Investigating Multi-Touch and Pen Gestures for Diagram Editing on Interactive Surfaces

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ABSTRACT

Creating and editing large graphs and node-link diagrams are crucial activities in many application areas. For them, we consider multi-touch and pen input on interactive surfaces as very promising. This fundamental work presents a user study investigating how people edit node-link diagrams on an interactive tabletop. The study covers a set of basic operations, such as creating, moving, and deleting diagram elements. Participants were asked to perform spontaneous gestures for 14 given tasks. They could interact in three different ways: using one hand, both hands, as well as pen and hand together. The subjects' activities were observed and recorded in various ways, analyzed and enriched with think-aloud data. As a result, we contribute a user-elicited collection of touch and pen gestures for editing node-link diagrams. The study provides valuable insight how people would interact on interactive surfaces for this as well as other tabletop domains.

Keywords

Multi-touch, hand gestures, pen interaction, bimanual input, tabletop, diagram editing, node-link diagrams

INTRODUCTION

Graphical models, networks and structure diagrams play an ever increasing role for activities such as data and software modeling, business process modeling or project management. Looking at entity-relationship diagrams, UML models, or other modeling notations, we can observe that most of them are represented as graphs or node-link diagrams. In general, they are used for understanding, designing and communicating. Therefore, they are frequently edited in collaborative settings and are constantly altered and evolving [5]. Interactive surfaces such as electronic whiteboards or multi-touch tabletops lend themselves for supporting crucial activities such as creating, editing, navigating, and discussing large diagrams. However, their potential has not been fully exploited yet.

Up to now, on the one hand, there exist structural editors to edit diagrams which employ traditional user interface techniques to create diagrams in formal notations. However, in domains such as software development these editing tools are often conceived as constrictive and inflexible [6, 10]. Screen space is often insufficient for huge graphs, navigation techniques are limited to simple zooming, and interaction techniques are relatively poor, e.g. by means of drag and drop interaction of elements from a toolbar. On the other hand, there are many situations where diagrams are sketched, often in collaborative settings on whiteboards or flip charts. There often exists the problem that the produced diagrams have to be captured and remodeled in digital tools which is a tedious process.

Electronic whiteboards try to solve these problems and offer digital techniques such as rearranging, grouping or scaling elements. However, they mostly support pen-only interaction. Instead, in our work we suggest and investigate surface computing with a combination of multi-touch and pen input for diagram editing as a novel tabletop domain with great potential. Thereby, multi-touch enabled tabletops allow for improved diagram editing and navigation, whereas added pen input suggests itself for sketching elements, annotations and hand-writing. We expect that these interaction techniques are able to make diagram editing more efficient and effective.

To our knowledge, we are the first to address the mentioned domain on interactive tabletops. As part of our fundamental work in this field we conducted a qualitative user study investigating how participants suggest their favorite gestures for a set of given diagram editing tasks. For that, they had the choice of using multi-touch with one or two hands and combinations of hand and pen input. As a result, we contribute a user-defined collection of gestures for 14 basic diagram editing tasks and discuss feedback gathered during the study.

The remaining paper is structured as follows. A section on related work will precede the detailed description of the study and its results. Thereafter, the results are discussed. The analysis of 658 recorded gestures gave valuable insight into the participants' behavior and applied mental models. The following conclusion again emphasizes the need to study such fundamental tabletop interaction techniques for particular domains and to generalize results to others.

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RELATED WORK

Digital diagram sketching

Various tools exist for sketching with augmented digital functionality such as copy, paste, scaling elements etc. In [15] several pen interaction techniques for electronic whiteboards are presented. They are domain-independent and also cover the recognition of node-link diagrams. Especially in the domain of software development, there are several tools such as [6], [10] or [4]. These digital diagram sketching tools run on pen-enabled whiteboards or Tablet PCs and convert sketches to formal notations such as UML. Beyond that, several studies have been conducted to investigate how software designers use whiteboards for diagram sketching [6, 5, 7]. As a result, design principles for digital sketch applications were concluded. However, to our knowledge, the combination of multi-touch and pen interaction has not been studied yet in the domain of diagram sketching.

Multi-touch and pen-based tabletops

In the past years, various multi-touch enabled tabletops and other surfaces have been introduced with approaches using computer vision [12] or capacitive technology such as DiamondTouch [8] and SmartSkin [17]. Flux [13] is a tabletop supporting multi-touch and pen input together and can be tilted to horizontal, vertical and slanted positions. For the study presented here and the ongoing project we are using a similar tabletop design. Another vertical-only solution is INTOI [1], including the capability of pen and hand gesture recognition.

Touch and pen gestures for tabletops

With the aforementioned technologies it is possible to detect multi-touch gestures. Gestures for SmartSkin are proposed in [17]. They cover panning, scaling, rotating, and picking up objects and can also be recognized above the table due to capacitive technology. In [21] a set of finger and whole-hand gestures for multi-user tabletops is presented. It is used within a furniture application and includes gestures for rotating, collecting objects, and for private viewing. Wu et al. [22] describe design principles for gesture design and built a prototype of a publishing application to illustrate the usage of their principles. Other research on gestures was done by Malik et al. [14]. They present gestures for a touchpad to control a wall-sized display. Beyond that, gestures employing the whole hand and their usage on interactive surfaces can be found in [18] and [3].

The combination of pen interaction and single touch is investigated in [23]. Beyond that, the usage of digital pens and multi-touch on tabletops has been studied in Brandl et al. [2]. Both approaches consider Guiard's Kinematic Chain Model [11], which proposes principles for asymmetric bimanual interaction and assigns different roles to hands. The dominant hand moves within the frame of reference set by the non-dominant hand, the non-dominant hand precedes the dominant hand, and the dominant hand performs more precise actions.

However, all these approaches present gestures designed by experts. In contrast to that, there are study designs to elicit input from users, as described by Nielsen [16]. In their work, Epps et al. [9] and Wobbrock et al. [20] use a similar approach for user studies. The latter applies a study design to develop a user-defined set of general one-hand and two-hand gestures and presents a respective taxonomy. For the user study presented in this paper, we employ a similar approach to [20], but investigate both touch and pen interaction for a particular tabletop domain.

USER STUDY

To introduce multi-touch gestures on tabletops into the domain of diagram and graph editing, we decided to apply a user-centered design approach. Therefore, we first conducted a qualitative user study to get a deeper understanding of how users would edit node-link diagrams on a tabletop system by means of gestural interaction. Our goal was to involve the users right from the beginning and to learn from their way of accomplishing particular tasks. The results shall then be used to develop an essential gesture set for this domain, which serves as a starting point for future research.

We expected the user-elicited gestures to depend on previous knowledge, available devices and known tools. As stated in the introduction, there are basically two typical approaches for node-link diagram editing. On the one hand there is *diagram sketching*. This means, diagrams are sketched freely on paper or whiteboards by using pens. Thereby, users do not necessarily follow a particular graphical standard. They often prefer informal ad-hoc sketches [5]. On the other hand diagrams are edited with digital modeling tools. Their interface is predominantly based on mouse input and the WIMP interaction style. Typically, users can drag elements from a tool palette and arrange them in a workspace. The node-link diagrams created in that way conform to semantic rules of the respective visual language. This is what we call *structural diagram editing*. These modes are not orthogonal, i.e., they can also be combined.

Before conducting the study, we considered the following preliminary aspects. We supposed that both aforementioned approaches are quite dominant in the users' mental models and that users will mainly refer to corresponding operations and methods. Therefore, we wanted to support both approaches by considering pure touch interaction (rather for *structural editing*), pen input (rather for *sketching*), and the combination of touch and pen. Based on these considerations, we wanted to clarify the following questions: What is the nature of the gestures performed by the participants? Will there be a high level of agreement between users for certain gestures and tasks? Will gestures be sufficiently distinguishable for all tasks? For which tasks will bimanual interaction be the preferred solution? Will the pen be used in combination with the non-dominant hand and for which tasks?

Method

Our user study employs a similar design to Wobbrock et al. [20]. However, our goal was not to come up with an unambiguous user-defined gesture set without conflicts, but to involve the users in the design process of a particular domain as early as possible. Our study uses a within-subjects design. Every participant was asked to complete 14 basic editing tasks in a fixed order. Overall, the tasks were from the following categories: creating, deleting, selecting and moving elements, changing the type of an edge from solid to dashed, scaling and copying nodes or parts of diagrams. For a detailed description of the tasks please refer to Figure 3 or to the first column of Table 1. This list of tasks is not intended to be exhaustive, e.g., specific semantic dependencies between elements or complex editing operations are not considered. However, we believe this set of tasks to be a good starting point, since it includes all important basic task types reaching from simple direct manipulation (e.g., moving a node) to complex abstract tasks (e.g., copying a sub-graph).

In order to produce results being applicable to a variety of modeling notations and diagram types, we used an elementary variant of node-link diagrams abstracting from particular notations (see Figure 1 for an example). A node is represented by a rectangle and can be resized and repositioned. A link (or edge) always connects two nodes and can either be directed (with arrow head) or undirected. Two link types, solid or dashed, are supported as examples. Nodes connected by links form a graph or node-link diagram; a part of it is called a sub-graph.

Participants

Seventeen right-handed participants (all male, aged 23 to 34) volunteered for the study. Except for three upper grade students, they were employees of the computer science department with a solid background in software engineering. The participants were not professional every-day modelers, but they knew digital modeling tools such as UML editors. Nobody had deeper knowledge in UI or interaction design. Eight of them stated that they regularly use smartphones with touch or pen input, one of them owned a multi-touch iPhone. In addition, none of the participants used a tabletop display before.

Apparatus

The tabletop display used for the study has a resolution of 1280x800 pixels placed on a screen of 100x80 cm in size; it uses Frustrated Total Internal Reflection [12]. An application was developed to present the 14 tasks on the display and to log the points of hand and pen contact on the surface. Beyond that, we captured the performed gestures with a video camera from above the table (see Figure 1) and with the vision system of the tabletop from underneath. For pen gestures, we used digital pens equipped with an IR light source, which can be detected by a tabletop camera. Beyond the digital capturing, two observers took notes during the procedure to log participants' think aloud comments.

Procedure

At the beginning of each session, participants were asked to fill out a questionnaire concerning demographic data and their previous experiences. Afterwards, the appearance of the node-link diagrams and the structure of the tasks were explained to the participants. Before solving each task, a short verbal explanation was given, e.g. "This task is about selecting a group of nodes". For each task, the tabletop display was horizontally split in two areas. The lower area displayed a diagram in the starting situation of the respective editing procedure, the upper area in its final state. The participants were then asked to perform spontaneous gestures in the lower area of the display which could lead from the starting to the final situation. Thereby, they stood in front of the tabletop and received no feedback from the display.

For every task, participants performed gestures with three different interaction techniques: with one hand (whereby they could use all fingers of the hand), with two hands and with pen and hand in combination. For the latter, it was free to use just the pen or to support the pen gesture with the non-dominant hand. Furthermore, each subject was asked to start with the variant he or she considered as most suitable to fulfill the respective task. Thereafter, gestures had to be performed with the two remaining interaction techniques, depending on their first choice. After each task, participants were asked to answer three questions concerning the suitability of each interaction technique for the respective task using a 5-point Likert scale. The average duration of a session was 16 minutes (with a minimum of 7 and a maximum of 23 minutes).

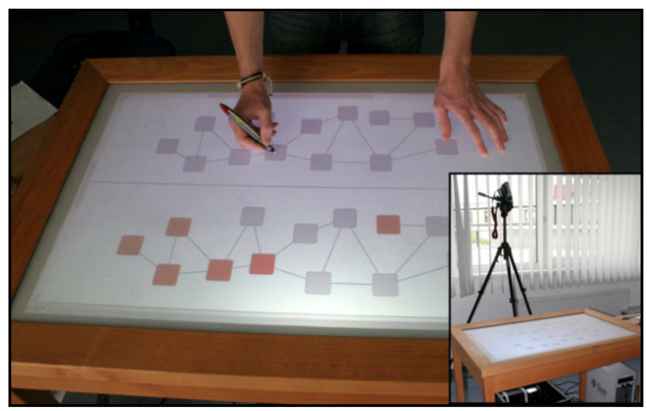


Figure 1: Technical setup of the user study. The novel tabletop fully supports multi-touch and pen input, which was used to track the user-elicited gestures.

RESULTS

Altogether, 658 gestures were recorded. Theoretically, a total of 17 x 14 x 3 = 714 gestures would have been possible. Three gestures had to be discarded due to participants' confusion. In 53 cases participants did not come up with a gesture: two times for one hand, 46 times for two hands and five times for pen/hand interaction. Refusal, i.e., users did not do the task in a particular modality, of two-handed interaction mainly took place in task 5 (change to dashed edge), task 6 (select node) and task 9 (move node) with 7 refusals each. Concerning pen interaction, only 28 of 232 pen gestures were done in a bimanual way; with support of the non-dominant hand. Most of the gestures which used pen in combination with hand were used in task 10 (scale node) and task 13 (zoom diagram) with 5 bimanual gestures each.

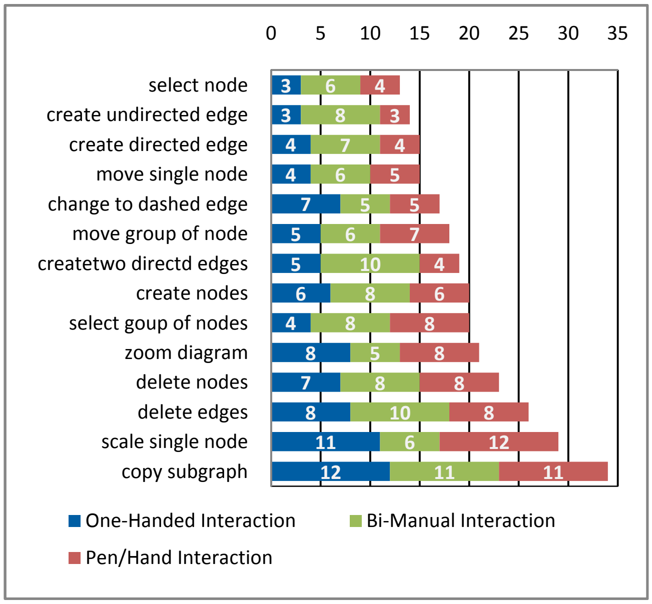


Figure 2. Number of equal gestures for each task and for each modality, sorted in ascending order. Low values show high consensus and high values show low consensus among participants.

Gesture Analysis and Classification

We created 26 internal abbreviations (e.g., "ST" for single tap) to group equal (or very similar) gestures for each task. This set of abbreviations was generated through a peer review process by analyzing the video material and the taken think-aloud protocols. Amongst others, we distinguished between discrete and continuous actions, sequential and parallel actions, and considered pen-only gestures opposed to using pen and hand together. Figure 2 depicts the number of groups with equal or similar gestures (gesture variants) for each task (rows) and for each modality (colored bars). They are ordered by the total number of groups and thus give an indication of the degree of consensus among participants.

The least number of groups in total (13) was identified for task 6 (*select node*): 3 for one-handed, 6 for two-handed and 4 for pen interaction. This can be interpreted as the highest level of agreement among participants. The most variants of gestures in total (34) and thus the least level of agreement could be found for task 14 (*copy sub-graph*) with the numbers for each modality (12, 11, 11) also being at the maximum.

In the picture column of Table 1 a collection of selected user-elicited gestures is depicted for each task. Thereby, we do not simply show those gestures with the largest agreement. Instead, we rather identified more than one top candidate gesture for each task. We also took the first choice data and the results of the suitability questionnaire into account to weigh the candidate gestures. Beyond that, we considered gestures of both mental models to equally support *structural diagram editing* and *diagram sketching* for the respective task. All gestures meeting these selection criteria are depicted in Table 1.

Evaluation of Suitability

The results of the suitability questionnaire are depicted in Figure 3 (top). Generally speaking, one-hand and pen interaction was rated more suitable than two-handed interaction. Exceptions are the *scale node* task and the *zoom diagram* task. Here, two-handed interaction was rated better than one-hand and pen/hand interaction. Beyond that, for the tasks *select group of nodes* and *move grouped nodes* two-handed interaction was also rated relatively well. Concerning the c*opy task*, all three interaction modalities were rated equally, which can be certainly attributed to the abstract nature of the task.

First Choice of Interaction

In 141 cases (59% of the tasks) participants decided to start with one-hand interaction. Bimanual interaction was chosen in 28 cases (12%) and pen/hand interaction in 68 cases (29%). Figure 3 (bottom) shows the absolute numbers of participants' first choice of interaction modality for each task. For the four *creation tasks* and the *change edge task*, mainly one-hand and pen/hand interaction was selected. This also reflects the ratings on the suitability questionnaire. Concerning the *select node* and the *move node* tasks, 15 participants preferred one-hand interaction as their first choice. This is highly significant in comparison to pen interaction ($F_{2,16} = 58.8$, $p < .001$ for both tasks). The same behavior could be observed for the *delete tasks*; again one-hand interaction was significantly preferred ($F_{2,16} = 52.0$, $p < .05$ for both tasks). Concerning one-hand interaction, we also observed that participants did not differentiate numbers of fingers for „single-point" touches. They were performed with one, two or even three fingers. This confirms the results by Wobbrock et al. [20].

For *selecting a group of nodes* and *moving a group of nodes,* one-hand interaction was also preferred as first choice. However, especially for the latter participants also tended to bimanual interaction. For *scaling a node* actually eight participants (47%) started with one hand, but this is not significant. *Zooming the diagram* showed a significant difference between both one and two-handed interaction compared to pen/hand ($F_{2,15} = 8.79$, $p < .05$). Nevertheless, participants rated the suitability of two-handed interaction significantly better than the two other techniques for both scaling tasks. Concerning the *copy sub-graph task,* 10 participants started with one-hand gestures, which is slightly significant ($F_{2,16} = 2.18$, $p < .05$).

User Observations

Mental Models

Most of the participants often stuck to the desktop paradigm. Especially for more abstract tasks, such as scaling a node or diagram or copying a sub-graph, it was hard for many participants to come up with a spontaneous gesture. Comments like "I would need a button here", "this is hard without a context menu" or dragging nodes to an imaginary recycle bin showed a strong influence of the desktop metaphor. One participant suggested to perform a zooming gesture with two fingers "like on the Mac". Beyond that, many participants requested a frame around the diagram or nodes with handles for scaling. Another

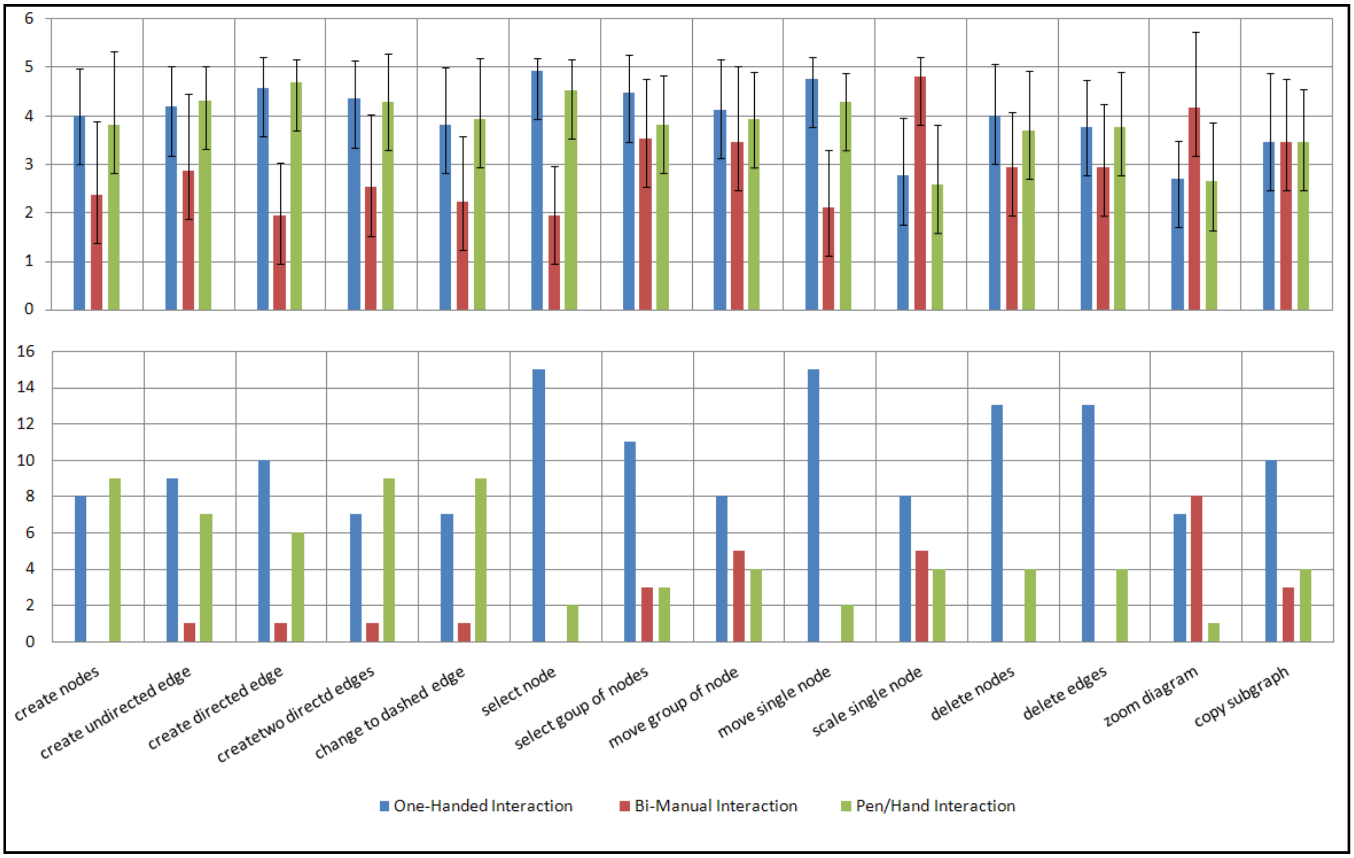


Figure 3. Top: mean values of the suitability questionnaire for each task (1 = not suitable, 5 = very suitable); Bottom: absolute values for the number of first choice interaction techniques for each task. Both diagrams show three modalities for each task: one-hand (blue), bimanual (red) and pen/hand (green) interaction.

frequently observed behavior was holding the non-dominant hand on the background to activate a certain mode while performing the actual gesture with the dominant hand. This is comparable to holding down a "Ctrl"-key on the keyboard.

In the study, we observed that clearly both ways of interaction – *diagram sketching* and *structural diagram editing* – played important roles for those tasks where both approaches are possible (creating elements, deleting elements and changing edges). For the *create node* task, seven participants drew rectangles with the pen or finger like on a whiteboard and five participants were tapping with fingers of one hand like in a digital editor. Beyond that, many participants suggested creating a node by copying an existing one with a two-hand gesture.

Concerning the creation of undirected and directed edges, drawing the edge with finger or pen was preferred. Eight people distinguished between a simple line for an undirected connection and a line with drawn arrow head for a directed connection, which closely resembles everyday experience. However, we also observed different bimanual variants, such as sequentially tapping source and target node or holding the source node while dragging an edge to a target. For changing the solid edge to a dashed one, we mainly observed metaphorical gestures inspired by interactions on whiteboards, such as drawing short lines orthogonally along an edge or performing a "rake"-gesture with three or four finger. For the *delete tasks*, doing a wipe-gesture was the most common solution for deleting edges and the second most common for nodes. Beyond that, it was interesting to observe that most of the users drew elements with fingers as well as with pen. There was no preference for one of these modalities.

Unexpected Gestures

We also observed some special and inspiring ways of user interaction. For *delete tasks* it was interesting to monitor gestures like "X" or "d" drawn on the background. We were surprised how many participants dragged nodes off the canvas and the tabletop frame. This behavior was not expected, since typical devices in this domain do not support this interaction mode.

Beyond that, there were gestures which cannot be recognized by our hardware, such as flipping a hand in the air, taking the graph with a grab gesture and dropping it at the target location to copy the diagram. Other users were laying the pen onto the surface and moving it entirely to translate elements underneath. However, these unusual gestures suggest future research in cross-device interaction beyond the frontiers of current interaction devices.

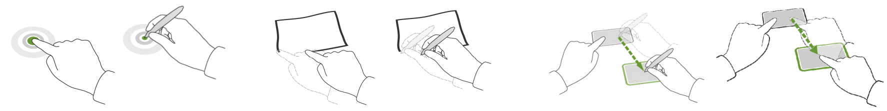
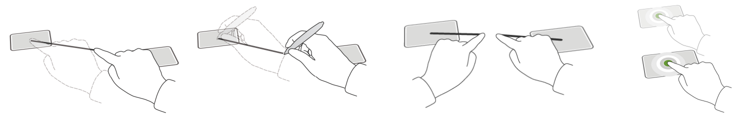
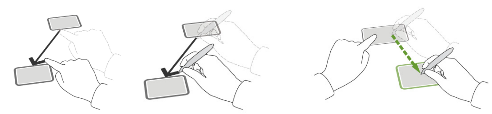
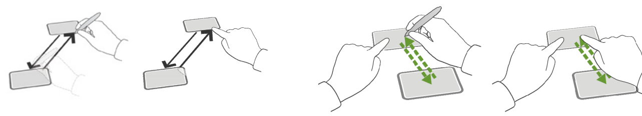
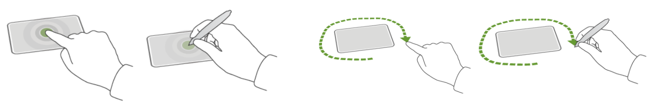
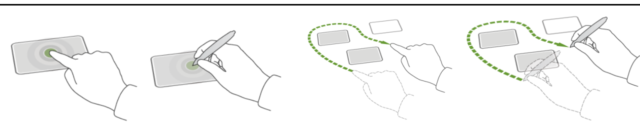
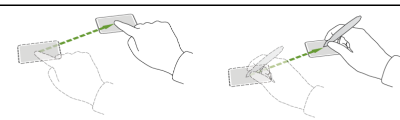
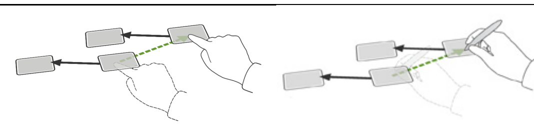
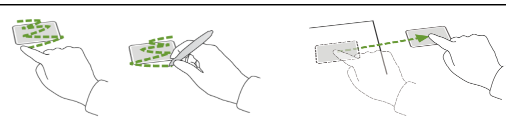
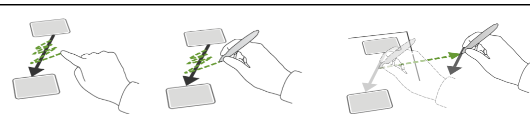
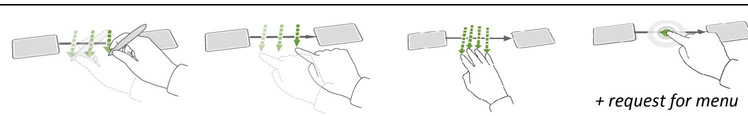
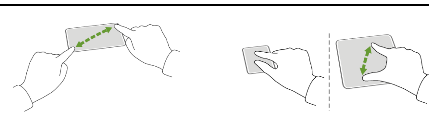
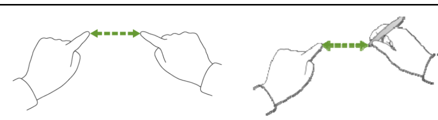
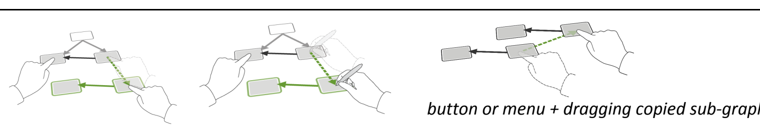
Description of Gesture	
1. **Create node** *Sequential tapping using finger of one or both hands, drawing outlines with finger or pen, copying an existing node by fixing the original node and dragging it with finger or pen.*	
2. **Create undirected edge** *Drawing a line using finger or pen. Dragging edge from source and target node to center. Sequential tapping of nodes.*	
3. **Create directed edge** *Drawing an arrow using finger or pen. Hold source node of edge by one hand and drag edge to target node by other hand using finger (not depicted) or pen.*	
4. **Create two directed edges** *Drawing two single arrows, one forth and one back, using finger or pen. Draw single line back and forth using finger or pen.*	
5. **Select single node** *Repeated tapping using finger or pen, encircling using finger or pen, also with both hands simultaneously (not all cases are illustrated).*	
6. **Select group of node** *Sequential tapping or encircling of nearby nodes using finger or pen.*	
7. **Move single node** *Touching the node and dragging the node with finger or pen.*	
8. **Move group of node** *Touching a node of the group and dragging with finger or pen.*	
9. **Delete node** *Performing a wipe gesture over a node using hand or pen. Dragging a node to off-screen using finger or pen (latter not depicted).*	
10. **Delete edges** *Performing a wipe gesture over edge using hand or pen. Dragging an edge to off-screen using finger or pen (former not depicted).*	
11. **Change type of edge** *Drawing short orthogonal lines along an edge with pen or hand, performing a "rake" gesture using three or four fingers. Tapping on edge followed by a menu for selecting type of edge.*	
12. **Scale size of node** *Scale gesture using two expanding fingers of one or two hands.*	
13. **Zoom whole diagram** *Zoom gesture using two expanding fingers of one or two hands (see task 12) or zoom gesture with finger and pen.*	
14. **Copy sub-graph** *One hand keeps holding the source, while the other hand drags the copy to target position using finger or pen. After menu/button, moving copy to target position using finger or pen.*	

Table 1. A user-defined collection of preferred gestures for typical and exemplary tasks in node-link diagram editing.

DISCUSSION

One-hand Gestures and Bimanual Interaction

One-hand interaction dominates for most of the tasks. This applies to the first choices of the users as well as to their suitability ratings. Exceptions were the *scale node* task and the *zoom diagram* task. Here, the well-known pinch gesture was performed with two fingers of different hands. Besides that, two-hand interaction received relatively good rates in the *select group of nodes* task. This is certainly due to the fact that it is faster to select nodes by tapping with two hands. Beyond that, seven participants encircled nodes with two hands or used a combination of tapping and encircling. Two-handed interaction was also rated very well for *moving a group of nodes*. As the group just consisted of three nodes, the preferred two-hand gesture was to place a finger on each node and drag them. Since this is attributed to the particular task, it cannot be generalized.

Pen and Hand Interaction

There were hardly situations where participants spontaneously used the non-dominant hand in combination with pen interaction. Exceptions were again the scaling and zooming tasks, where the pen was supported by a finger to perform a pinch gesture. However, the usage of pen and hand in combination was not significant here. We see the reason for this in the asymmetry of this gesture (compare [11]), and in people being conditioned through one-hand interaction on whiteboards and paper. There, the non-dominant hand is also rarely used. Nevertheless, we observed several situations where the non-dominant hand was used for mode switches, e.g., by holding the hand on the background. Hence, this is certainly a promising way to resolve the existing conflicts within the gesture set.

Beyond that, we were quite surprised that participants hardly distinguished between fingers and pen, especially for creating diagram elements. When it comes to more precise input – which our study did not require – it is expectable that the pen will be used more often.

Sketching and Structural Editing

Due to the aforementioned observations on mental models, we highly recommend to care for versatile gesture design in the diagram editing domain. Where appropriate, respective gesture sets should support the prevalent mental models *diagram sketching* and *structural diagram editing*. This allows users to create ad-hoc sketches as well as models based on formal notations without barriers.

A number of tasks can be done equally well in sketching environments and structural editors. These are the tasks for creating and deleting elements and changing solid edges to dashed ones. For example, to create a node we propose synchronous or sequential tapping gesture like in structural editing *and* directly drawing a node to support the sketching approach. Beyond that, gestures which are based on the sketching paradigm can be further categorized. Drawing a node or edge is a *physical gesture*, whereas deleting an element by wiping or creating a dashed edge by performing a "rake"-gesture is *metaphorical*.

Tasks such as scaling nodes or copying a sub-graph are of a more abstract nature. They cannot be easily accomplished by sketching, but are better supported by structural editors, e.g., by using a copy command in a menu. Nevertheless, we also observed pen and hand gestures for these tasks, e.g., copying a node or sub-graph by fixing it with a finger and performing a simultaneous dragging gesture with the pen. Since there is no obvious physical or metaphorical analogy, the design of gestures for these tasks requires special attention.

Observed Ambiguities

During the study, there occurred several ambiguities where the same gesture was done for different tasks. Since we deliberately did not ask for a consistent set of unique gestures, this is no surprise. For example, many participants did not distinguish between directed and undirected edges in the *create edge tasks*. There were also conflicts for the scaling tasks. Besides the popular pinch gesture, one of the main solutions was to move pen or finger diagonally across the diagram, which cannot be distinguished from a dragging gesture. The most conflicts appeared in the *copy sub-graph task,* which is certainly based on its very abstract nature. Again, most of the participants did simple dragging gestures and assumed a mode change before, e.g., by means of a button or context menu.

Gestures are inherently exhibiting ambiguities unless they are designed more abstract and less metaphorical, thus requiring the user to learn gestures. However, this is not preferable, at least not for novices. The study clearly shows that users solve this ambiguity by trying to include context. This needs to be especially taken into consideration for gestural interfaces. From that we conclude that it might be better to at least provide contextual help and gesture disambiguation for simple but powerful gestures instead of forcing the users to learn quite abstract ones. As mentioned above, the gesture collection presented in Table 1 is not free of conflicts. Therefore, an important next step is to consolidate the collection by analyzing and resolving the observed ambiguities.

CONCLUSION & FUTURE WORK

With this paper, we contribute a basic set of user-defined gestures for node-link diagram editing on multi-touch and pen-enabled tabletops. To our knowledge this is the first application of tabletop gestures to this domain. We conducted a user study in order to learn how users would spontaneously accomplish a set of given tasks by means of three different input modalities. As a result of this qualitative study, a large number of user-elicited hand and pen gestures could be observed and classified for each task.

The analysis provided valuable insight into the suitability of gestures and bimanual interaction on tabletops in general. Examples are the dominance of one-hand interaction, the requirement to equally support the mental models *diagram sketching* and *structural diagram editing* as well as the preference of simple gestures with disambiguation instead of unique but complex gestures being difficult to memorize. In addition, the observed unusual gestures suggested a need to further investigate interaction modes beyond device limitations. In summary, besides laying the foundation for the field of diagram editing on tabletops, we hope to inspire a discussion of the presented results in other tabletop domains, too.

For future work we will further develop and extend the gesture set. First, bimanual interaction and contextual assistance will be investigated as means of resolving ambiguities. Second, gestures for more specific and complex diagram types need to be considered and developed. All gestures will be implemented and carefully studied in follow-up usability evaluations.

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