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# Photo4Action: phone camera-based interaction for graph visualizations on large wall displays

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**Abstract** We present Photo4Action, a system that integrates mobile devices and large wall display devices for efficient network visualization. Our work allows users to locate a region of a large graph visualization on a wall display by photo taking. An efficient match algorithm is proposed to match the subgraph users select with the full graph. Sets of interaction techniques have been designed to support various graph exploration and visualization tasks. The system also supports interactions for multi-users' collaborative analysis for graphs. We also report the interaction patterns and collaboration behaviors of users during the visual exploration as observed during our study

**Keywords** Mobile device · Interaction technique · Wall display

## 1 Introduction

Graph visualizations are applied in many areas, like social networks, visualizing people and their relationships. With the increasing size of graphs, however, regular displays are limited to the amount of information that can be shown. Many researchers take large wall displays as analysis environments since they can support exploration of large amounts of data (Marner et al. 2014; Horak et al. 2018; Badam et al. 2016 with both overview and details. Increasing the physical size and resolution of the display can significantly improve the quantity and breadth of insights acquired by users. Moreover, it is found that a

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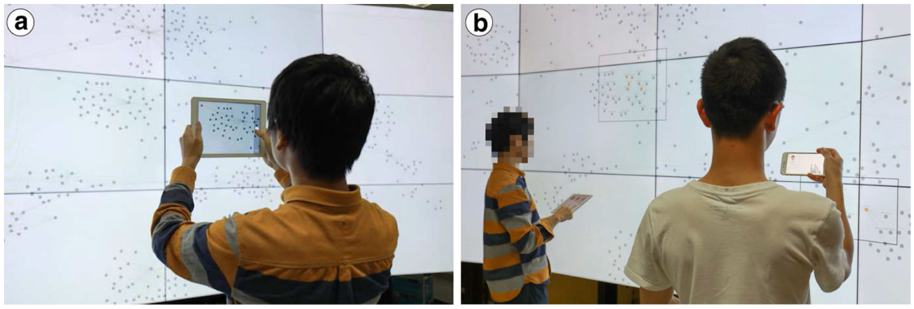

**Fig. 1** Photo4Action supports graph visualization exploration on the wall display through mobile devices. Users can take photo to select the subgraph (**a**) and explore details on mobile devices (**b**)

spatially larger visualization interface can improve user engagement and engender more effective exploratory behaviors (Reda et al. 2015).

Despite the fact that the wall display is superior to a standard desktop for visualizing large datasets, there are challenges in interactions with the wall display. Traditional input mechanisms on the desktop, mouse and keyboard require users to sit at a fixed position, which lacks natural interactions and intuitiveness. More, the mouse can hardly support accurate long-distance movements and small-object pointing (Bezerianos and Isenberg 2012).

In order to interact with large wall displays, researchers take mobile devices for their advantages of direct input capabilities via touch or movement of the device (Vogel and Balakrishnan 2005; Nancel et al. 2011; Kister et al. 2017). Mobile devices can also provide personal display space for multiple user collaboration scenarios. Only a few works have examined the use of mobile displays in combination with wall displays for information visualization (Kister et al. 2017; Langner et al. 2016; Horak et al. 2018). For example, Kister et al. (Kister et al. 2017) developed a prototype to help users interact with wall display with a mobile device. To help users determine their focus, they used a track system to calculate the pointing area of the device. As users move, the system will automatically track the mobile device and visual feedback on the wall display indicates the current region of interest.

Different from their tracking method, which requires additional hardware systems, we exploit the inherent function, i.e., camera to determine users' current focus area. Users can take a photo to select a rectangle focus region of the data (Fig. 1a). Then, the subgraph will be displayed on the mobile device and users can further explore the details (Fig. 1b). Although there are previous works (Ballagas et al. 2005; Boring et al. 2010; Chang and Li 2011) interacting with large wall displays by photo taking, we first introduce this method into graph visualization and propose an efficient matching algorithm to determine the focus area from the taken photo considering graph topology. It is free from extra equipment and much reduces the cost in the economic model of visualization by Jarke J. van Wijk (van Wijk 2005).

From a visualization perspective, we use different navigation methods to help users explore their focused subgraphs. Users can select nodes to explore them in detail with the context on the display walls. Modification of data like editing layout or annotations is also supported. We also consider multiple users scenarios where users can explore the different areas on the display or collaborate to finish path-related tasks in graph analysis.

In summary, we present an interaction technique called Photo4Action, to support easy focus area selection by taking a photo and fluent interactions with visualizations on large wall displays. To demonstrate the effectiveness of Photo4Action, we have conducted two user studies. The first quantitative study evaluates accuracy and time between camera-based pointing and mouse pointing. The second qualitative study reports participants' feedback and corresponding observations. The contributions of our work are as follows:

– We introduce the idea of photo taking to interact with graph visualization on a large wall display.
– We propose a graph matching algorithm to support selecting focus area efficiently.
– We develop an interaction system combining mobile devices and large wall displays to help exploration of graph data.

The remainder of this paper is organized as follows. We will first review related work in Sect. 2. In Sect. 3, technical details of Photo4Action will be introduced. The implementation and deployment of our prototype system are described in Sect. 4. The user study results are shown and discussed in detail in Sect. 5. At last, we conclude the paper with a brief review and discuss the future work.

## 2 Related work

In this section, we review related work about remote control, interaction with wall displays and graph exploration on wall displays.

### 2.1 Interactions with wall displays

Large high-resolution wall displays are now popular in industrial or academic areas for presentation to a large audience, more efficient collaborative work, or facilitating visualization of large and complex datasets. In these scenarios, traditional interaction methods mouse and keyboard over the desktop, which limit the users to a fixed position, cannot satisfy the requirements of users. More flexible and intuitive interaction methods are needed. In order to interact with the wall display, lots of interaction methods are proposed by researchers (Ardito et al. 2015).

Touch is one common interaction method, based on users' fingers or pens on the touchable screen surface to move, zoom, rotate or provide other types of input. For example, FI3D (Yu et al. 2010) is a direct-touch interaction system for 3D scientific visualizations. Users can control the view in 7 degrees of freedom with the combination of different gestures. Although touch is easy to learn and competitive in interaction speed, it is not suitable for wall-sized displays, which are too large for users to touch. Meanwhile, touch needs users to be close to the display which is bad for them to have the global view displayed on large wall displays.

Mid-air interaction applies gestures, postures and movements of users' hands or body to interact with distant displays (Koutsabasis and Vogiatzidakis 2019). Vogel and Balakrishnan (Vogel and Balakrishnan 2005) designed a system for pointing and clicking from a distance with a down and up gesture of the index finger. Furthermore, Nancel et al. (Nancel et al. 2011) differentiated two hands as the dominant hand and the non-dominant hand, which brings more complex interactions, like pan and zoom. It has been shown that movement of the user in front of wall displays improves user performance for navigating information spaces (Ball et al. 2007). Kister et al. (Kister et al. 2015) introduced a special kind of magic lens for large wall displays, called the BodyLens. User's distance to the display can change the size or position of the lens and their arm gestures can modify the shapes of lens. Although mid-air interactions are the most natural form, they are generally less efficient and more prone to fatigue than other methods (Nancel et al. 2011). Also, tracking devices and real-time image processing methods are necessary for their application.

Compared with previous methods, interaction with wall displays by using an external device comes with its own advantages. Besides direct contact with a wall display for pointing (Song et al. 2011; Dachselt and Buchholz 2009), mobile devices like phones or tablets can be used for navigation (Olwal et al. 2011), annotation (Tsandilas et al. 2015), setting parameters (Jansen et al. 2012), etc. Moreover, detailed information or selected parts of interest can be shown on mobile devices (Nancel et al. 2013; Kister et al. 2017). In our work, we employ mobile devices to interact with wall displays by taking photos. Although previous works (Ballagas et al. 2005; Boring et al. 2010; Chang and Li 2011) have used phone cameras for pointing, we first introduce this idea into interaction with visualization on wall displays. A corresponding matching algorithm is also proposed. Users only have to take a photo of the interested local region, and then they could interact with the wall display through manipulating the local visualization on the phone.

### 2.2 Interactive graph exploration

In this work, we focus on the exploration of a large graph on the wall display, combining the interaction advantages of mobile devices. There are many researches of graph navigation and exploration (Langner and Dachselt 2018; Lehmann et al. 2011) on large wall displays. They utilize sensors to locate the user's location and then the display shows different graph views according to the distance and head orientation. Besides the physical navigation methods, mobile devices can also help users with interactions. Spindler et al. (Spindler et al. 2010) add a mobile display to the usual desktop view for semantic zooming, a specific graph interaction. Cheng et al. (Cheng and Müller-Tomfelde 2012) distinguish mobile devices and large wall displays, the former one for the detailed views, while the latter one for the overview in a multi-user collaborative situation. Chegini et al. (Chegini et al. 2019) discuss the design space of interactions on the mobile devices to navigate the graph on the large wall display.

The most similar work to Photo4Action is the GRASP system (Kister et al. 2015). GRASP tracks the position and pointing of the mobile devices to control the wall display. Different interactions are designed to help user explore details of the graph on their local devices. However, Photo4Action does not need extra tracking equipment. It locates areas on the display by photo taking, which has very low requirements on the hardware.

In summary, we aim to make the combination of a large wall display and mobile devices with an efficient and economic way. The mobile device is not only as input, but a second display to show details of users selection. We apply the advantages of these devices to support a diverse tasks of graph analysis.

## 3 Photo4Action

For our method, users can walk freely in front of wall displays, perceiving the global view from a distance or stepping closer to focus on local details. When users are interested in a certain local region, and willing to deeply investigate data there, they just need to take a photo with the mobile device. In the camera view, users can further adjust the camera focus to narrow the focused area. After the photo is taken, nodes in the photo will be extracted and matched to the graph on the wall display. The matched subgraph will be rendered on the screen of the phone. Then users can start the exploration of their interested region flexibly by operations on their own mobile device.

### 3.1 System overview

The procedure of Photo4Action consists of three parts (Fig. 2). First, the graph data are preprocessed and the layout is calculated by the server. When all the calculations are finished, the server will transmit the layout message to the wall display to generate a graph visualization. Next, when users open Photo4Action on mobile devices, it will connect to the server node and register with a unique ID. After users take a photo of a region, the picture will be transmitted to the server, where the subgraph in the picture is detected and matched with the graph rendered on the display. The matched subgraph will then be transmitted back to the device and drawn. The layout of the subgraph will be consistent with the nodes' positions on the display wall. Finally, users can interact with the display by manipulating the local view on the device. In the following, we will introduce the subgraph matching algorithm and interactions in detail.

### 3.2 Subgraph matching

Different from previous work (Kister et al. 2017; Badam et al. 2016), which utilizes spatial-aware equipment to track the position of the users' focus, the wall display in Photo4Action detects users' intended focus by the photos they take. After users take a photo of an area on the wall display, the key is how to match the

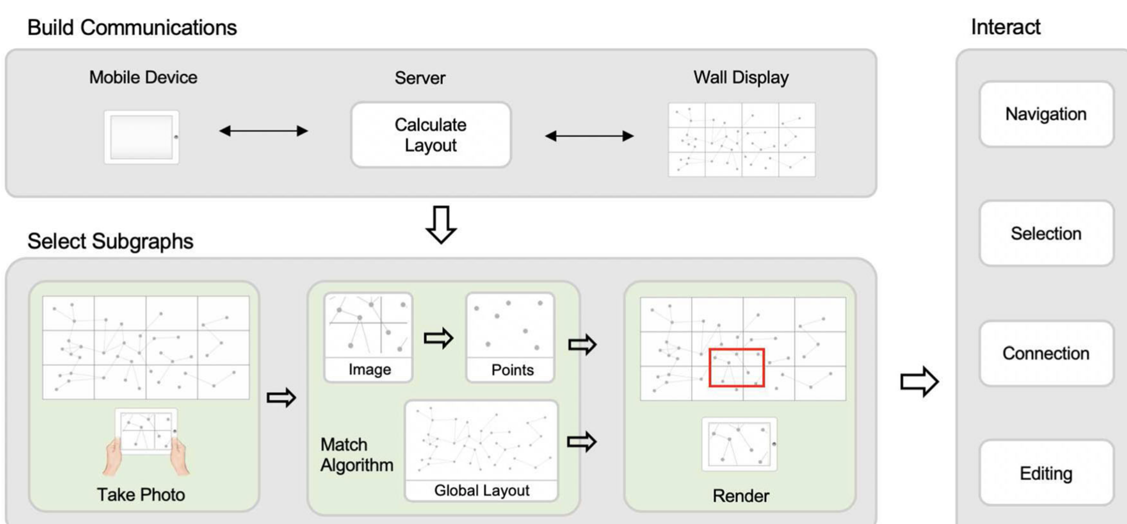


**Fig. 2** System overview. The system consists of three parts, visualization rendering on wall-sized display, local view selection by photoing, and interaction on display through the mobile device

area in the taken photo with its real position on the wall display. This is a common problem in the field of computer vision, called Image Registration, which transforms different sets of data into one coordinate system. Existing algorithms highly depend on the feature points extracted from image (Zitová and Flusser 2003), which are more suitable for information-intensive visualizations such as volume rendering and trajectory maps. These systems tend to occupy the whole screen with little blank space and therefore provide lots of feature points for image registration. On the contrary, visualizations such as graphs, scatter plots, and parallel coordinates are mostly formed by lines and points, lacking local features to extract. Moreover, in the large wall displays scenes, matching between the taken photo and the origin graph may face additional disturbances, for example, the borders of screens and Moire fringes (Gustafsson 2000). So we propose a layout-based graph matching algorithm, which is more robust.

After users take the photo, we first extract nodes from the image using Otsu's method (Otsu 2007) and circle Hough Transform (CHT) (Ioannou et al. 1999). Otsu's method assumes that the image contains only two classes of pixels, foreground pixels, and background pixels. It calculates the optimal threshold to separate the two classes of pixels so that an image can be turned into a binary image. In our case, however, when the user takes photos on the wall display at a close distance, Morie fringe would happen, which causes strange-looking wavy patterns in the image. Sometimes, the nodes in the image may become indistinguishable even for human eyes. To conquer the Morie effect and ensure the accuracy of detecting nodes, we adapt an erode-and-dilate step to amplify the nodes and eliminate noises. Once we separate all the nodes from the background and edges, CHT can be used to locate every single node in the image.

From the detection result, we can get the relative position of each node in the photo. However, it is hard to detect links of nodes in the photo as they are strips, similar to the borders of the screen and easily blocked by Morie fringes. Different from the traditional graph match algorithm that pairs the structure of node-link diagrams, our method directly matches the extracted nodes with the original full graph (Algorithm 1). The algorithm makes full use of the graphical layout information with the assumption that the user takes the photo directly against the screen with little rotation of the camera. Figure 3 illustrates the steps of the matching algorithm. It first selects two nodes in the subgraph and matches the two nodes. Two candidates in the full graph are selected, and then the full graph will be rescaled according to the length difference of the two lines. For the rest nodes in the subgraph, it is matched to the node in the full graph according to angle. Next, the distance variance of the match results will be calculated. The match result with the minimal error will be selected as the final result. To increase the efficiency of the algorithm, we preprocessed angles between nodes in the full graph. The complexity of the algorithm is O(MN), where M and N are the numbers of nodes in the full graph and subgraph, respectively.

Once the subgraph matched successfully, the matched nodes and their links will transmit to both the display and mobile device by the server. On the mobile device, since the matched nodes already have a layout on the wall display, we do not recalculate their layout. We only rescale the subgraph to fit the screen size of the mobile device. On the display wall, a rectangle box is shown to provide feedback on users' photo-taken areas (Fig. 1 b). The box size is calculated according to matched nodes, which guarantees the matched nodes inside the box. The tests show that the proposed algorithm has good accuracy and speed in the application, and the detailed results will be shown in the user study.

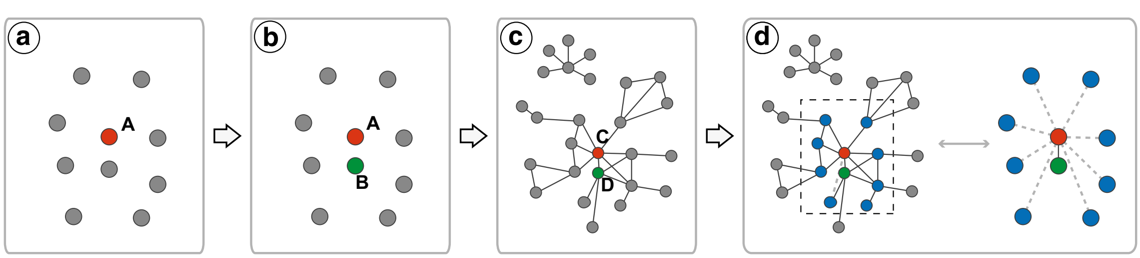


**Fig. 3** Graph match algorithm. **a** Select the centroid node in the subgraph; **b** Choose the nearest neighbor as an anchor; **c** Loop through the full graph to match the node pairs; **d** Match the rest nodes

**Algorithm 1** Graph Match Algorithm

**Input:**

The full graph $G_{full}$, with a list of nodes $T_i$, $i = 1,2...M$, $M$ is the graph node number, with id $T_i.id$
A list of nodes $V_i$ extracted from the image, $i = 1,2...N$, $N$ is the subgraph node number

**Output:**

A list of nodes $N_i$, with id $N_i.id, i = 1,2...K$

$N_a \leftarrow$ most center node of $N_i$
$N_b \leftarrow$ nearest neighbor of $N_a$
$angle_{ab} \leftarrow$ angle from $N_b$ to $N_a$
$dis_{ab} \leftarrow$ distance between $N_b$ and $N_a$
$error = DOUBLE\_MAX$
for $i = 0; i < M; i++$ do
    $current\_error = 0$
    $N_a.id = T_i.id$ ▷ Start the match process
    $T_c \leftarrow$ nearest neighbor of $T_i$ along direction $angle_{ab}$
    $dis_{ci} \leftarrow$ distance between $T_i$ and $T_c$
    Rescale the full graph by $dis_{ci}/dis_{ab}$
    $N_b.id = T_c.id$
    for $j = 0; j < N; j++$ do ▷ Match the rest nodes
        if $N_j == N_a$ or $N_j == N_b$ then
            continue
        end if
        $angle_{aj} \leftarrow$ angle from $N_j$ to $N_a$
        $dis_{aj} \leftarrow$ distance between $N_j$ and $N_a$
        $T_l \leftarrow$ nearest neighbor of $T_i$ along direction $angle_{aj}$
        $dis_{il} \leftarrow$ distance between $T_i$ and $T_l$
        $N_j.id = T_l.id$
        $current\_error += |dis_{il} - dis_{aj}|$
    end for
    if $current\_error < error$ then
        Save the current match result
        $error = current\_error$
    end if
end for

## 3.3 Interactions on mobile devices

After the focus view is selected, users can refine the selected area or explore the subgraph further on the mobile display. To obtain generalizable interaction techniques for graph exploration, accepted task taxonomies and frameworks are considered. Lee et al. (Lee et al. 2006) summarize a list of graph tasks, including topology-based, attributed-based, browsing, and overview tasks. To support these tasks, we simplify the interactions by Yi et al. (Yi et al. 2007) with three general techniques, i.e., navigation, selection, and connection. Editing on graphs is also supported.

### *3.3.1* ***Navigation***

Navigation helps users refine their selection area. After matching the selected area, the display shows a box as a hint of the current focus area. Users can further navigate on the display by the shown box. The box helps users refine the selection areas, free them from taking too many photos and relax their posture. Since the camera view is a rectangle, the navigation box is also a rectangle. Here, we provide common interaction gestures pan (Fig. 4 a) to move the box and pinch (Fig. 4 b) to scale the box. Also, we provide a widget to help users rotate the box to make navigation more flexible (Fig. 4 c). When users navigate on the device, the

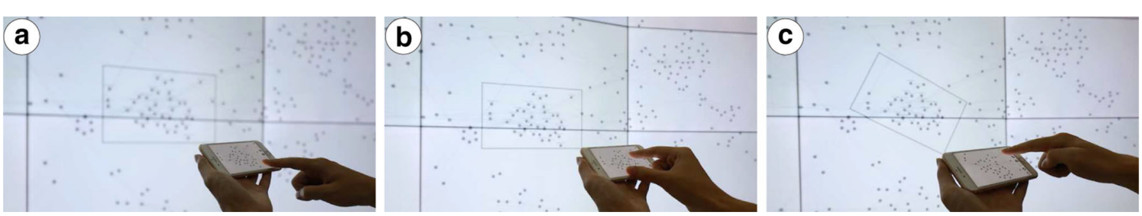


**Fig. 4** Users can pan, zoom, or rotate on the screen to further refine the focus area. **a** Fingers pan on the screen to move the selection area. **b** Two fingers pinch to zoom in/out the graph. **c** Extra widget is provided to rotate the focus

selection area on the display will be synchronized automatically. Users do not need to focus their attention on the mobile device and can walk freely before the display wall. With the navigation techniques, users can control the selected subgraph more precisely and quickly.

#### 3.3.2 Selection

As the users navigate different parts of the graph on the wall display, different techniques are designed to support the selection of nodes to check more details. Users can tap a node (Fig. 5a) or select groups of nodes by lasso (Fig. 5b). As only the local view is shown on the device, it is hard for users to explore the connectivity of nodes. We implemented a variation of the 'Bring & Go' (Moscovich et al. 2009) technique which pulls adjacent nodes in focus (Fig. 5c) after users long-press a node. Then, users can further investigate detailed information about these nodes. We do not change the layout of the graph on the wall display so that users can always have the global context in mind. Besides the above selection methods based on the graph structure, users can also select nodes according to their attribute values (Fig. 5d). A configurable attribute filter lens is provided to help users highlight nodes with certain attribute values or within a specific value range. After users select nodes by the above methods, these nodes will also be highlighted on the wall display.

#### 3.3.3 Connection

Connection refers to interactions used to highlight relationships between data items or show hidden data items (Yi et al. 2007). More information will display on the mobile device after users' selection. For example, in a co-author network, when a single node is selected, detailed information about an author, like the number of publications, co-authors is shown (Fig. 5a). For selecting a group of nodes, individual information is presented in a grid view (Fig. 5b). This view can also show summary information of selected nodes with different visualizations like scatter plots or parallel coordinates. While the wall display presents an overview of the graph topology, the mobile device changes to a second screen, showing a detailed view with more information about the selected nodes.

#### 3.3.4 Edit

Besides exploring the relationships of data items after selection, graph editing is also supported in Photo4Action. We divide editing into two categories. One is editing layout, and the other is attributes. For layout editing, users can drag a node to adjust its location or select a group of nodes and apply a predefined layout. For editing attributes, users can attach tags or comments to the nodes which is very important in co-located collaborative work. We have implemented two interaction modes in Photo4Action, namely local mode and global mode. Local mode allows users to adjust the local visualization in the mobile device without transferring the interaction message to the large wall displays, while global mode would transfer the message to large wall displays all the time, providing feedback at once after users interactions. Here, the mobile device is not only an output device, but also a personal input device, like a keyboard.

### 3.4 Multi-user collaboration

Photo4Action enables multiple users to work together in front of the display wall (Fig. 1b). We provide each user with an individual box with different marks to help them aware of their work areas and avoid overlapping with others. When one user explores his/her focused region, modification induced by other users will not affect the personal region. To better support the collaboration scenario, we set the scale of the visualizations like bar charts or scatter plots unified so that multiple users can better compare the detailed information of different nodes by juxtaposition alignment of their screens. Besides, special interactions are designed to support collaborative tasks. For example, it is time-consuming to find the shortest path between two nodes for one user since he/she has to locate two different areas when the two nodes are far away from each other. In the collaborative scenario, two users can tap two nodes, respectively, and the shortest paths between the two nodes will be highlighted on the screen, which can improve the analysis efficiency (Prouzeau et al. 2017). Our system can be further extended to other collaboration methods.

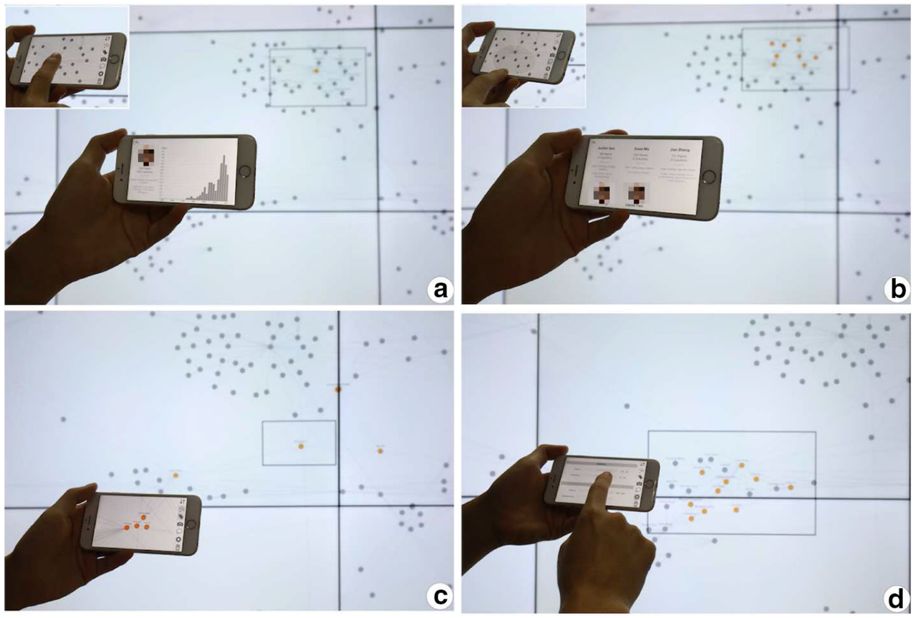


**Fig. 5** Different types of selection methods are supported. **a** Tap a node and show its details; **b** Select a group of nodes by lasso; **c** Select neighbors of nodes; **d** Select nodes within the data range

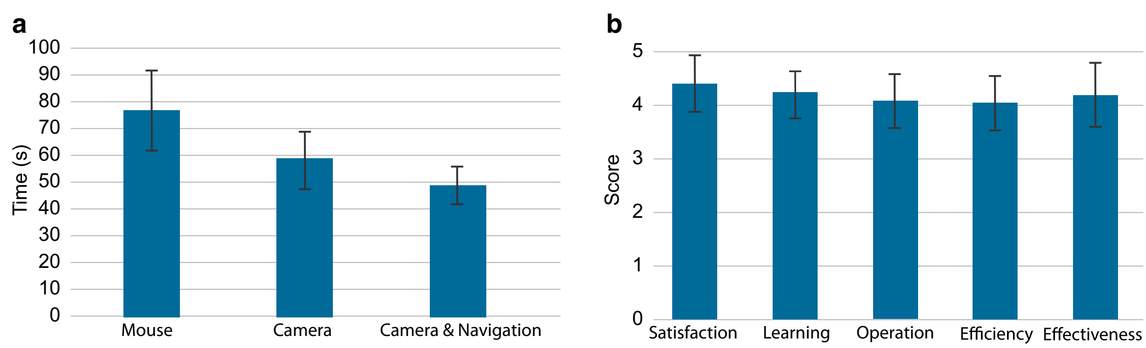


**Fig. 6** **a** Task complement time of the participants with different interaction methods. Error bars indicate the standard deviations. **b** Feedback of the questionnaires. Five criteria are evaluated by the participants

## 4 Implementation and setup

Our prototype was developed using D3.js (Bostock et al. 2011) as the basis for the user interface. We use WebSocket as the protocol to handle the communication for the wall display and mobile devices to the server. The display consists of 12 Samsung UD55E-B screens, 4.8 m in width, and 2.0 m in height, with a resolution of 7680 x 3240 pixels in total. All display contents are processed on 10-core Intel Xeon CPU, clocked at 2.40GHz, and with 8 NVIDIA M6000 graphics cards. We used iPhone 6 and iPad 4 as mobile devices with 8 and 5-megapixel cameras, respectively, in our study. Other smart mobile devices with WIFI function and camera can also work in our study. Users only need to install Photo4Action APP first and then connect to the same network with the server.

## 5 Evaluation

To validate the efficiency and usability of Photo4Action, we conducted a quantitative user study and the following qualitative study.

### 5.1 Efficiency study

In Photo4Action, users interact with the wall display through mobile devices instead of the mouse-based approach. In the first study, we aim to evaluate the camera-based interaction method about selection efficiency on the wall display since time performance is an important factor for the evaluation of a new interaction method (Olwal et al. 2008; Nancel et al. 2011).

*Participants and Apparatus* We recruited 12 participants (10 males and 2 females) between the age of 22 and 28 from different departments in the university. The mean age is 24. Among these participants, three have experience in graph visualizations. Our prototype system is deployed as described in the previous section. All participants use mobile devices daily but have little experience with large wall displays. The tasks are finished in the environment mentioned in Sect. 4. The wall display supports the mouse clicking on the screen.

*Tasks* The task is selecting a sequence of 20 highlighted nodes in a large graph visualization with different interaction methods. We choose selection efficiency to test as it is a basic step for the exploration of data in visualization. The graph contains 1606 nodes and 6503 edges. Each participant needs to select the highlighted node with the required interaction methods. We compare three different interactions, i.e., "Mouse", "Camera", and "Camera & Navigation". In the "Mouse" mode, participants are only equipped with a mouse to control the movement of the cursor on the screen and click the mouse to select nodes. In the "Camera" mode, participants can take photos and tap nodes on the screen of the mobile device. The navigation functions are forbidden in this mode. In the "Camera & Navigation" mode, participants can freely take photos or navigate to locate the highlighted nodes. We test the three methods because Mouse is the most basic way to interact with the wall display and it is easy to test. Moreover, we want to understand the roles of navigation techniques in the selection of nodes on the wall display. Each participant is required to finish the task with the three different interaction methods, respectively. In each task, the highlighted nodes appear randomly on the wall display. The order of interaction methods is counterbalanced.

*Procedure* In the beginning, participants are required to complete a background questionnaire. Then we provide a tutorial on Photo4Action. After the explanation, participants are free to interact with the wall display through mouse or Photo4Action. This part takes around 20 minutes. During the practice, we encourage participants to think aloud and ask questions.

After getting familiar with the display wall and interactions, participants perform the tasks in different modes. In each mode, when participants are ready, they click the "start" button on the display or tap it on the screen to begin the task. After finishing the task with one mode, the system will record the time cost automatically. In 'Mouse' mode, participants sit in front of the center of large wall displays with 2.5 meters away. The cursor of the mouse is placed on the center of the screen. In other modes, participants stand at the position that is 2 meters away from the center of large wall displays at the start of a task, but can walk freely then. After participants select the highlighted node successfully, the next highlighted node will appear on the screen at once. If participants cannot select the required node in 1 minute, the node will be passed. After participants finish the task with one mode, they will have 5 minutes to relax. The entire study lasts around 30 minutes for each participant.

*Results* All participants can finish the tasks with different interaction modes in the study. Figure 6a shows the results of task completion time with different interaction methods. It shows that the camera-based interaction methods are superior to the mouse-based interaction. Participants can select nodes more quickly with Photo4Action, especially in the 'Camera & Navigation' mode. After analyzing their interaction histories, we identified that some participants could not find the location of the mouse cursor for a long-distance movement on the screen, which took them extra time to locate. Sometimes participants need to pick up the mouse to return to the start position in order to have enough movement distance. With Photo4Action, some participants preferred to take a photo of a large area. However, too dense nodes are shown on the screen, which is hard to select the target node directly. Sometimes, Photo4Action failed to locate the correct area in the photo, and participants would do extra times of photo taking. In the 'Camera & Navigation' mode, participants preferred to pan or zoom on the screen of the mobile device to select the next target node if it was near the currently selected area. With the navigation techniques, participants can select nodes more flexibly, which improves the interaction efficiency with the wall display.

This study proves that Photo4Action has advantages over the mouse for selection of nodes on the display wall. The navigation techniques can further improve the efficiency of selection.

### 5.2 Usability study

This study is to evaluate the usability of Photo4Action for large graph exploration on the wall display. In this study, participants use Photo4Action in the 'Camera & Navigation' mode. The dataset is a co-author network with 2452 nodes and 3865 edges. Each node represents an author with attributes including affiliation, publication number, papers. Each edge represents the collaboration between two authors. We recruited the same participants in the previous study. They were required to explore the dataset and finish three types of tasks. *Topology* Participants are required to investigate the collaboration of the given two authors. They need to answer when the two authors started collaboration and how many papers they have co-authored. *Attribute* Participants need to compare the difference of publication in topics and time of the given two authors. They have to explore the research topics and publication trend of each author. *Overview* Participants need to find the largest cluster in the co-author graph. We summarized the participants' behaviors and extracted interesting observations.

*Observations* Participants were very successful in solving the given tasks. They often started the task by taking a photo of the region interested. For photo taking, some participants prefer to adjust the camera view to get their satisfied area, while other participants directly take a photo of the target area and then further adjusted the selection by the navigation techniques. All participants switched their focus between the mobile device and wall display frequently, especially for topology-based tasks, as they need to watch the context of the target node in the whole graph. There are different patterns for participants' distances to the wall display. Most participants naturally resided at their individual neutral distances (approx. 2 m from the display wall), which seemed to be their comfortable position. They moved parallel to the wall display and take photos of different target areas according to tasks. Two participants were consistently at a distance of approx. 3.5 m from the display wall. They only took photos to get the selection box at the beginning of the study. Then, they rarely moved and only adjust the position of selection box by navigation for the following tasks. However, it often took them much time to locate the target task areas. All participants can use the interaction techniques without others' help. In particular, they can solve the topology-related tasks by the 'Bring & Go' method.

In summary, Photo4Action could be used by the participants to finish these graph exploration tasks, which are independent of position and movement in front of the display wall. It is natural for participants to explore graph details on their personal devices and get the large context from the wall display during the study.

### 5.3 Feedback

After participants finished the two studies, they rated Photo4Action on five satisfaction criteria using a five-point Likert scale. Figure 6b indicates that participants were satisfied with the system and thought Photo4Action was easy to learn, operate, and helpful for large graph exploration on the wall display. Along with the user studies, participants were interviewed about the pros and cons of the system. Most participants felt that interaction with the wall display through the phone camera is novel and it is more efficient than the mouse. Several participants commented: "*The interaction on the mobile platform is simple but convenient for the specific graph tasks*." "*Photo for selection is far more user-friendly than the mouse, although precision still remains to be improved. The system can further support multi-user collaborations*". These can be good resources for proposed improvements in the future.

## 6 Discussion

Photo4Action combines the advantages of mobile devices and large wall displays. The wall display provides much more space for visualizing much information, while mobile devices enable more flexible input capabilities beyond mouse and keyboard. Compared with previous work, Photo4Action provides an easy and convenient method to build communications between mobile devices and wall displays by photo taking.

No extra tracking systems are needed and the camera-based method can be easily set up and extended to other visualization scenarios. The multiple devices enable different levels of views shown. However, users need to switch their attention between different screens, which may lead to additional focus and cognitive load for tracking changes. Therefore, consistent and clear feedback are needed to reduce these efforts.

In Photo4Action, after users take a photo of an area on the display, we get the match result by visualization features in the photo. Although there are lots of image registration algorithms in computer vision, they are not robust in the visualization scenario. On the one hand, screen borders or moire fringes can be easily taken as lines, which are common visualization elements. One the other hand, visualizations on the display are not static images and change with user interactions. All these make the accuracy of image registration methods not acceptable. In our approach, we extract nodes from the photo and get the focus area according to the relative positions of nodes. One limitation of our method is that if users only take a very sparse area with few nodes inside in, it’s hard to match the nodes in the whole graph since limited information of nodes is given. In practice, the display is rendered with a big graph, which takes most areas on the display. If users are only interested in a very small dataset, they can take a larger area first and then zoom in to refine their selection. Other match algorithms can be further considered, for example, by tags on the visualization.

In our current version, only limited interactions are designed to solve graph exploration tasks. Taking these interactions as the basis, further investigations could enrich graph exploration by allowing more diverse interactions and views. The mobile device works as a personal toolbox for graphs and thus enable independent parallel work on the same context visualization without disturbing other collaborators. However, the current system does not prevent editing conflicts and further extension is required. For multi-user collaboration, more interactions could be investigated to support more diverse cooperation. For example, users often need to share findings with each other in collaborative scenarios. Interaction supporting directly sharing screen interface to others would be effective.

For evaluation, we compare our approach with traditional mouse interaction by the selection of nodes on the wall display. However, the study only requires the user to select one node at a time. Tests like selecting a group of nodes may bring different findings. For the usability study, we only report participants’ behaviors with the given tasks. It remains to further investigate how these techniques can help analyze other real-world datasets. Also, other interaction techniques such as touching, gazing, and gestures are not compared with our method due to the limit of hardware.

## 7 Conclusions

In this paper, we present Photo4Action, a set of interactive techniques for graph visualizations that combine a large wall display and mobile devices. Photo4Action supports users to select areas of interest on the wall display by photo taking. An efficient algorithm is proposed to match the selection area by the layout of the subgraph inside. Users can explore the large graph on the wall display with local interactions on mobile devices. The mobile devices also serve as an additional view to show details of the selected subgraph. The current user studies demonstrate that Photo4Action is more efficient than traditional mouse interaction and effective for large graph exploration on the wall display.

In the future, we plan to improve the matching algorithm and apply it to other data types and fields of visualizations. Furthermore, we would like to provide more functions to support multi-user scenarios and enrich the interaction techniques on mobile devices to provide a more convenient analysis of data visualization.

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