI:http://dx.doi.org/10.1145/1936652.1936676

10. Jeremy P. Birnholtz, Tovi Grossman, Clarissa Mak, and Ravin Balakrishnan. 2007. An Exploratory Study of Input Configuration and Group Process in a Negotiation Task Using a Large Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 91–100. DOI: http://dx.doi.org/10.1145/1240624.1240638

11. Staffan Björk and Jussi Holopainen. 2004. Patterns in game design (game development series). (2004).

12. Ann Blandford, Dominic Furniss, and Stephann Makri. 2016. Qualitative HCI Research: Going Behind the Scenes. *Synthesis Lectures on Human-Centered Informatics* 9, 1 (2016), 1–115. DOI: http://dx.doi.org/10.2200/S00706ED1V01Y201602HCI034

13. Yvonne A. W. De Kort, Wijnand A. IJsselsteijn, and Karolien Poels. 2007. Digital games as social presence technology: Development of the Social Presence in Gaming Questionnaire (SPGQ). In *Proceedings of the 10th Annual International Workshop on Presence*. 195–203.

14. Saul Greenberg, Nicolai Marquardt, Till Ballendat, Rob Diaz-Marino, and Miaosen Wang. 2011. Proxemic Interactions: The New Ubicomp? *interactions* 18, 1 (Jan. 2011), 42–50. DOI: http://dx.doi.org/10.1145/1897239.1897250

15. Jens Grubert, Ann Morrison, Helmut Munz, and Gerhard Reitmayr. 2012. Playing It Real: Magic Lens and Static Peephole Interfaces for Games in a Public Space. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '12)*. ACM, New York, NY, USA, 231–240. DOI: http://dx.doi.org/10.1145/2371574.2371609

16. Edward Twitchell Hall. 1966. The hidden dimension. (1966).

17. Niels Henze. 2012. Hit It!: An Apparatus for Upscaling Mobile HCI Studies. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM, New York, NY, USA, 1333–1338. DOI: http://dx.doi.org/10.1145/2212776.2212450

18. Niels Henze, Enrico Rukzio, and Susanne Boll. 2011. 100,000,000 Taps: Analysis and Improvement of Touch Performance in the Large. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)*. ACM, New York, NY, USA, 133–142. DOI:http://dx.doi.org/10.1145/2037373.2037395

19. Niels Henze, Enrico Rukzio, and Susanne Boll. 2012. Observational and Experimental Investigation of Typing Behaviour Using Virtual Keyboards for Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2659–2668. DOI: http://dx.doi.org/10.1145/2207676.2208658

20. Wijnand A. IJsselsteijn, Yvonne A. W. De Kort, and Karolien Poels. 2013. The game experience questionnaire. (2013), 9.

21. Giulio Jacucci, Ann Morrison, Gabriela T. Richard, Jari Kleimola, Peter Peltonen, Lorenza Parisi, and Toni Laitinen. 2010. Worlds of Information: Designing for Engagement at a Public Multi-touch Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 2267–2276. DOI: http://dx.doi.org/10.1145/1753326.1753669

22. Mikkel R. Jakobsen and Kasper Hornbæk. 2014. Up Close and Personal: Collaborative Work on a High-resolution Multitouch Wall Display. *ACM Trans. Comput.-Hum. Interact.* 21, 2, Article 11 (Feb. 2014), 34 pages. DOI:http://dx.doi.org/10.1145/2576099

23. Daniel Klinkhammer, Markus Nitsche, Marcus Specht, and Harald Reiterer. 2011. Adaptive Personal Territories for Co-located Tabletop Interaction in a Museum Setting. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '11)*. ACM, New York, NY, USA, 107–110. DOI: http://dx.doi.org/10.1145/2076354.2076375

24. Edith Law and Luis von Ahn. 2009. Input-agreement: A New Mechanism for Collecting Data Using Human Computation Games. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 1197–1206. DOI: http://dx.doi.org/10.1145/1518701.1518881

25. Lars Lischke, Sven Mayer, Jan Hoffmann, Philipp Kratzer, Stephan Roth, Katrin Wolf, and Paweł W. Woźniak. 2017. Interaction Techniques for Window Management on Large High-resolution Displays. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (MUM '17)*. ACM, New York, NY, USA, 241–247. DOI: http://dx.doi.org/10.1145/3152832.3152852

26. Lars Lischke, Sven Mayer, Katrin Wolf, Niels Henze, Albrecht Schmidt, Svenja Leifert, and Harald Reiterer. 2015. Using Space: Effect of Display Size on Users' Search Performance. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1845–1850. DOI: http://dx.doi.org/10.1145/2702613.2732845

27. Lars Lischke, Paweł W. Woźniak, Sven Mayer, Andreas Preikschat, and Morten Fjeld. 2017. Using Variable Movement Resistance Sliders for Remote Discrete Input. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA, 116–125. DOI: http://dx.doi.org/10.1145/3132272.3134135

28. Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, and Eric Lecolinet. 2016. Shared Interaction on a Wall-Sized Display in a Data Manipulation Task. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2075–2086. DOI: http://dx.doi.org/10.1145/2858036.2858039

29. Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, Eric Lecolinet, and Wendy E. Mackay. 2014. Effects of Display Size and Navigation Type on a Classification Task. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 4147–4156. DOI: http://dx.doi.org/10.1145/2556288.2557020

30. David Machaj, Christopher Andrews, and Chris North. 2009. Co-located Many-Player Gaming on Large High-Resolution Displays. In *International Conference on Computational Science and Engineering (CSE '09)*, Vol. 4. IEEE, 697–704. DOI: http://dx.doi.org/10.1109/CSE.2009.65

31. Nicolai Marquardt, Robert Diaz-Marino, Sebastian Boring, and Saul Greenberg. 2011. The Proximity Toolkit: Prototyping Proxemic Interactions in Ubiquitous Computing Ecologies. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. ACM, New York, NY, USA, 315–326. DOI: http://dx.doi.org/10.1145/2047196.2047238

32. Paul Marshall, Richard Morris, Yvonne Rogers, Stefan Kreitmayer, and Matt Davies. 2011. Rethinking 'Multi-user': An In-the-wild Study of How Groups Approach a Walk-up-and-use Tabletop Interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 3033–3042. DOI: http://dx.doi.org/10.1145/1978942.1979392

33. Florian Mueller, Sophie Stellmach, Saul Greenberg, Andreas Dippon, Susanne Boll, Jayden Garner, Rohit Khot, Amani Naseem, and David Altimira. 2014. Proxemics Play: Understanding Proxemics for Designing Digital Play Experiences. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 533–542. DOI: http://dx.doi.org/10.1145/2598510.2598532

34. Kenton O'Hara, Maxine Glancy, and Simon Robertshaw. 2008. Understanding Collective Play in an Urban Screen Game. In *Proceedings of the 2008 ACM Conference on Computer Supported Cooperative Work (CSCW '08)*. ACM, New York, NY, USA, 67–76. DOI: http://dx.doi.org/10.1145/1460563.1460576

35. Martin J. Osborne and Ariel Rubinstein. 1994. *A course in game theory*.

36. Peter Peltonen, Esko Kurvinen, Antti Salovaara, Giulio Jacucci, Tommi Ilmonen, John Evans, Antti Oulasvirta, and Petri Saarikko. 2008. It's Mine, Don'T Touch!: Interactions at a Large Multi-touch Display in a City Centre. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 1285–1294. DOI: http://dx.doi.org/10.1145/1357054.1357255

37. Roman Rädle, Hans-Christian Jetter, Simon Butscher, and Harald Reiterer. 2013. The Effect of Egocentric Body Movements on Users' Navigation Performance and Spatial Memory in Zoomable User Interfaces. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces (ITS '13)*. ACM, New York, NY, USA, 23–32. DOI: http://dx.doi.org/10.1145/2512349.2512811

38. Stacey D. Scott, M. Sheelagh T. Carpendale, and Kori M. Inkpen. 2004. Territoriality in Collaborative Tabletop Workspaces. In *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work (CSCW '04)*. ACM, New York, NY, USA, 294–303. DOI: http://dx.doi.org/10.1145/1031607.1031655

39. Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. 2006. Collaborative Coupling over Tabletop Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. ACM, New York, NY, USA, 1181–1190. DOI: http://dx.doi.org/10.1145/1124772.1124950

40. Cagdas 'Chad' Toprak, Joshua Platt, and Florian 'Floyd' Mueller. 2012. Bubble Popper: Considering Body Contact in Games. In *Proceedings of the 4th International Conference on Fun and Games (FnG '12)*. ACM, New York, NY, USA, 97–100. DOI: http://dx.doi.org/10.1145/2367616.2367628

41. Jouni Vepsäläinen, Petri Savolainen, Jouni Ojala, Antonella Di Rienzo, Matti Nelimarkka, Kai Kuikkaniemi, Sasu Tarkoma, and Giulio Jacucci. 2016. Web-Based Public-Screen Gaming: Insights from Deployments. *IEEE Pervasive Computing* 15, 3 (July 2016), 40–46. DOI: http://dx.doi.org/10.1109/MPRV.2016.60

42. Daniel Vogel and Ravin Balakrishnan. 2004. Interactive Public Ambient Displays: Transitioning from Implicit to Explicit, Public to Personal, Interaction with Multiple Users. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology (UIST '04)*. ACM, New York, NY, USA, 137–146. DOI: http://dx.doi.org/10.1145/1029632.1029656

43. Luis von Ahn. 2006. Games with a Purpose. *Computer* 39, 6 (June 2006), 92–94. DOI: http://dx.doi.org/10.1109/MC.2006.196

44. Luis von Ahn and Laura Dabbish. 2004. Labeling Images with a Computer Game. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*. ACM, New York, NY, USA, 319–326. DOI: http://dx.doi.org/10.1145/985692.985733

45. Luis von Ahn and Laura Dabbish. 2008. Designing Games with a Purpose. *Communications ACM* 51, 8 (Aug. 2008), 58–67. DOI: http://dx.doi.org/10.1145/1378704.1378719

46. Ulrich von Zadow, Daniel Bösel, Duc Dung Dam, Anke Lehmann, Patrick Reipschläger, and Raimund Dachselt. 2016. Miners: Communication and Awareness in Collaborative Gaming at an Interactive Display Wall. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces (ISS '16)*. ACM, New York, NY, USA, 235–240. DOI:http://dx.doi.org/10.1145/2992154.2992174

47. James R. Wallace, Nancy Iskander, and Edward Lank. 2016. Creating Your Bubble: Personal Space On and Around Large Public Displays. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2087–2092. DOI: http://dx.doi.org/10.1145/2858036.2858118

48. Paweł Wozniak, Nitesh Goyal, Przemysław Kucharski, Lars Lischke, Sven Mayer, and Morten Fjeld. 2016. RAMPARTS: Supporting Sensemaking with Spatially-Aware Mobile Interactions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2447–2460. DOI: http://dx.doi.org/10.1145/2858036.2858491