Including Blind People in Computing Through Access to Graphs

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ABSTRACT

Our goal in creating the Graph SKetching tool, GSK, was to provide blind screen reader users with a means to create and access graphs as node-link diagrams and share them with sighted people in real-time. Through this effort, we hoped to better include blind people in computing and other STEM disciplines in which graphs are important. GSK proved very effective for one blind computer science student in courses that involved graphs and graph structures such as automata, decision trees, and resource-allocation diagrams. In order to determine how well GSK works for other blind people, we carried out a user study with ten blind participants. We report on the results of the user study, which demonstrates the efficacy of GSK for the examination, navigation, and creation of graphs by blind users. Based on the study results, we improved the efficiency of GSK for blind users. We plan more enhancements to help meet the need for accessible graph tools as articulated by the blind community.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces*;* K.4.2 [**Computers and Society**]: Social Issues – *assistive technologies for persons with disabilities;* K.3.2 [**Computers and Education**]: Computer and Information Science Education; G.2.2 [**Discrete Mathematics**]: Graph Theory.

General Terms

Human Factors.

Keywords

GSK; Universal Design; Accessibility.

1. INTRODUCTION

Combinatorial graphs, often conveyed as node-link diagrams, are very important in the field of computing as well as in other STEM disciplines. To be successful in these disciplines, it is important that blind students and professionals be able to create and access graphs and share them with sighted colleagues. Others have created graph applications intended specifically for blind people. AudioGraf was an early attempt to make graph-like diagrams accessible via a touch panel and auditory display [13]. The Kevin system aimed to make data flow diagrams accessible to blind students and engineers [3]. Kekulé was created to enable blind students to examine the structure of chemical molecules [4] and PLUMB was developed to help them comprehend graphs and data structures [6]. The TeDUB project strived to make existing Unified Modeling Language (UML) and other diagrams accessible to blind people [14]. While the Deep View graph application allowed for collaboration between blind and sighted users, each used a separate interface [17]. We created the Graph SKetching tool, GSK, to adhere to universal design principles by including both blind and sighted users in the same interface [2, 5]. Although the sonification and tactile/haptic feedback approaches employed by others [8, 9, 22] may aid blind users in comprehending the spatial layout of a graph, we wanted to create a simple, portable graph application with no need for specialized hardware devices. Thus, we designed GSK to allow blind and sighted users to employ interaction mechanisms that are standard for them (keyboard, mouse, monitor, screen reader).

The second author, who is a blind computer science student, successfully used GSK in his automata theory, operating systems, software engineering, and artificial intelligence courses to work with graphs, both alone and in conjunction with sighted instructors. It is not surprising that, as a co-creator of GSK, he found the tool intuitive and useful. We wanted to determine how well GSK would work for other blind students and recent graduates. We therefore carried out a user study in which blind participants used GSK and Microsoft Excel, as a control, to examine and navigate graphs. They also used GSK to create several graphs. This paper provides information about the study, its participants and results, as well as improvements made to GSK that increase its efficiency for blind users.

2. OVERVIEW OF GSK

The GSK interface provides two different views of the same graph. Connection View, as shown in Figures 1 and 3, displays a graph as a node-link diagram. In this view, blind users navigate the graph via the keyboard – each time a node or edge receives focus, information about the node/edge is displayed in the status bar and voiced by the screen reader. Grid View allows blind (and sighted) users to create new nodes in the preferred layout. Sighted users may also use the mouse in Connection View to create new nodes. More information about the GSK interface may be found in our previous paper [2] and on our website, go.ncsu.edu/gsk, where GSK may be downloaded as well.

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ASSETS'14, October 20–22, 2014, Rochester, NY, USA.
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http://dx.doi.org/10.1145/2661334.2661364

3. USER STUDY

Each of the ten user study sessions spanned five hours and consisted of three individual studies, each of which took about an hour. In the first two studies, participants *examined* and *navigated* graphs using GSK and Microsoft Excel. We chose Excel as a control because it is a standard means of representing tabular data that is in common use by both blind and sighted people. In the third study, participants used GSK to *create* graphs. Complete study details may be found in [1].

We conducted the user study on a Windows computer running the Vista Operating System. Participants used the keyboard and version 10.0 of the JAWS screen reader to interact with GSK and Microsoft Excel 2007. Because GSK is a Java application using Swing components, we installed the Java Access Bridge, which facilitates communication between the screen reader and the Java Virtual Machine. Our use of Java 6 (6u21) necessitated this installation. The Java Access Bridge is now included with Java 7 Update 6 (7u6) and later.

Table 1. Participant Characteristics

Participant	JAWS Rate	Excel Use	Graph Familiarity 1 (Low) – 5 (High)
P1/P1R	125	5-10 yrs	4
P2	115	2-3 yrs	1
P3	123	> 10 yrs	5
P4	80	5-10 yrs	5
P5	29	2-3 yrs	2
P6	113	3-5 yrs	4
P7	73	2-3 yrs	1
P8	74	< 1yr	3
P9	131	3-5 yrs	5

3.1 Participants

Obtaining a large number of blind participants was difficult due to their relatively low representation in the general population [11]. Nine different blind screen reader users participated individually in the study. All participants were novice GSK users with no prior exposure to the program, except for participant P1/P1R, who repeated the study with an improved version of GSK. Though our sample was small, the first eight study participants demonstrated the effectiveness of GSK for completing a number of graph-related tasks. They also provided us with enough information to make improvements that allowed the ninth and repeating participant to use GSK more efficiently. Each person received an honorarium for participating in the study. Prior to beginning the study, we obtained Institutional Review Board (IRB) approval from our university.

In order to maintain confidentiality with such a small group, we provide most information about the participants in aggregate form and provide individual information that may have an impact on the study results in Table 1. The participants (4 male, 5 female) ranged in age from 14 to 30 and consisted of 3 secondary students, 3 undergraduate students, 2 college graduates, and 1 graduate student. All but two participants had been legally blind since birth; the other two became blind before the age of 5. All were experienced computer users and most were experienced JAWS users. Some participants used a very fast JAWS speech rate, which is unintelligible to most people, while others used a much slower rate.

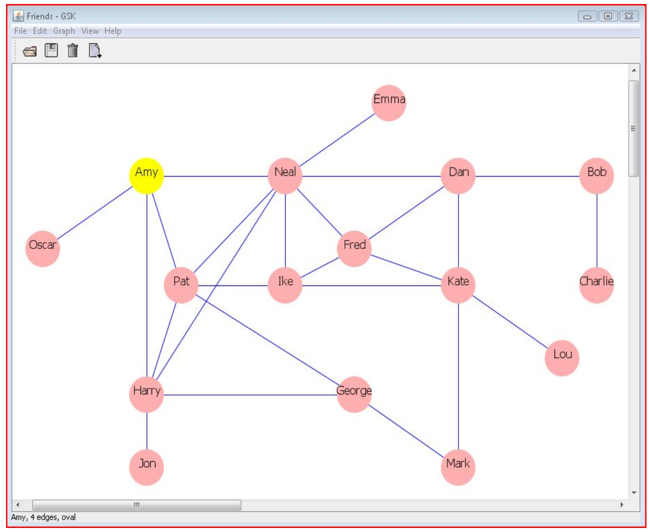


Figure 1. GSK Friends Graph

	A	B	C	D	E	F	G	H	I
1	Amy	4	Oscar	Pat	Neal	Harry			
2	Bob	2	Dan	Charlie					
3	Charlie	1	Bob						
4	Dan	4	Bob	Fred	Kate	Neal			
5	Emma	1	Neal						
6	Fred	4	Dan	Kate	Ike	Neal			
7	George	3	Mark	Pat	Harry				
8	Harry	5	Amy	George	Jon	Pat	Neal		
9	Ike	4	Fred	Kate	Pat	Neal			
10	Jon	1	Harry						
11	Kate	5	Dan	Fred	Mark	Lou	Ike		
12	Lou	1	Kate						
13	Mark	2	George	Kate					
14	Neal	7	Amy	Dan	Fred	Ike	Pat	Emma	Harry
15	Oscar	1	Amy						
16	Pat	5	Amy	Neal	Harry	George	Ike		

Figure 2. Excel Friends Graph

3.2 Graph Examination Study

For the graph examination study, we used a friends graph that was based on the Acquaintance graph in an undergraduate discrete mathematics textbook [20]. Each node in the Friends graph represents a person with undirected edges joining people who are friends. We found that all participants, regardless of their background and degree of familiarity with graphs, could relate to this simple example. A friends graph rendered using GSK is shown in Figure 1. The same graph represented as an Excel table is shown in Figure 2. Each row of the Excel table contains a person's name followed by the person's number of friends followed by the names of the friends. We created six versions of the Friends graph with different edges, each of which contained

16 nodes and 25 edges. All graphs used the same set of person names for the nodes, one for each letter of the alphabet – Amy, Bob, Charlie, ..., Pat. We randomly assigned node names to each GSK graph. We then created a random pairing of those names that we used to label the nodes in the corresponding Excel graph. We configured the Excel tables so that the JAWS screen reader would read the row (person's) name when navigating from cell to cell and turned off the reading of cell coordinates, e.g., A1, to eliminate confusion.

The participants were first trained to use GSK and Excel to examine a friends graph and given time to practice answering each of the four types of questions listed below. The questions correspond to graph theory concepts without being explicit. Each participant was asked one question of each of the four types for each of the six graphs using both GSK and Excel for a total of 48 trials. For each question/graph pair, we were careful to use corresponding GSK/Excel nodes. The participant response times and answers for each trial were recorded. Examples of each question type are given below.

Q1: *How many friends does Amy have?* (Node degree)

Q2: *Is Bob a friend of Dan?* (Adjacent node)

Q3: *Who is a friend of both Charlie and Dan?* (Path of length 2)

Q4: *Name two friends of Kate who are also friends with each other.* (Clique of size 3)

3.3 Graph Navigation Study

For the graph navigation study, we used a town graph in which places are connected by one-way roads (labeled directed edges). Again, this simple example was understandable by all participants. Figures 3 and 4 contain town graphs rendered in GSK and Excel respectively. Each row of the Excel table contains the name of a place followed by the number of roads leaving the place followed by each road and its destination, e.g., "Oak to Library."

We created six versions of the Town graph with different edges, each of which contained 12 nodes and 24 edges. All graphs used the same places and set of road names, one for each letter of the alphabet – Apple, Birch, Cherry, ..., X-ray. We randomly assigned node names to each GSK graph. We then created a random pairing of those names that we used to label the nodes in the corresponding Excel graph. We configured the Excel tables so that the JAWS screen reader would read the row (place) name when navigating from cell to cell and turned off the reading of cell coordinates.

Participants were first trained to use GSK and Excel to navigate a town graph and given time to practice answering the navigation question listed below. Each participant was asked one question for each of the six graphs using both GSK and Excel for a total of 12 trials. Their response times and answers for each trial were recorded. An example of a navigation question is given below.

N: *Starting at the Park, take Birch, King, Pine. Where do you end up?*

3.4 Graph Creation Study

During the graph creation study, participants were taught to use GSK to create undirected graphs. They were then asked to create the four graphs listed below. The first two graphs were presented to them in tactile form and the last two were described for them. The time taken to create each graph was recorded.

G1: *Graph with 3 nodes and 3 edges laid out as an equilateral triangle.*

G2: *Graph with 4 nodes and 4 edges laid out as a square with one diagonal and a missing side.*

G3: *Graph with 4 nodes that are all connected to each other.*

G4: *Graph with 5 nodes and 5 edges.*

4. ANALYSIS AND RESULTS

4.1 Examination and Navigation Studies

All participants were able to use Excel and GSK to answer the examination and navigation questions in a timely and accurate manner. The mean response time ranged from 2 to 17 seconds for the relatively straightforward questions, Q1 and Q2, and from 10 to 55 seconds for the much more difficult questions, Q3 and Q4. The mean response times for the navigation question, N, fell between these two ranges with times ranging from 7 to 33 seconds. The overall accuracy rate was very high (99.3% using GSK, 97.6% with Excel). When calculating the mean response times, we omitted the response time for any question answered incorrectly from both the Excel and GSK calculations. The bar charts in Figures 5 – 9 provide comparisons of the Excel/GSK participant response times for each question.

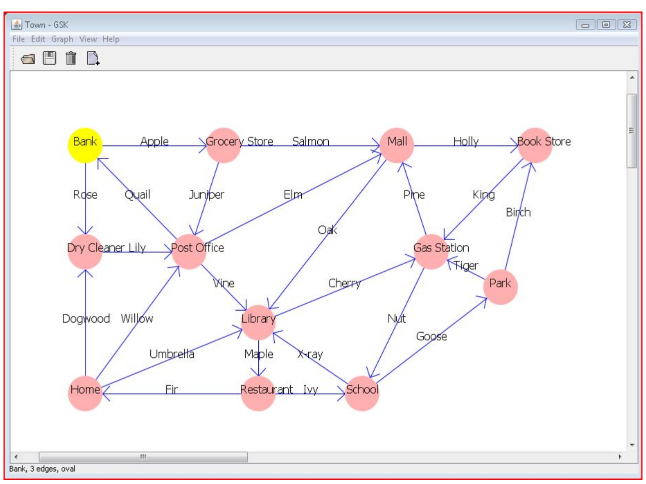


Figure 3. GSK Town Graph

	A	B	C	D	E
1	Bank	2	Apple to Grocery Store	Rose to Dry Cleaner	
2	Book Store	1	King to Gas Station		
3	Dry Cleaner	1	Lily to Post Office		
4	Gas Station	2	Nut to School	Pine to Mall	
5	Grocery Store	2	Salmon to Mall	Juniper to Post Office	
6	Home	3	Umbrella to Library	Willow to Post Office	Dogwood to Dry Cleaner
7	Library	2	Maple to Restaurant	Cherry to Gas Station	
8	Mall	2	Holly to Book Store	Oak to Library	
9	Park	2	Tiger to Gas Station	Birch to Book Store	
10	Post Office	3	Quail to Bank	Elm to Mall	Vine to Library
11	Restaurant	2	Fir to Home	Ivy to School	
12	School	2	X-ray to Library	Goose to Park	

Figure 4. Excel Town Graph

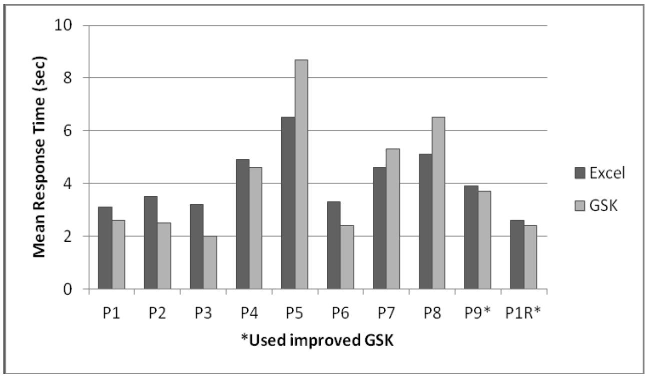


Figure 5. Examination Study Q1

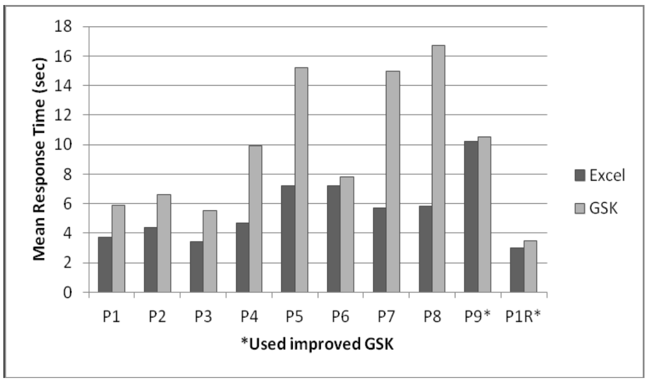


Figure 6. Examination Study Q2

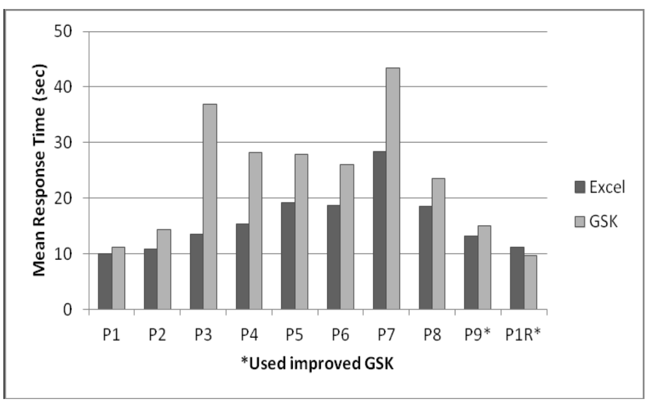


Figure 7. Examination Study Q3

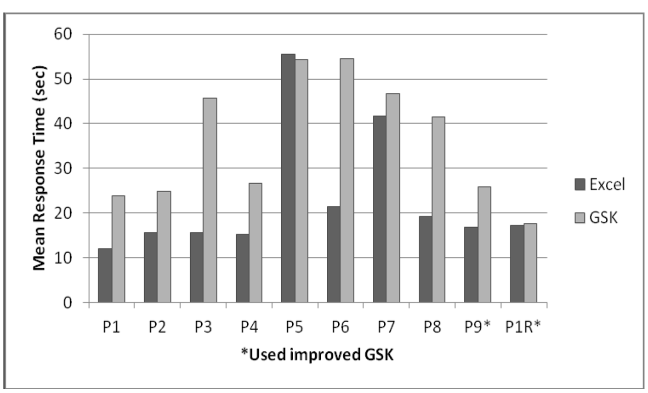


Figure 8. Examination Study Q4

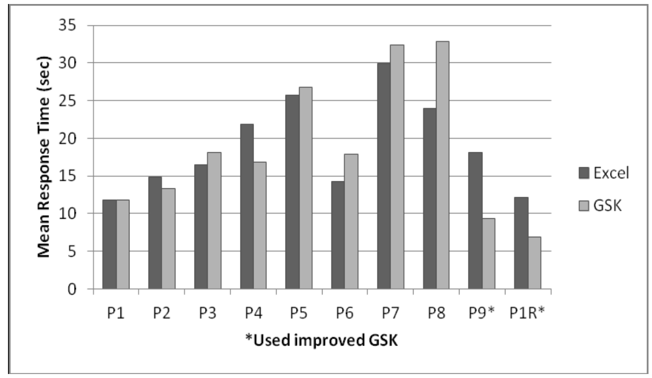


Figure 9. Navigation Study N

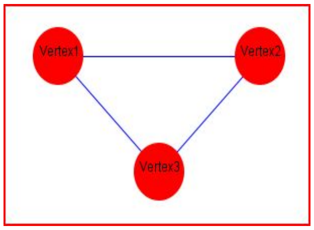
4.2 Creation Study

The participants were also successful in creating graphs using GSK. Participant P1, who had had no prior GSK experience, rendered all four creation study graphs perfectly, as shown in Figure 10, in less than 10 minutes. Figure 11 provides the response times for all study participants, who created the four graphs in total times ranging from 5 to 25 minutes.

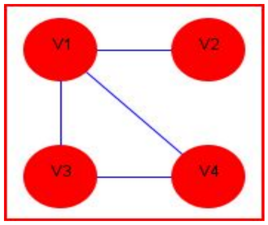
To quantify the quality of the graphs, we awarded 1 point for each of the following items for each graph for a total of 5 points per graph:

a. Correct number of nodes
b. Correct number of edges
c. Correct edges
d. Correct/acceptable layout
    - *Does the layout of G1 and G2 match that of the tactile graphs presented to the participant?*
    - *Is the layout of G3 and G4 acceptable (reasonably proportioned, etc.)*?
e. Visually accessible (viewable by a sighted person)
    - *Is there enough contrast between the foreground and background colors so that the node labels are visible?*
    - *Are the nodes far enough apart so that the edges joining them are visible?*
    - *Are individual edges visible (or are several nodes laid out in a line so as to render the edges between them indistinguishable)?*

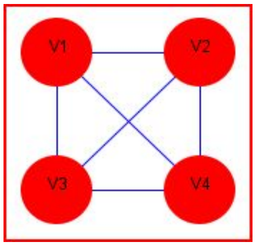
Table 2 provides the individual graph scores and the total score for each participant. The average total score for the participants was 16.6 out of a possible 20. Most of the graphs (82.5%) were accurate in that they contained the correct number of nodes/edges and the correct edges. While we did not direct the participants to create visually accessible graphs, most of the graphs (70%) were viewable by a sighted person. Those that were not could easily be made so in the case of collaboration between a blind and sighted person. However, if a blind person were creating a graph to export as an image and include in a document, a visually inaccessible graph would be problematic. Detecting and reporting visual accessibility problems as well as options to automatically improve graph layouts are potential areas for future work.



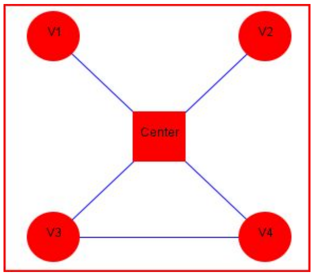
G1



G2



G3



G4

Figure 10. Creation Study graphs as rendered by P1

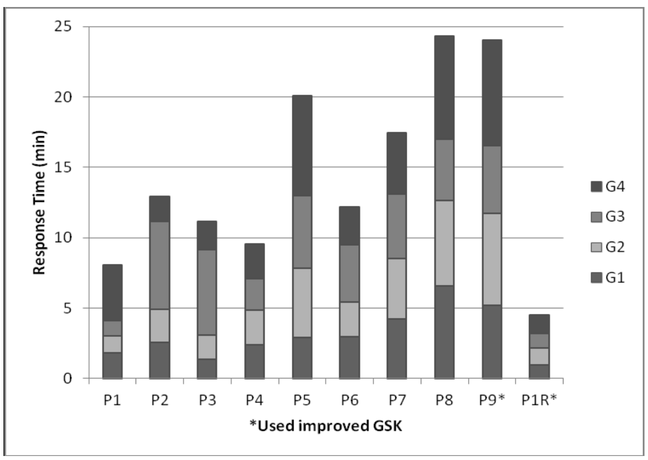


Figure 11. Creation Study

Table 2. Creation Study Scores (total(abcde) – see Sec 4.2)

	G1	G2	G3	G4	Total
P1	5(11111)	5(11111)	5(11111)	5(11111)	20
P2	4(11110)	5(11111)	5(11111)	5(11111)	19
P3	4(11110)	4(11110)	3(11100)	4(11110)	15
P4	5(11111)	5(11111)	5(11111)	5(11111)	20
P5	4(11101)	3(10011)	5(11111)	5(11111)	17
P6	5(11111)	5(11111)	5(11111)	5(11111)	20
P7	2(10001)	3(11001)	5(11111)	0(00000)	10
P8	2(10001)	3(10011)	4(11110)	5(11111)	14
P9	5(11111)	5(11111)	3(11100)	4(11110)	17
P1R	4(11011)	4(11110)	3(11100)	3(11100)	14

4.3 GSK vs. Excel

We had planned to do ten user studies, but after the first eight studies, the trends in terms of efficiency were clear. At that point we decided to analyze the data and attempt to improve the efficiency of GSK for the remaining two participants.

As appropriate for our within-subject design, we first calculated the difference between the Excel and GSK mean response times for each question for each of the first eight participants. We then analyzed the results using the Wilcoxon Signed-Rank Test rather than a paired t-test due to the non-normality of the differences. We found no significant difference between the Excel and GSK mean response times for questions Q1 and N. However, we found that the response times for Excel were significantly lower for Q2 ($p = .005$), Q3 ($p = .005$), and Q4 ($p = .001$).

These results are not surprising considering that most participants had had several years experience using Excel and no prior GSK experience. In addition, navigating the Excel tables required only the use of the arrow keys, which are located in close proximity on the keyboard. On the other hand, in addition to the arrow and escape keys needed to navigate the GSK graph, the CTRL+J (“jump to node”) key combination followed by first letter navigation was used to place focus on a specific node; with more practice, these key combinations and sequences would likely become automatic. A number of participants remarked that the studies gave an advantage to Excel for two reasons. First, in the Excel Friends graph, the alphabetical listing of people, one for each letter of the alphabet, made it very easy to take shortcuts when navigating the table. Second, in the Excel Town graph, only the outgoing edges for each place were listed, whereas navigating the GSK Town graph required examining both incoming and outgoing edges.

4.4 GSK Improvements

To make GSK more efficient for blind users, we added an *advanced verbosity level* and *edge filtering,* and *simplified the edge navigation* as described in the following subsections. Participant P9 used the improved version of GSK and participant P1R repeated the study using the improved GSK. These participants used the *simplified edge navigation* throughout the user study and the *advanced verbosity level* for questions Q3, Q4, and N. They also used *edge filtering* for question N.

As shown in Figures 5 – 9 and Table 3, there was a marked improvement in their GSK response times as compared to Excel. In particular, the addition of edge filtering allowed these last two participants to answer the navigation question with GSK in about half the Excel time. We attribute the decrease in quality of the graphs created by P1R using the improved GSK, as shown in Table 2, to focusing on speed rather than attention to detail.

Table 3. Mean Response Time (sec)

Question	Original GSK (P1-P8)			Improved GSK (P9-P1R)		
	Excel	GSK	Diff	Excel	GSK	Diff
Q1	4.28	4.32	-0.04	3.25	3.05	0.20
Q2	5.26	10.32	-5.06	6.60	7.00	-0.40
Q3	16.81	26.42	-9.61	12.20	12.35	-0.15
Q4	24.60	39.79	-15.19	17.10	21.70	-4.60
N	19.84	21.24	-1.4	15.10	8.15	6.95

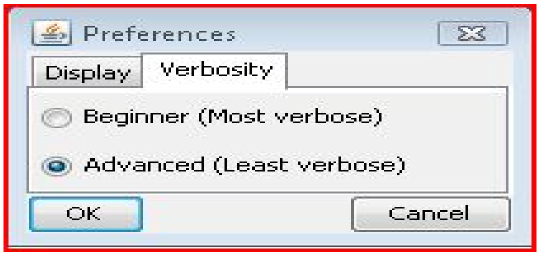


Figure 12. Verbosity Level Dialog

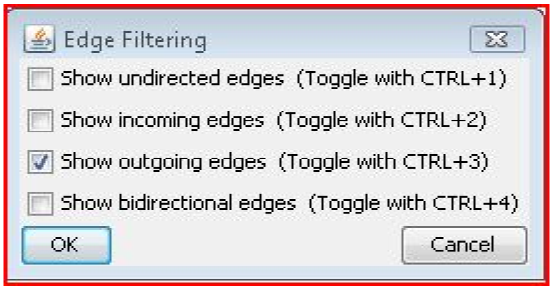


Figure 13. Edge Filtering Dialog

4.4.1 Beginner and Advanced Verbosity Levels

While the auditory cues heard by participants when using GSK provided more contextual detail than the Excel cues, they were quite verbose and often the most important information came last. For example, the auditory cues for a friends graph node and a town graph edge are “oval Amy, 4 edges” and “Outgoing edge Pine to oval Mall.” Stefik, et al., recommend that auditory cues be short, “browsable,” and give the most important information first [21]. We therefore decided to provide users with Beginner and Advanced Verbosity levels as shown in Figure 12. The Beginner level provides the more verbose auditory cues as described above. Using the Advanced level, the same cues are rendered as “Amy, 4 edges, oval” and “Pine, Mall, Outgoing, oval,” thus allowing screen reader users to more quickly access the necessary information.

4.4.2 Edge Filtering

During the navigation study, only the outgoing edges for a node were important, but participants had to examine both the incoming and outgoing edges for each place. We added an Edge Filtering dialog, as shown in Figure 13, that allows users to select the type(s) of edges (undirected, incoming, outgoing, bidirectional) that receive focus during keyboard navigation with the left/right arrow keys. In this way, it is possible to navigate a graph using only the type(s) of edges that make sense for the problem at hand.

4.4.3 Simplified Edge Navigation

In the original GSK interface, the left arrow key placed focus on the selected node’s “first” edge and the right arrow key was then used to navigate to its other edges. Likewise, the right arrow key placed focus on a node’s “last” edge and the left arrow key was used to navigate to the other edges. We realized that this “context switch” was inefficient and simplified the navigation scheme by eliminating it. In the improved GSK, whenever focus is on a node, subsequent presses of the left arrow key moves focus from edge to edge as does the right arrow key, but in the opposite direction.

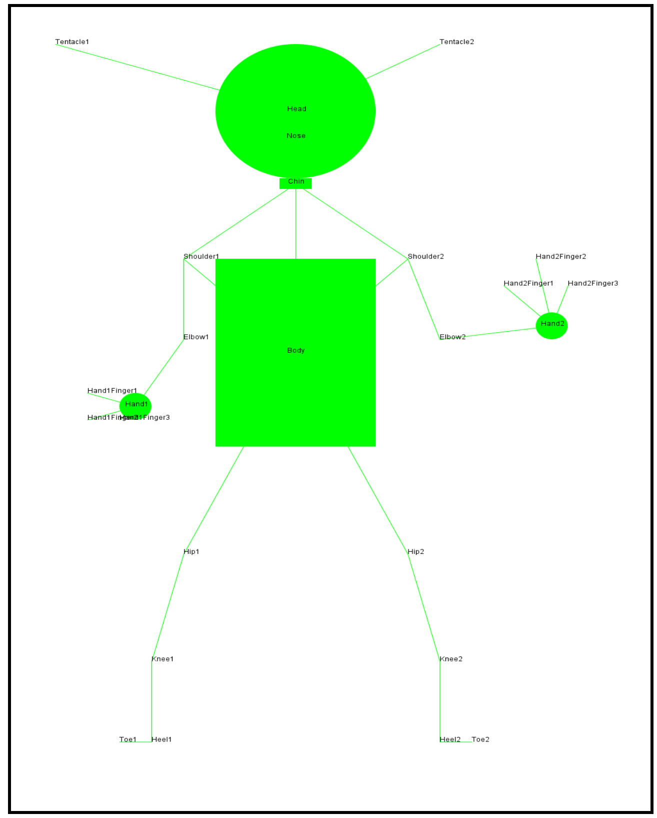


Figure 14. Alien created by a blind user with GSK

5. CONCLUSIONS AND FUTURE WORK

Through our user study, we found that GSK was effective in allowing blind users to examine, navigate, and create graphs in a reasonable amount of time. In the first two studies, we controlled for memory by having participants use a different graph for each question. In normal situations, blind users would typically work with the same graph and be able to build up a mental model of the graph. The second author has found that using GSK helps him more easily memorize which nodes are adjacent to one another and this would likely extend to other blind users as well.

We believe GSK has the potential to be very helpful to blind people for creating and working with graphs and other two-dimensional diagrams. Immediately after the user study, one blind participant used GSK to create the drawing of an alien shown in Figure 14. His sighted friend has since used GSK to create Dungeons and Dragons maps to share with him. Listed below are comments from the user study participants:

> *GSK has an advantage over Excel in that it is good for showing connections, especially involving towns, buildings, walls and infrastructures. I like how I can follow a path from one place to another and keep following the path.*

> *I started to take an easy gen ed math course and switched to a different course because most of the course centered around graph theory. If I had stayed in that course, this program (GSK) would have helped me.*

> *It’s easier to edit your work (using GSK) than using a raised line drawing kit and make revisions or minor*

changes. You can save your work and make multiple copies for classmates and professors.

I can now make graphs that are attractive and presentable.

It makes me a lot more hopeful about producing combinatorial graphs in a visually appealing manner.

Using GSK to represent and work with graphs has advantages over Excel in that it is easier to connect things, if you are a visual learner. GSK is more fun, like "connect the dots," while Excel is just a list.

GSK also helps meet the need for accessible graph tools that has been articulated by the blind programming community [16]. Our introduction of GSK to the program-l: Visually Impaired discussion list in response to a request for accessible mind-mapping tools was met with interest by blind users around the world [18, 19]. One blind analyst/programmer commented, "My initial thoughts about how this tool might help me is in my communication with sighted co-workers. I can see it would be a very good tool for me to make graphs for them to view or print and for them to generate in a form I can then explore." [19]

We hope GSK will serve as a useful tool for both blind and sighted users alike and one that allows them to collaborate more easily. To that end, we plan to investigate the appeal of GSK for sighted users and make any necessary improvements. Based on the results of our user study and suggestions by blind users, we are also considering the following enhancements to GSK:

Graph Checker Creating visually accessible and appealing graphs could be facilitated by a Graph Checker option that lists potential problems with the visual layout of a graph -- node labels that are indistinguishable from the node color or that extend beyond the node itself, isolated nodes, excessive numbers of edge crossings, poorly proportioned layouts, etc. A user could then choose to automatically correct some or all of the problems, perhaps through the incorporation of graph drawing algorithms.

Annotation Capability The ability to annotate nodes or subgraphs, mark a node as the home or root node, and mark nodes as having been visited may be helpful for examining and navigating graphs.

Professional Presentation GSK is intended as a simple graph sketching tool in which the user controls the layout. Improved layout and/or presentation could potentially by obtained by use the Graphvis – GraphVisualization Software [7, 10] or another professional tool. By exporting a GSK graph in the tool format, the tool could then be used to create an improved visual representation.

Graph Examination Graphs created by inaccessible tools could be converted into GSK format, which would allow blind users to examine them.

Extension to Other Domains Currently GSK allows users to draw undirected and directed graphs with self-loops and/or single edges between nodes. Available nodes shapes include rectangles, ovals, and those pertaining to automata theory (state, start state, accepting state, accepting start state). Extending GSK to other domains by including entity relationship diagrams, UML class and other diagrams, resource-allocation graphs, etc., as well as providing additional general node shapes would allow it to serve more purposes.

Tactile Representation By leveraging techniques employed by the Tactile Graphics Assistant (TGA) [12, 15], Braille-labeled textured graphs could be created and output to a Braille embosser, thus providing tactile representations of graphs.

6. ACKNOWLEDGMENTS

We would like to thank Dr. Richard Ladner for the AccessComputing mini-grant that supported this work via NSF Award #CNS-1042260.

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