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Published in:
Proceedings of the 26th International Conference on Information Visualisation

DOI:
10.1109/IV56949.2022.00038

Published: 19/07/2022

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Cerioli, N., Vyas, R., Reeve, M. P., & Masoodian, M. (2022). Mapping the Colocalization Network: A Wayfinding Approach to Interacting with Complex Network Diagrams. In *Proceedings of the 26th International Conference on Information Visualisation* (pp. 186-193). (Proceedings : International Conference on Information Visualisation; Vol. 26). IEEE. https://doi.org/10.1109/IV56949.2022.00038

Mapping the Colocalization Network: A Wayfinding Approach to Interacting with Complex Network Diagrams

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***Abstract*—Although network visualizations are becoming increasingly common, designing such visualizations can be challenging due to the number of visual elements and non-linear relations that they need to display. The main design challenge faced is finding the right trade-off between providing a sufficient level of information detail while keeping the visual complexity of the visualization as low as possible. One way of overcoming this challenge is to rely on the use of mental models that are familiar to the users of network visualizations. In this paper, we propose the use of a mental interaction model similar to that of map visualizations – generally based on geographical maps – as the basis for visual design of network diagrams. We argue that such a mental model would foster a set of network interaction tasks that can be defined broadly as *wayfinding*. We present the process of wayfinding from a semiotic standpoint, and match its main key points to those of interaction tasks with network diagrams. As a case study for this analysis, we also present a prototype network diagram visualization tool, called Colocalization Network Explorer, which we have developed to support the exploration of the relationships between various diseases and the portion of the human genome that is potentially involved in their onset. Additionally, we describe how the design process has benefited from the adoption of the wayfinding mental model.**

***Index Terms*—Network visualizations, network diagrams, map visualizations, visualization, wayfinding.**

I. Introduction

The use of network data structures and associated visualizations is becoming increasingly common in many fields – such as natural sciences, medicine, humanities and social sciences – as a means of organising, presenting and analysing highly complex data sets.

As with most visualizations of complex data sets, network visualizations can often become very challenging to understand and use effectively, particularly due to the number of visual elements and non-linear relations they represent [1]. Therefore, such visualizations often need to reduce the amount of information being represented or displayed, as a way of reducing their visual complexity.

Another method of reducing complexity is by adopting a visual model that better matches any mental models that the user is already familiar with. Norman [2] has emphasised the crucial role that familiar mental models play in assisting users in their interactions with complex objects and processes.

While, like network visualizations, maps [3] and map-like visualizations [4] present highly complex data sets, yet they are generally much easier to understand and use. This ease of use can largely be due to the interaction models used in map visualizations [5], [6]. For instance, most maps foster a range of exploratory user interactions – that can be broadly defined as *wayfinding* [7] – based on already familiar navigational mental models from real world.

In this paper, we analyse the process of wayfinding from a semiotic standpoint – as proposed in [8] – and match its main parts with the network interaction tasks – as identified by [1] – to identify network visualization functionalities that are needed to help users with their orientation and information seeking tasks.

Based on this, we then discuss our findings using a case study of a network diagram visualization tool – called Colocalization Network Explorer (CNE) – we have developed for exploration of the relations between human diseases and those parts of the human genome that are potentially involved in their onset.

II. Network Diagrams

One of the most widely used forms of visualizations for interacting with networks is network diagrams [9]. Such visualizations display network structures as a set of individual nodes of data items, connected together using a set of edges representing different existing relationships between the nodes. Despite its simple underlying structures, network diagrams can be used to visualise very complex data sets.

Network diagrams can support a diverse range of visual information seeking tasks related to local nodes and edges, global structural features, circumscribed areas of the network, and the relationships that exist between these at different scales. Yoghourdian et al. [1] have identified four categories of such tasks performed by users in their interactions with a network diagram:

- *Topology-based tasks*: in which users attempt to detect node adjacency, accessibility, common connection, and connectivity.
- *Attribute-based tasks*: that support identification of nodes and their links using the data attributes associated with them.
- *Browsing tasks*: which require following or revisiting a path.
- *Overview tasks*: that are high-level and deal with the properties of the network itself.

All these tasks require the user to develop and re-shape a mental model of the location and relationship of various network elements (e.g., nodes, edges, sub-networks) in some form within the visualization space.

As with network diagrams, map visualizations also often rely on a similar approach from their users, in terms of their mental models, to support different kinds of interactions.

III. Maps and Wayfinding

Maps as visualizations have existed in many forms [10] for centuries, if not millennia. The most common type of such visualizations is of course geographical, which visually display geographical or geography-related information, often in a projected 2-dimensional space. These include, for example, cartographic maps [11], tourist maps [12], or even illustrated tourist maps [13]. As such, cartography – the discipline that is concerned with the craft of creating maps – combines scientific perspectives with artistic and semiotic ones [14].

Geographical maps are usually divided into three main categories of *general-purpose*, *thematic*, and *special-purpose* maps [15]. General-purpose maps are concerned with emphasising the location of spatial phenomena (e.g., streams, roads, building), while thematic maps display spatial patterns of geographically located data (e.g., population density, family income, temperature) [16] . Special-purpose maps, on the other hand, are targeted at users with specific needs (e.g., weather, water, soil) [15].

Regardless of the category of maps used, their readers perform similar tasks, such as determining the location of places of interest, getting information about particular locations, getting information about spatial patterns, or making comparison between patterns of different parts of the same map or between different maps [16].

Another important type of tasks performed using maps is that of wayfinding, particularly when using interactive maps [17]. In fact, maps can be considered as a crucial tool for the task of orientation in space, both physical and metaphysical. This task requires some degree of user interaction, in order to allow the acquisition of information on one's position. To support wayfinding, most maps are designed in such a way that the view the provide is "that of a bird looking down on a world where the user has to imagine him or her as an object traveling over the map" [17].

In his seminal work on wayfinding [7], Lynch introduces five elements that have a key role in the act of reading – i.e., understanding – a space:

1) The districts into which the space is divided.
2) The edges that define and delimit the districts.
3) The paths that connect different points within the districts and between the districts.
4) The nodes shaping where the paths intersect.
5) The landmarks in the space, as relevant architectural elements that can be perceptively isolated.

It is clear that these elements are also related to wayfinding when reading a geographical map, which in essence is a visualization of a physical space. In the next section we discuss how, based on these above elements, wayfinding plays an important role in users' interaction with network diagrams, and as such, can be used for better designing this type of visualizations.

IV. Wayfinding in Network Diagrams

Since all visualizations define some form of a visual space, it is easy to understand why some of users' interactions with that space might be similar to wayfinding. For instance, Munzner et al. [18] take a wayfinding approach for interactions with their *TreeJuxtaposer* visualization, by adopting the concept of landmark – originally proposed in the field of urban planning by Lynch [7] – to facilitate the navigation of phylogenetic trees.

In the context of network diagrams, due to the topological nature of the data, the amount of information portrayed, and the necessity to transition between different levels of viewing, a wayfinding-based interaction model can be adopted as well. Here we adopt a semiotic perspective on the process of wayfinding – originally conceived in the context of urban exploration [8] – which defines the following five steps for wayfinding:

1) Mentally build and rebuild the map of the place.
2) Recognise the syntax of the place and of its signal system by evaluating layouts, distances and travel times.
3) Determine the semantic value of the parts and areas of a place by identifying the desired destination's location.
4) Find the instructions about the paths to use to reach the desired destination.
5) Take decisions without hesitation.

Based on this notion of the process of wayfinding, we consider the overall approach to orientation, and then we map the semiotic tasks that constitute the process of wayfinding as they relate to network diagram interaction tasks.

The process of information retrieval in complex networks relies heavily on the topological characteristics of the network. Additionally, users have to orient themselves within a multiplicity of interconnected geometrical elements that can challenge human cognitive abilities [1], [19], [20]. Hence, a semiotic perspective on wayfinding can provide an effective model of how users can navigate the semantic topology which characterises a network diagram.

The first step of the process of wayfinding underlines the fact that the orientation task is iterative, and it cannot be compartmentalised in one step of the user's journey – there needs to be a fluid transition between movement in the network and building of the mental map. The second and third steps highlight that the syntactic aspects of the network should be clear – these can be achieved using a consistent visual notation or language. Finally, the fourth and fifth steps emphasise the importance of clear instructions – there is a need for visual cues to point to precise areas of the network and flag nodes of interest to generate personalised landmarks.

V. Mapping Network Diagram Interactions to Wayfinding tasks

In order to map network diagram interactions and wayfinding tasks, we used the categorisation of network interaction tasks outlined in [1], and the wayfinding tasks enumerated in [8]. The two categorisations are rather fuzzy and there is a degree of intersection between the categories – both within and across the two categorisations. Despite their loose boundaries we could identify a rather marked compartmentalisation. Each wayfinding task can be expressed as a question, whereas every network interaction task is characterised by a number of steps taken to answer a question. Table I provides a summary of the mapping between network diagram interactions and wayfinding tasks.

Mapping **orientation** type wayfinding tasks is perhaps the most challenging one, since orientation is a recursive process. As noted in [8], orientation is about "mentally building and rebuilding the map of the place", and it requires local as well as global information. In other words, if a user wants to answer the question *"where am I?"* while focusing on a node, they will need to know the structural characteristics of the network, and be able to identify the syntactic descriptors of the node they are focusing on.

However, those interactions defined as *attribute-based tasks* are aimed at understanding the local attributes – e.g., which partition of the network the node does belong to. Such information allows the user to understand what the characteristics of the node are without necessarily contextualising it within the network diagram.

The *overview tasks*, on the other hand, have the objective of understanding the global properties that characterise the node in terms of its position within the network structure. Such tasks might entail inquiring whether, for instance, the node of interest is part of a tightly interconnected community of nodes or if it is isolated in the periphery of the network diagram, or if it is a bridge or a hub intersecting several paths of otherwise isolated nodes.

There are a large number of possible inquiries that users might want to perform in order to orient themselves in the network diagram, and be able to extract the information they are looking for. These inquiries are very different in nature, and the sequence that the user might need to follow is not explicit, but extremely contingent – and as such, the possibility of seamlessly switching from one inquiry to another is very likely – regardless of whether they are local or global.

The **exploration** type wayfinding tasks aim to answer the question of *"where can I go?"*. This inquiry can be mapped to topology-based network interaction tasks, involving node connectivity and adjacency – knowing for instance how well-connected a node is, or what it connects to. The exploration can be more or less structured – in other words it can involve a spontaneous random movement between neighbouring nodes, or it can be motivated by expectation. For this reason, exploration tasks should provide insights on connectivity, by highlighting the set of nodes that are reachable from the selected one. The issue here relates to hiding the noise – those edges and nodes that happen to be positioned close to each other without being immediately connected. Also, edges can hinder the perception of connectivity, when they cross the immediate neighborhoods of a node, without being directly related to it.

Finally, the **navigation** type wayfinding tasks are a key part of network diagram interaction, and they aim to answer the question *"how do I proceed?"*. These tasks are related to browsing by following network diagram paths. As noted in [8], navigation can be performed by deploying existing knowledge or using signs offered by the environment.

Navigation is a crucial task that allows actual information extraction from the network diagram, and depends on the two previously described tasks – orientation and exploration. Here the actual interconnection between tasks emerges prominently, and the challenge is to facilitate users' navigation through orientation and exploration – keeping navigation in mind as the ultimate necessity when designing network diagram user interactions. Hence, the user should be able to read the network, understand the topological features of it, and know about the possibilities to connect to neighbouring nodes. However, there are also exceptions to this pattern of interaction, and in fact, it might be the case that the user wants to start from a very specific node of interest. Furthermore, it could be the case that users are interested in specific sections of the network diagram, and therefore might need to be able to highlight a portion of the network as a first step, instead of a singular node or the overall topology of the network.

TABLE I
Mapping of network interactions to wayfinding tasks.

Wayfinding	**Network Interactions**
Orientation *where am I?*	Attribute-based task and Overview *reading the network and understanding the structure*
Exploration *where can I go?*	Topology-based task *node connectivity and adjacency*
Navigation *how do I proceed?*	Browsing task *following paths*

VI. Colocalization Network Explorer

We have developed a prototype network visualization tool, called *Colocalization Network Explorer* (CNE), based on the wayfinding tasks described earlier. In the next section we will use CNE as a case example to discuss its underlying interaction model for network diagrams using the mapping introduced in the previous section.

CNE has been designed and developed in collaboration with the Finnish Institute of Molecular Medicine (FiMM)[1]. CNE is a web application, targeted at molecular biologists, clinicians, data analysts from bioinformatics, and pharmaceutical researchers – enabling tasks ranging from exploration of FinnGen[2] colocalization[3] results to drug design.

In particular, CNE aims to support the exploration of the complex network of diseases and portions of the genome (loci) that contribute to their onset. The connections between nodes (loci and diseases) and the strength of the connections are estimated using colocalization. The results of colocalization studies performed by FinnGen researchers can be mapped as a bipartite graph. CNE is conceptually based on a network visualization [22] portraying the interconnection between loci and diseases.

VII. Network Diagram Interactions

The network diagram interactions provided by CNE supports wayfinding tasks in two different phases of the user's interactions:

1) *Landing phase*: when the user initially views the visualization and has to find a starting point.
2) *Information seeking phase*: during the process that follows, once a starting point has been selected.

It is important to note that in each of these two phases, the wayfidning questions presented earlier – *"where am I?"*, *"where can I go?"*, *"how do I proceed?"* – are in fact rather different, and have to be answered by following a different set of network diagram interaction tasks. Here we present those interactions based on each of the two separate phases.

A. Landing phase

Figure 1 shows an example view of the CNE interface which users get initially at the *landing phase* of their interaction. Faced with a complex network diagram, it is understandable that the user would be unable to answer the first wayfinding question, ***"where am I?"***. In fact, since the users are initially presented with a bird's-eye view of the network diagram, in a sense, they are still externally placed in relation to the diagram, and have to start their interaction by first asking, ***"where can I go?"***. The answer to this question would obviously be related to the user's information seeking aim – i.e., the second phase of their interaction. We identified three possible options at this stage:

- the user is interested in a specific node (e.g., locus, gene, disease).
- the user is interested in a set of edges for a number of reasons (e.g., tissue, strength of the colocalization).
- the user is interested in a specific sub-network (e.g., one ICD-10 category[4] or the intersection between multiple interesting ones).

The last question of landing phase – ***"how do I proceed?"*** – would naturally lead the user into the second phase of their interaction. Answering this question is dependent on the perceived interactive functionality provided to the user in the landing phase through the interface. CNE provides a browsable network diagram – essentially a map – as well as searching functionalities and filters options. Through these other functionalities, the user can exclude uninteresting edges in the network by filtering, find specific nodes by searching, or select an area of interest by zooming into the network diagram.

B. Information seeking phase

After the *landing phase*, and once the starting point has been selected, the actual *information seeking phase* begins. At this point the user has positioned themselves in the network diagram, either on a specific visual element – a node or an edge – or in a loose neighborhood.

During the *information seeking phase* the user is likely to ask the same three wayfinding questions – *"where am I?"*, *"where can I go?"*, *"how do I proceed?"* – and carry out several network diagram interactions in an attempt to answer those questions. This process is then likely to be repeated cyclically.

Once again, ***"where am I?"*** is likely to be the first question asked by the user. As previously pointed out, the question is in itself deeply complex because it initially encompasses two tasks: 1) reading/viewing the network diagram, and 2) understanding its structure. In order to facilitate the first task, a consistent visual syntax must be adopted in representing different elements of the network, and to facilitate the second task, a suitable structure layout algorithm must be followed. In the case of CNE we have used the network spatialization algorithm *forceAtlas2* [23], [24]. Using this algorithm, the communities appear as groups of nodes drawn closer to each other, while hubs attract poorly connected nodes that are connected to them – this provides a strong visual hierarchy.

In addition to the above two tasks, answering the question of *"where am I?"* requires performing two other related tasks: 3) attribute-based tasks, and 4) overview tasks. These tasks are also expected to be performed in a recursive manner, as the users will update their mental map of the network space. To support these tasks, CNE provides a smooth zooming and panning functionality to allow the user to move through the different viewing scales, following the interaction model of a typical interactive map visualization tool – e.g., Google Maps[5].

Although computationally more demanding, the fluid transition between viewing scales has proven to help the users not to lose track of their visual reference [5]. CNE uses *semantic zooming*, in which the magnification factor influences different

[1] https://www.fimm.fi/en/

[2] https://www.finngen.fi/en

[3] Colocalization is a statistical method utilised in molecular medicine to assess whether two association signals are consistent with a shared causal variant [21]

[4] International Statistical Classification of Diseases and Related Health Problems (ICD). For more information see https://www.who.int/standards/classifications/classification-of-diseases.

[5] https://www.google.com/maps/

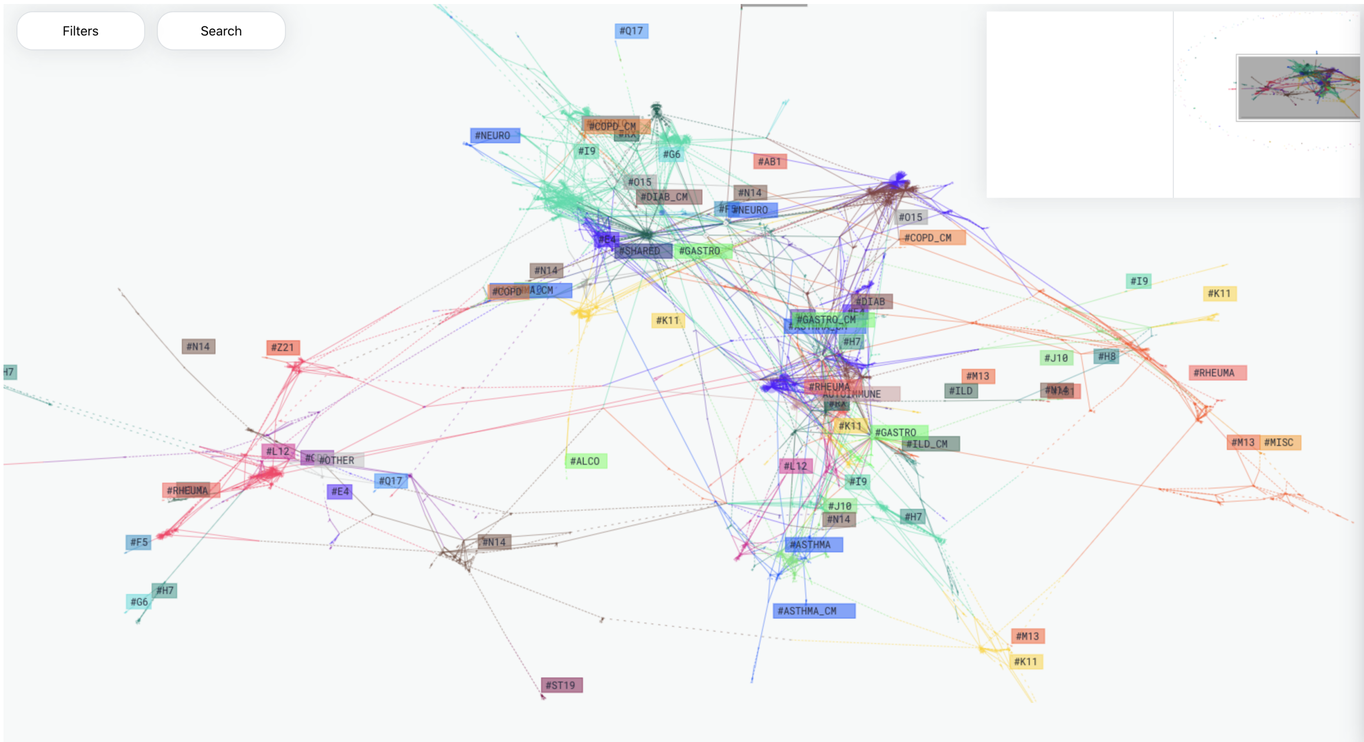

Fig. 1. In the *landing phase*, CNE user is presented with a bird's-eye view of the network diagram.

aspects of the rendering process of the network diagram, as shown in Figure 2. It revolves around three stages:

1) *Global view*: in which the disease nodes are visible, particularly interesting loci are displayed, and the names of disease nodes appear when the mouse pointer hovers over them. In addition, a set of labels – illustrating the ICD-10 code of each relevant neighbourhood – is also displayed. The labels are placed in the centroids of the clusters, obtained by calculating mean shift [25], [26] of the coordinates of the individual nodes of each separate diseases group. This allows identifying the main districts as potential areas of interest in the network diagram.
2) *District view*: is meant for taking a closer look at the neighbourhoods, once the user has found some area that is potentially interesting. In this view, the portion of the network diagram under observation also displays the loci, their code, and neighbouring genes – visible through a label appearing when the mouse pointer hovers on them. The labels are rearranged in function of more detailed clusters, obtained by reducing the bandwidth in centroid calculation.
3) *Local view*: in which the name of each disease node appears as a label positioned close to it.

Given the iterative nature of orientation, it is important to support the users by showing their position within the network diagram, by keeping a reference to the global view. In CNE this achieved adopting an *overview+detail* approach, and displaying a miniature view of the network diagram in a separate area in the top right corner of the visualization, and displaying the position of the main view as a grey rectangular area within the miniature view. This *overview+detail* approach has been found particularly useful in interactive map visualizations [5], [6].

In addition to providing a global view, CNE also supports *focus on details* around where the mouse pointer is hovering. Our informal user testing has shown that in global and district views, the users require some hint on their precise position – as another example of the need between locating oneself locally and globally at the same time. CNE provides a magnified *focus on details* view of the immediate surrounding of the mouse cursor, and positions it close to the global view of the network diagram. This weighted-triptych approach allows the three views we have identified to be available fluidly during the process of orientation. In this way, the user can decide which level of overview they want to have, and consequently, what level of detail they need in forming and updating their mental model of the network diagram. However, in order to avoid the redundancy and the resulting hindered performance – related to *overview+detail* and *semantic zooming* as noted by Cockburn et al. [5] – we removed the *focus on details* option from the local view.

The second question of ***"where can I go?"*** becomes more relevant once users have an idea of their current position in the network diagram, and would start inquiring about its connectivity to the other parts of the network – i.e., start thinking about topology-based tasks. CNE shows connectivity once the user has clicked on a node. At that point, the rest of the network fades, leaving visible the selected node, the

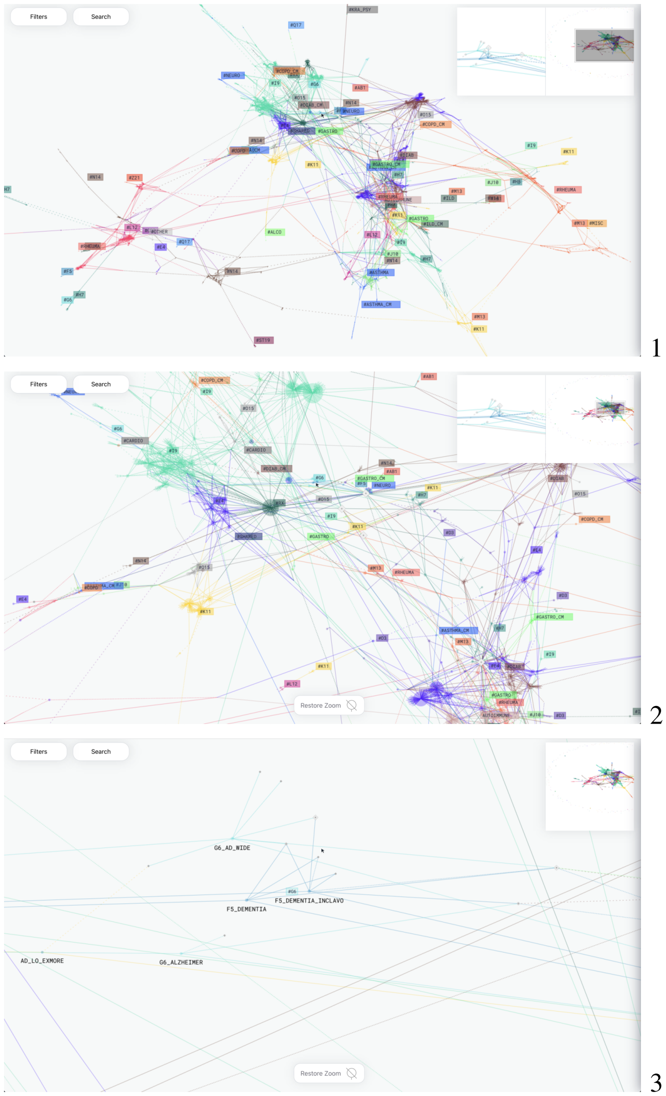

Fig. 2. CNE supports three levels of semantic zooming: 1) global view, 2) district view, and 3) local view.

nodes that are immediately connected to the selected node, and the relative edges. This, in turn, provides a visible choice of possible nodes to move to from the selected position.

There are, however, cases in which even the immediate neighbours are located far away – in terms of the euclidean coordinates on the visualization display – from the selected node. This is due to the non-linear nature of the network structure where neighbours can belong to different communities or be under the influence area of different hubs. As such, the spatialisation algorithm prioritises some connections over others due to the global structure of the network diagram.

In CNE, cases like this can potentially disclose relevant information about peculiarities in locus-disease interconnection. To keep track of displaced neighbours, CNE provides a scrollable list, enumerating all the nodes in the selection. When hovered over with the mouse pointer, each item in the list triggers a visual cue pointing at the relative node on the network diagram – in the form of a grey line that connects the list item and the node in the network. A similar approach has also been adopted for cases where users would be interested in a specific sub-network. CNE makes it possible to compose such a sub-network by clicking on several new nodes, or by selecting all of the nodes belonging to, for instance, one ICD-10 category by clicking on the relative label.

The third question of ***"how do I proceed?"*** can be answered by undertaking browsing type network diagram interactions. To support browsing, CNE provides a mouse interaction that highlights hovered nodes, and their neighbourhood, once a node is selected.

Given the semantic nature of the space represented by a network diagram, another possible browsing action is to jump from the local position to another node that is not connected to the previous one. This might perhaps be to investigate a possible relationship between two unconnected nodes, or to start a new *information seeking task* from another location. This in turn might entail a transition back to the *landing phase* – i.e., questioning once again the current position by asking *"where am I?"*.

As this scenario shows, the two questions – in fact all three questions – are tightly related and the transition between the tasks involved in answering one or the other can be fuzzy. To support this fuzzy relationship between information seeking interactions, CNE makes the search menu available at all the three viewing scales – global, district, local. Additionally, the textual input includes a filtered list of nodes. As with the list of clicked nodes, hovering on the list items triggers a visual aid that points at the relative node, even if it is not being viewed in the current viewport. To keep consistency within the visual representation, CNE uses a grey line to show such connections – as used in the list supporting the exploration tasks discussed above.

VIII. Conclusions

In this paper, we have discussed the idea of using a wayfinding-based mental model, which is already familiar to most people, as a means of easing users' interactions with network diagram visualizations. To support this, we have mapped the three main wayfinding type tasks performed using map visualizations – i.e., orientation, exploration, navigation – to three categories of network diagram interactions. Our case study example has also shown that this mapping can aid the design process as well. In fact, by subdividing the interpretative task into parts that are characterised by different properties – e.g., user needs – it is possible to individuate different design opportunities [2]. Additionally, this would allow to identify and implement familiar functionalities that are commonly used in interactive maps.

This work presents an initial attempt at better understanding the concept of complexity in general, and visual complexity in particular, and defining ways of making complex visualizations navigable through intuitive user interactions. Our aim is to analyse complexity in the context of other types of visualizations and formulate appropriate means of dealing with complexity in a wide range of visualizations, perhaps using alternative existing mental models and metaphors to support the design of such visualizations and users' interaction with them.

ACKNOWLEDGEMENTS

The work of Nicola Cerioli is supported by funding from the FinnGen project (https://www.finngen.fi/en).

ETHICS STATEMENT AND MATERIALS AND METHODS

Patients and control subjects in FinnGen provided informed consent for biobank research, based on the Finnish Biobank Act. Alternatively, separate research cohorts, collected prior the Finnish Biobank Act came into effect (in September 2013) and start of FinnGen (August 2017), were collected based on study-specific consents and later transferred to the Finnish biobanks after approval by Fimea (Finnish Medicines Agency), the National Supervisory Authority for Welfare and Health. Recruitment protocols followed the biobank protocols approved by Fimea. The Coordinating Ethics Committee of the Hospital District of Helsinki and Uusimaa (HUS) statement number for the FinnGen study is Nr HUS/990/2017. The FinnGen study is approved by Finnish Institute for Health and Welfare (permit numbers: THL/2031/6.02.00/2017, THL/1101/5.05.00/2017, THL/341/6.02.00/2018, THL/2222/6.02.00/2018, THL/283/6.02.00/2019, THL/1721/5.05.00/2019 and THL/1524/5.05.00/2020), Digital and population data service agency (permit numbers: VRK43431/2017-3, VRK/6909/2018-3, VRK/4415/2019-3), the Social Insurance Institution (permit numbers: KELA 58/522/2017, KELA 131/522/2018, KELA 70/522/2019, KELA 98/522/2019, KELA 134/522/2019, KELA 138/522/2019, KELA 2/522/2020, KELA 16/522/2020), Findata permit numbers THL/2364/14.02/2020, THL/4055/14.06.00/2020, THL/3433/14.06.00/2020, THL/4432/14.06/2020, THL/5189/14.06/2020, THL/5894/14.06.00/2020, THL/6619/14.06.00/2020, THL/209/14.06.00/2021, THL/688/14.06.00/2021, THL/1284/14.06.00/2021, THL/1965/14.06.00/2021, THL/5546/14.02.00/2020, THL/2658/14.06.00/2021, THL/4235/14.06.00/2021 and Statistics Finland (permit numbers: TK-53-1041-17 and TK/143/07.03.00/2020 (earlier TK-53-90-20) TK/1735/07.03.00/2021). The Biobank Access Decisions for FinnGen samples and data utilized in FinnGen Data Freeze 8 include: THL Biobank BB2017_55, BB2017_111, BB2018_19, BB_2018_34, BB_2018_67, BB2018_71, BB2019_7, BB2019_8, BB2019_26, BB2020_1, Finnish Red Cross Blood Service Biobank 7.12.2017, Helsinki Biobank HUS/359/2017, Auria Biobank AB17-5154 and amendment #1 (August 17 2020), AB20-5926 and amendment #1 (April 23 2020), Biobank Borealis of Northern Finland_2017_1013, Biobank of Eastern Finland 1186/2018 and amendment 22 § /2020, Finnish Clinical Biobank Tampere MH0004 and amendments (21.02.2020 & 06.10.2020), Central Finland Biobank 1-2017, and Terveystalo Biobank STB 2018001. We want to acknowledge the participants and investigators of FinnGen study. The FinnGen project is funded by two grants from Business Finland (HUS 4685/31/2016 and UH 4386/31/2016) and the following industry partners: AbbVie Inc., AstraZeneca UK Ltd, Biogen MA Inc., Bristol Myers Squibb (and Celgene Corporation & Celgene International II Sàrl), Genentech Inc., Merck Sharp & Dohme Corp, Pfizer Inc., GlaxoSmithKline Intellectual Property Development Ltd., Sanofi US Services Inc., Maze Therapeutics Inc., Janssen Biotech Inc, Novartis AG, and Boehringer Ingelheim. Following biobanks are acknowledged for delivering biobank samples to FinnGen: Auria Biobank (www.auria.fi/biopankki), THL Biobank (www.thl.fi/biobank), Helsinki Biobank (www.helsinginbiopankki.fi), Biobank Borealis of Northern Finland (https://www.ppshp.fi/Tutkimus-ja-opetus/Biopankki/Pages/Biobank-Borealis-briefly-in-English.aspx), Finnish Clinical Biobank Tampere (www.tays.fi/en-US/Research_and_development/Finnish_Clinical_Biobank_Tampere), Biobank of Eastern Finland (www.ita-suomenbiopankki.fi/en), Central Finland Biobank (www.ksshp.fi/fi-FI/Potilaalle/Biopankki), Finnish Red Cross Blood Service Biobank (www.veripalvelu.fi/verenluovutus/biopankkitoiminta) and Terveystalo Biobank (www.terveystalo.com/fi/Yritystietoa/Terveystalo-Biopankki/Biopankki/). All Finnish Biobanks are members of BBMRI.fi infrastructure (www.bbmri.fi). Finnish Biobank Cooperative -FINBB (https://finbb.fi/) is the coordinator of BBMRI-ERIC operations in Finland. The Finnish biobank data can be accessed through the Fingenious® services (https://site.fingenious.fi/en/) managed by FINBB.

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