Understanding and Improving Directly-Follows Graphs: The Cognitive Perspective

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Abstract

Visualizations are a key component for effectively communicating the results of process mining, supporting analysis capabilities and enabling informed decision-making. The most commonly used visualization in process mining is the directly-follows graph (DFG), preferred by practitioners due to its simplicity. However, despite their prevalence, there is a lack of systematic research into how users cognitively process DFGs and which factors influence their comprehension. This PhD project aims to extend the scarce research on this topic by establishing an initial understanding of DFG comprehension, translating these insights into design guidelines, and developing visual guidance. First, we analyze the extent to which existing empirical insights from traditional process model comprehension and graph visualization can be transferred to DFGs. Second, it employs an eye-tracking study to qualitatively uncover the comprehension strategies and patterns users naturally follow. Third, it conducts a series of quantitative controlled experiments to measure the impact of layout on DFG comprehension Lastly, it explores how visual guidance mechanisms can be actively applied to support users during DFG exploration.

Keywords

Directly-Follows Graphs, Cognitive Perspective, Process Discovery, Visualizations, Comprehension

1. Introduction

Visualizations are a key component to effectively communicate the results of process mining, supporting analysis capabilities [1, 2] and enabling informed decision-making [3]. Only if users can retrieve the necessary information from these visualizations, business value can be created [4]. The most commonly used visualization in process mining are directly-follows graphs (DFG), a process-mining-specific notation, where nodes represent activities and edges represent directly-follows relations between them, i.e., one activity is directly followed by another [5, 6]. This notation is preferred by practitioners over others due to its simplicity, as DFGs only consist of nodes and edges and contain no explicit decision points [6, 7]. Thus, DFGs are most commonly used to gain a first understanding of the process [6, 7].

To actually comprehend a DFG, users need to cognitively extract, hold, and integrate information from it to build a mental representation, i.e., an internal model of the underlying information. This cognitive process is constrained by working memory, i.e., the limited cognitive capacity available for active information processing. Because this capacity is limited, various aspects, e.g., the design of the representation, directly impact the cognitive effort required for comprehension [8, 9]. Therefore, understanding DFG comprehension and its underlying cognitive efforts is essential for process mining, as research on it provides important insights into the human-computer interaction of DFGs, e.g., how users navigate, interpret, and understand them [10, 11]. These insights could guide researchers and vendors in the visual design of DFGs, enabling them to provide users with more comprehensible, and hence more useful DFGs [10]. Consequently, this could lead to a more aligned DFG use, advancing long-term process mining adoption due to a better user experience.

However, despite the widespread adoption and relevance of DFGs, research on their comprehension remains scarce. Only a few existing studies analyzed isolated aspects of DFG comprehension [12, 6]. Thus, this PhD project aims to extend research on it by developing an initial and systematic

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understanding of DFG comprehension, translating these insights into design guidelines, and creating visual guidance, addressing four specific issues. First, it is unclear to what extent existing knowledge from related fields can explain DFG comprehension, or where DFG-specific research is necessary. Establishing this understanding will ensure subsequent studies are well-grounded and targeted, focusing on the parts where DFG-specific research is needed. Second, we currently lack empirical evidence on how users actually engage with and navigate DFGs. This understanding is essential, as DFG designs can only be meaningfully improved if they are aligned with the cognitive strategies users naturally employ. Third, while the design of a representation is known to affect comprehension, it remains unknown which specific factors impact DFG comprehension and how. Addressing this would provide tool vendors with concrete, evidence-based design guidelines. Finally, even well-designed DFGs may leave users without sufficient support during exploration. Therefore, it is necessary to understand how visual guidance can be used for DFGs to actively assist users where other improvements alone are insufficient.

Consequently, we address the following four research questions (RQ), building upon the first one:

RQ1: To what extent can insights and empirical findings from related domains be transferred to DFG comprehension or where is DFG-specific research necessary?

RQ2: How do users engage with and navigate through DFGs when performing process analysis tasks?

RQ3: How do specific factors influence user comprehension of DFGs?

RQ4: How can visual guidance support comprehension of and what mechanism can be used for DFGs?

To answer these questions, we employ different methods, including a systematic literature review (SLR) [13], qualitative and quantitative empirical research [14, 15, 16], and design science [17].

The rest of the paper is structured as follows: In Section 2 we provide the state of the art on this topic. Next, we outline in Section 3 the research agenda with a detailed description of each RQ, including its aim, employed research method, current status and (preliminary) results. Afterwards, in Section 4, we outline the remaining steps and open challenges.

2. State of the Art

Research on the comprehension of process mining visualizations remains limited, and work specifically addressing DFGs is almost absent. Process mining researchers have acknowledged the importance of suitable visualizations for supporting analysis and decision-making [2, 3, 18, 19], but their development has largely been left to tool providers, each of whom designs visualizations according to their own context and goals. This leads to substantial differences between same visualization types across tools [18, 6].

Recent work has started identifying and categorizing what visualizations exist in process mining and what they contain [5, 20], yet research still lacks to consider the cognitive perspective, i.e., how users cognitively process the information presented to them [10, 11]. Mendling et al. [10] have called for greater attention to this perspective, arguing that such insights are essential to improve human-computer interaction by tailoring visualization design to users' information needs. One such lens is the PEM4PPM model [11], which conceptualizes process mining as a cognitive cycle. Within this cycle, DFGs are primarily used in the Focus and Explore steps, on which this PhD project centers.

For DFGs specifically, only two relevant studies exist to our knowledge. One empirically compares the usability and expressiveness of DFGs with that of a state-of the-art tool for visualizing human activities based on sensor logs [12]. The other study highlights limitations and key considerations for practitioners without assessing comprehension [6]. Thus, currently no holistic understanding of how DFGs are processed cognitively exists.

3. Research Agenda

The research agenda (Figure 1) is structured into four parts, building all on the first RQ. In the following, we describe each RQ, including its objective, employed method, current status and (preliminary) results.

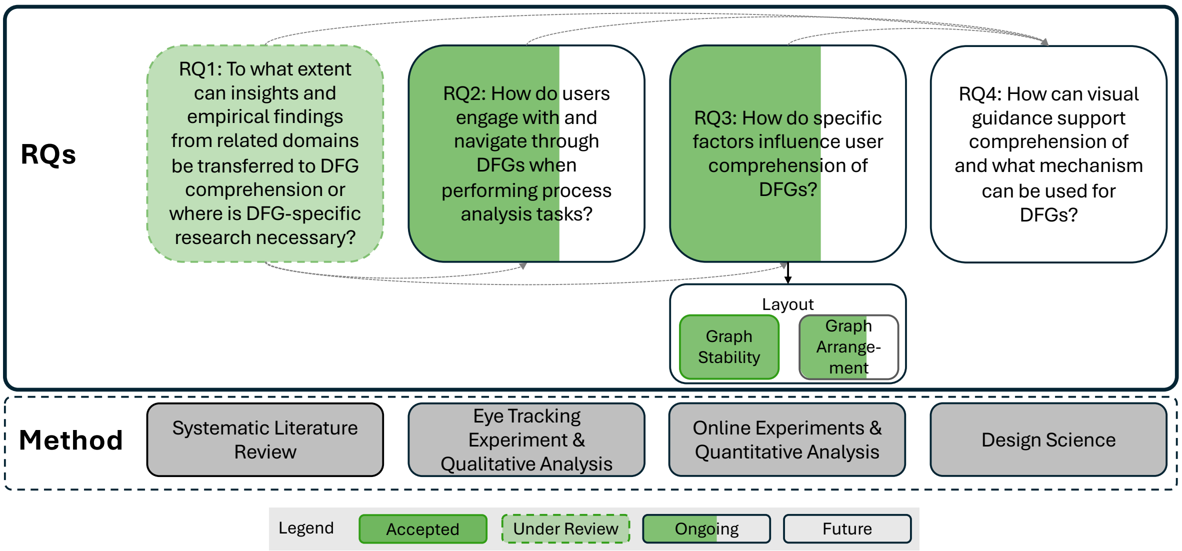

Figure 1: Research Agenda of this PhD project, including research questions, methods and current status

3.1. RQ1: Overview of Insights from Relating Fields and Relevance to DFGs

Objective. With the first research question, we aim to analyze, which insights from relating fields, looking beyond the immediate domain of process mining, specifically process model comprehension and graph visualization, are also of relevance and can be applied to DFGs. We selected these fields due to similarities between their models or graphs and DFGs. However, DFGs remain a specialized notation within process mining, with significant differences that may limit the direct transferability of these insights [5, 6]. Thus, we aim to identify which influencing factors and research methods from these fields can be applied to DFGs and where specific research is needed. Based on this analysis of differences and similarities, we build a research agenda outlining what future research needs to tackle.
Method. We chose as the method a SLR [13]. We extended existing SLRs from two related fields using specific search strings and following the PRISMA flow [21]: the comprehension of manually constructed process models, such as Business Process Modeling Notation (BPMN), as reviewed by Figl (2017) [22], and the comprehension of (dynamic) graph visualizations, as reviewed by Burch et al. (2021) [23]. By analyzing the influencing factors studied and methods used in these fields, we aimed to identify those applicable to DFG comprehension and to highlight where DFG-specific research is still needed.
Current State & (Preliminary) Results. We have conducted the SLR, which provides an overview of the related fields, and analyzes influencing factors from these fields (process modeling and graph visualization). Based on these insights, we establish a research agenda for DFG comprehension, highlighting research gaps and paths for DFGs. It describes in detail what influencing factors and research methods should be tested and applied for DFG comprehension. This work is currently under review [24].

3.2. RQ2: DFG Comprehension Strategies and Behavior of Users

Objective. Among the research gaps identified in RQ1, the second research question addresses one of the most relevant ones: the lack of empirical evidence regarding how users engage and navigate through DFGs. Building on this gap, RQ2 aims to uncover the fundamental cognitive strategies and behaviors users employ when interacting with DFGs. Understanding this is critical for determining if current tool designs align with users cognitive behavior. The objective is to identify comprehension strategies, i.e., the procedural steps taken to solve specific tasks, and comprehension patterns, i.e., the overarching approaches users take when exploring processes with DFGs of varying complexity. Thus, we aim to provide an initial empirical understanding of how users navigate DFGs.
Method. To address this, we conducted an eye-tracking study [25, 26, 27] using a within-subject design with 49 participants. We employed eye-tracking to capture objective, high-resolution data on visual

attention that is not accessible through other methods [26]. Users needed to perform representative process analysis tasks across different DFGs of varying layout and complexity. To analyze the resulting eye-movement data, we followed an exploratory approach based in grounded theory [15] through a qualitative and inductive coding process [14]. By synthesizing the users' scanpaths, we aimed to identify distinct comprehension strategies and patterns across users applied when working with DFGs.
Current State & (Preliminary) Results. Our first analysis provides initial insights into how users navigate and process DFGs of varying complexity. We identified varying comprehension strategies and patterns showing differences between users and highlighting the need for further support when complexity increases. Currently, we are extending this initial analysis to strengthen its methodological rigor and to synthesize them into higher-level findings with broader implications for DFG research.

3.3. RQ3: Influencing Factors of DFG Comprehension

Objective. Also identified as a promising research gap in RQ1, RQ3 complements RQ2's qualitative focus on user behavior by quantitatively isolating the causal effect of specific factors on comprehension. We particularly want to evaluate how layout, conceptualized through graph stability and graph arrangement, impacts comprehension, and consequently, performance. We selected these factors, as they seem promising and of high relevance based on our findings in RQ1. Moreover, due to the dynamic nature of DFGs, especially graph stability is unique and critical to DFGs [28]. When considered together with graph arrangement, which focuses on the underlying data, the process, and has been so far often overlooked when designing DFGs [29, 30], we aim to provide deeper insights into how layout affects comprehension. By analyzing these influencing factors, we provide design guidelines for process mining tools on how to improve DFG comprehension through layout.
Method. We address this question through a series of controlled experiments following a between-subject design to quantify the effects of the different influencing factors. For each experiment, we derive a research model grounded in established information systems theories [8, 9, 31, 32]. These theories have also been used to study process model comprehension in related fields. After the data collection, we analyze the results quantitatively using appropriate statistical models. For our first study, where we analyzed how graph stability affects comprehension [28], we built our research model on Cognitive Fit theory [9, 33], as this theory allowed us to analyze the cognitive processes considering both the representation and the task. Next, we aim to extend this study by comparing not only graph stability but also by considering graph arrangement, and thus the layout of the DFG [29].
Current State & (Preliminary) Results. We have so far analyzed graph stability as an influencing factor. Thus, we assessed the concept of the mental map as an influencing factor and found that, contrary to common assumptions in dynamic graph research [28], mental map preservation did not lead to an improvement in performance. This study has been accepted and presented at BPM 2025 [34].

3.4. RQ4: Visual Guidance for DFGs

Objective. Building on the insights gathered in the previous RQs, RQ4 goes one step further by directly supporting users during exploration through visual guidance, i.e., a computer-assisted process that supports users through targeted visual techniques during interactive exploration [35]. The comprehension strategies and patterns identified in RQ2, together with our RQ3 findings that layout optimization alone cannot fully address comprehension challenges, motivate the need for guidance mechanisms that go beyond passive design improvements. Thus, we aim to design and evaluate concrete guidance mechanisms, such as visual highlighting or adaptive recommendations , tailored to the specific challenges users face. These mechanisms actively assist users in their cognitive processes to comprehend DFGs.
Method. Consequently, we aim to follow a design science research approach [17]. First, we need to gain a systematic understanding of visual guidance and how it can be applied to DFGs, building on findings from visual analytics [35]. Second, we aim to design and prototypically implement specific guidance mechanisms, e.g., visual highlighting. Third, we empirically evaluate the implemented mechanisms

through controlled experiments [16], measuring their impact on comprehension and performance. These results then offer evidence-based guidance mechanism for DFGs in process mining tools.
Current State & (Preliminary) Results. We have not yet started working in detail on this RQ.

4. Discussion

In the following, we highlight the remaining steps and open challenges of this PhD project.
Remaining Steps. Concerning RQ2, we need to extend the initial analysis on the identified DFG comprehension strategies and patterns by strengthening its methodological rigor and synthesizing the results on a higher level with more concrete implications for DFG research.

For RQ3, we still need to study the combined effect of graph stability and arrangement. Thus, we need to finalize our theorizing, currently building on the Cognitive Load and Fit theory [9, 33, 8], as their combination allows us to analyze the dilemma we encounter cognitively with DFGs due to their arising complexity and their dynamic nature. To operationalize this, we developed a between-subject online experiment, which considers graph stability and process-aligned graph arrangement [29]. It compares three different layout concepts ([36] vs. [29] vs. [34, 28]). We still need to conduct the experiment and afterwards statistically analyze the results. We also aim to revisit the eye-tracking data collected for RQ2, which also captures user behavior across DFGs of varying graph arrangement, to extract additional cognitive insights specific to layout. This data still needs to be analyzed quantitatively, considering specific eye-tracking measures, e.g., fixations [26].

For RQ4, all steps remain to be completed. Following design science research, we first need to develop a systematic understanding of visual guidance for DFGs by identifying which mechanisms applied in visual analytics are applicable to our case. Based on this, we select specific guidance mechanisms to implement and empirically evaluate them in a controlled setting [37]. Based on our findings from RQ1, we identified visual highlighting as one commonly applied mechanism, which we aim to compare through different options for newly added or changed information in DFGs, specifically no highlighting vs. color highlighting vs. animation [22, 23]. To ground this theoretically, we still need to evaluate candidate theories, including Cognitive Theory of Multimedia Learning [31] and Physics of Notations [32]. However, this still requires further elaboration and assessment.
Open Challenges. A primary challenge is the construction of rigorous empirical experiments that balance the experimental control needed to isolate individual DFG factors with the practical complexity of how DFGs are actually used in process mining practice [16]. Furthermore, the scarcity of existing empirical research on cognitive aspects and model comprehension in process mining means there are few established experimental procedures, or tasks taxonomies, against which we or others can validate or compare our findings. Moreover, the theoretical grounding of our studies is challenging, as it requires a careful selection and adaption of theories from related fields with a justification of their applicability to our use case. Finally, a substantial challenge lies in the interdisciplinary integration of process mining, visual analytics, and information systems, being all essential to develop a understanding of DFG comprehension. However, they differ significantly in their focuses, methodological standards, and research approaches, making it difficult to fulfill the expectations from all three of them. Especially for RQ4, we need to evaluate how well we can transfer guidance mechanisms from visual analytics to DFGs, a question that remains largely unexplored, and how easily they can be implemented.

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Declaration on Generative AI

During the preparation of this work, the author used Claude in order to: check grammar and spelling, and improve writing style. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the publication's content.

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