ABSTRACT

MAHTANI, RAUNAK. Analyzing Research Practices, Mapping Problem Dynamics, and Fusing Frameworks: a Systemic Design Inquiry in Postpartum Healthcare. (Under the direction of co-chairs Professors Carolina Gill and Kelly Umstead).

As design is increasingly interested in the wicked problems of this age, the tools, and techniques we use must effectively enable us to make sense of complexity. Systems thinking offers a rich array of tools such as causal loop diagrams and stock-and-flow diagrams for this purpose. The more nascent field of systemic design explores the possibilities at the overlap of the two disciplines. Grounded in the domain of postpartum healthcare, this dissertation is a systemic design exploration from three perspectives: understanding the current state of practice, applying systemic design to understand postpartum health education, and ideating novel systemic design frameworks. In aim 1, through a systematic review of the literature, we build a comprehensive picture of the qualitative coding approaches used by researchers across domains. We also review the challenges experienced in this process, the techniques by which leverage is identified, and the visualization practices used for causal diagrams. We hence identify practices for designers to benefit from, and opportunities for design to contribute to. By deconstructing the current state of practices, we identify a range of coding activities that researchers can use to build their own analysis approach. In aim 2, we conduct a qualitative analysis of a focus group discussion with postpartum birthing persons and produce a causal loop diagram. As a result, we build a preliminary dynamic hypothesis of the drivers of postpartum health education and patient health for hypertension. We also test a combination of methods that draw on our learnings from the systematic review. In aim 3, we reflect on the causal visualization-related challenges described in the systematic review supplemented by additional literature and review the ways in which these have currently been resolved. We then propose two alternative types of diagrams or visual

frameworks that combine practices from systems thinking and design. We believe that these diagrams can help engage stakeholders and can communicate additional valuable analytical information.

Analyzing Research Practices, Mapping Problem Dynamics, and Fusing Frameworks: a Systemic Design Inquiry in Postpartum Healthcare

by
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BIOGRAPHY

Raunak Mahtani is a multi-disciplinary designer and researcher with experiences across various design fields such as user experience design, industrial design, and design research. He is interested in a transdisciplinary practice of design with the long-term goal of contributing to solving complex social problems. Hence, he is interested in various approaches that can usefully complement design, such as systems thinking, psychology, behavioral economics, and data science.

His design work has spanned experiences in the industry and academia and ranged from various in projects in healthcare, e-commerce, and consulting. He strives to stay curious, to continue to learn, to explore, and to make. Outside of work, he enjoys silly jokes, good conversation, fresh air, complex food flavors and good music.

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Introduction

ABOUT THIS DISSERTATION

The field of design is evolving from having a product and artifact centric focus to one that is increasingly broader, and considering issues such as experience, sustainability, and transformation. I am deeply interested in design for health and design for social impact, both of which are fields with no shortage of complexity - plenty to go around for us all to keep racking our brains and hearts for hours, days, years on end! Yet, the monolithic, capital D design thinking approach by itself seems insufficient for many complex problems of the day. We as designers and design researchers need synergy with other disciplines that have strengths complementary to ours. I believe that systems thinking is one such discipline. Systems thinking has been described as a paradigm, a language and a technology (1). I believe that the language component is key here. The vocabulary of systems thinking enables very new ways of looking at problems, that indirectly can shift our paradigms. I believe that if we do the hard work of translating, combining, and trying to communicate across the "language barriers" of the worlds of design and systems thinking, we might be able to see the complexity in this world better, and we might be able to design and act in more sophisticated ways, as this beautifully complex world surely deserves.

Two sets of experiences in the years of my Ph.D. journey form the ground for this project. For a large part of this duration, I have been a research assistant with the Postnatal Patient Safety Learning Lab with my advisors and team at NC State University. Along with our team at this multi-university collaborative, we have studied the complexity behind postpartum maternal healthcare experiences, and learned about the journeys of patients, support persons, and care team members as they navigate the postpartum journey. I have been involved with data collection activities such as workshops and interviews, data analysis, developing interventions,

and storytelling efforts. In parallel, I have explored the world of systems thinking at UNC Chapel Hill thanks to my advisor, friends, and teammates there. This has been an engagement that started with a course in systems thinking and evolved into partnering over multiple projects and participating as finalists in a global systems thinking competition.

This dissertation hence explores the overlap of design and systems thinking in three specific ways, each represented by a research paper:

- Chapter 2 is a systematic review of the literature about qualitative coding for the generation of causal loop diagrams, a common systems thinking visual framework or diagram. This review also investigates how the included studies identify leverage or opportunity areas, their visualization practices, and challenges faced. Hence, the goal here is to learn of the different ways to study a complex systems issue and to identify leverage. Qualitative approaches investigated here may have greater compatibility with design methods.
- Chapter 3 applies systems thinking to the complex problem of postpartum health education about hypertension. This paper analyzes the data for a focus group with postpartum birthing persons through a rigorous method developed by combining practices learned through the systematic review in chapter 2. This leads to the development of a preliminary dynamic hypothesis in the form of a causal loop diagram describing the interrelated drivers of postpartum health education and patient health. Using methods of leverage analysis, potential opportunity areas for intervention are identified.
- Chapter 4 explores the combination of visual frameworks or diagram types from systems thinking and design. The systematic review in chapter 2 suggests challenges for causal diagrams to be comprehended by its users, and to represent nuances of causal complexity. Considering these problems through a design lens, two alternative types of diagrams – causal loop storyboards and causal loop journey maps – are proposed.

POSITIONALITY STATEMENT

I approach this project with a deep interest in design for social change and complexity. Also, I identify as a male person and have never closely experienced someone in my adult life go through the pregnancy or postpartum journey. These are key aspects of my positionality that shape how I approach this work.

Drawing from a gradual realization that many contemporary social problems are highly complex or 'wicked', I have developed an interest in complexity over time. This interest or belief shapes my usage of systems thinking as a theoretical perspective for this project. It brings the potential benefit of understanding complex interactions and building a holistic view. But opposite to the typical phrase of 'missing the forest for the trees', this runs the risk of 'missing the trees for the forest'. There is a possibility that the localized or micro-level details that may only be glanced at through such a perspective may be very important. There is the possibility that zooming out far enough to see the whole system, I might find myself squinting a bit.

Lastly and most importantly, my perspective as a male individual has a deep impact on my work studying postpartum healthcare experiences. The distance I have from the experience of maternal health and healthcare makes it difficult for me to fully relate to or to deeply empathize with issues faced by the research participants I have worked with. It also implies that I have less content knowledge, to begin with. This might impact the knowledge generated in this work. It is a challenge of empathy that I have hoped to overcome to the best of my abilities. With this same relationship to the topic, there is also the potential benefit of having a neutral and detached perspective on the issue - an 'etic' as opposed to an 'emic' viewpoint.

Chapter 2

Qualitative Coding Practices for Generating Causal Diagrams: A Systematic Literature Review

Project team includes Hiba Fatima, Doyoung Kim, & Dr. Kristen Hassmiller Lich

Abstract

Wicked problems of the present times demand research practices that enable understanding the various layers and facets of causal complexity. Systems thinking offers impactful tools and practices for this. Causal diagrams such as causal loop diagrams and stock-and-flow diagrams are one such genre of tools. Qualitatively generating causal diagrams can be an effective way to incorporate rich information, and to make findings accessible for diverse stakeholders. Yet the methodological development of qualitative coding approaches for developing causal diagrams has been quite limited. In our observation, substantial methodological developments began to emerge in the literature since 2012 beginning with the work of Kim and Andersen (2). To understand the landscape of how the methods have evolved, and the gaps and challenges that remain, we conduct a systematic literature review of qualitative coding practices of applied and methodological studies involving the generation of causal loop diagrams across disciplines, as described in published research over a more than ten-year period from January 1, 2012, until September 2, 2022. By analyzing the core activities and variations of the methods, we describe practices related to qualitative coding activities and steps, artifacts and documentation used, type of information coded, identification of leverage points (i.e., high-impact points for action), diagram visualization, and describe challenges reported by the studies. Our findings present a comprehensive picture of causal diagramming practices that can be used by researchers to develop their own methodological approach. We also identify multiple areas needing future research. By studying qualitative methods for documenting complexity, our findings present useful approaches for design researchers interested in wicked problems, as well as areas of opportunity for designers to impact contemporary problems in systems thinking.

Relevance for design:

- Identifying qualitative practices to strengthen ways to investigate wicked problems in design and identify areas of leverage
- Identifying opportunities for using design practices to improve coding and visualization practices in systems thinking

Relevance for systems thinking:

- Comprehensively reviewing current state of qualitative causal coding practices
- Deconstructing current state of practice to identify methodological activities that researchers can consider and assemble to create their own coding practices

Introduction

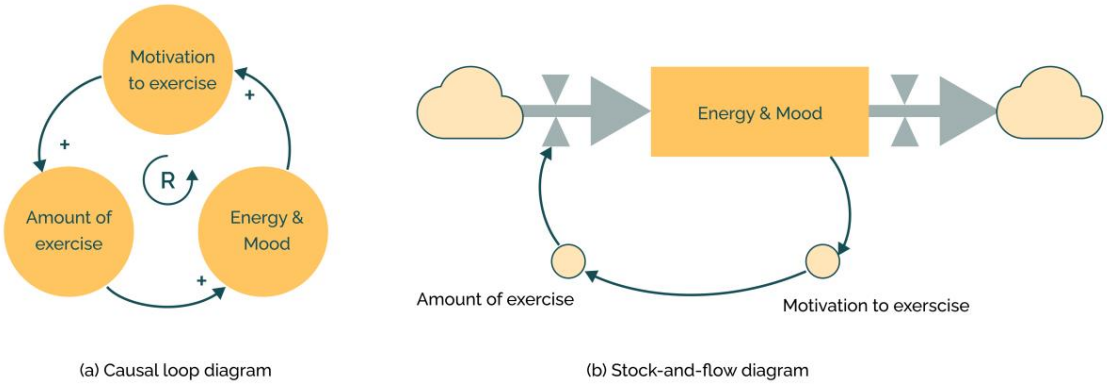
Wicked problems are by their nature ill-defined and messy, and the way wicked problems are described determines their possible solutions (3). Many important global challenges of present times are wicked by nature – climate change, social and racial disparities, and public health, among many others. Wicked problems include complex dynamics and causal interactions (4). To begin to address the wicked problems of today, we must be able to grasp and understand their various layers, facets, and emergent dynamics. Systems thinking (here, interchangeably described with the related concepts systems theory, system dynamics and systems view) is a domain-agnostic discipline with the potential to address the wicked challenges of the day. At its core, it is about holistic and integrative thinking – with the tenet that the sum is greater than its parts and cannot be understood through reductionism and isolation (1). It focuses on understanding behavior and structure (5). Originating as a response to reductionist science in the early 20th century, a systems view was born in the field of biology as General Systems Theory (1). Since then, systems thinking has taken multiple forms and been applied in various fields across the physical and social sciences. It is simultaneously a paradigm, language, and technology - it can be a way to think about the world and relationships, a way to diagram systemic understanding, and as technology for modeling and simulation of systems, respectively

(6). Hence, by taking a holistic and integrative view that considers relational aspects, systems thinking has the potential to impact wicked challenges.

The language of systems thinking is key to communicating complexity through its various visual and analytical tools, a subset of which are causal diagrams. Causal loop diagrams and stock-and-flow diagrams are two such diagrams that are often used to represent complex causality (1,7). Figure 2.1 shows simple examples of causal loop diagrams and stock-and-flow diagrams. A causal loop diagram consists of a network of causal relationships between variables, represented by variables and arrows/linkages between them. Arrows indicate causal linkages wherein a change in the first variable will trigger a change in the connected variable, all else equal. A '+' or 's' sign corresponding to a link is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding increase (decrease) in the connected variable, or that they move in the same direction. A '-' or 'o' sign is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding decrease (increase) in the connected variable, or that they move in opposite directions. This sign is also referred to as the polarity of the relationship. Chains of arrows that close a circle (and thus repeat) are important structures and can be of two types. A reinforcing feedback loop is like a 'vicious cycle' or 'virtuous cycle' (depending on whether results are desired or not), where an increase in one of its variables leads to its own continued increase over time, or a decrease in the variable leads to its continued decrease over time. Reinforcing loops are powerful and drive exponential change. A balancing feedback loop on the other hand 'keeps the system in check', where an increase in a variable is balanced by a decrease in it over time, and vice versa. Balancing loops are also important in that they resist change.

A stock-and-flow diagram (8) takes a similar form of a combination of variables and linkages. Stocks are focal variables that represent quantities that can accumulate over time, such as the amount of a resource like water or money, or even non-physical quantities such as love or anger (1). Flows change a stock over time, hence in-flows and out-flows represent system elements that can increase or decrease the stock's quantity over time (1). The valves on the in-flow and out-flow indicate the flow rate. The cloud symbols represent sources and sinks for the stock that are assumed to have an infinite capacity. Links connect dependencies between different stock-and-flow diagram elements. Hence, the language of systems thinking makes it effective at understanding and representing complex system structures.

Figure 2.1. Examples of simple causal loop diagram and stock-and-flow diagram.



(a) Causal loop diagram

(b) Stock-and-flow diagram

In addition to design and systems thinking, various other disciplines are interested in the visual representation of complex causality including distributed systems, system analysis & design, process engineering, visual analytics, and data analysis. Some examples of visual representations of causality from other disciplines include:

- Hasse diagrams: Diagram with parallel lines that describe different processes and connecting lines between them describe relationships along the timeline (9)

- X-Y plots: Two dimensional plot describing the relationship between any two variables or factors from a system (10)
- X-Y-Z plots: Visualization of the relationship between three variables, with one considered as dependent and other two as independent (10)

Causal diagrams can be both quantitative or qualitative in nature and can be generated using various sources of data. While traditionally, the quantitative development of causal diagrams in the form of simulations and system dynamic models is common, there is benefit to the qualitative generation of such diagrams as well. Either type of diagramming has its own place and benefits (11,12). Qualitative diagrams can be highly effective at engaging a larger set of stakeholders with varied skill levels in mapping practices to leverage the useful theoretical ideas embedded in causal diagrams such as feedback thinking (11). Furthermore, the amount of rich descriptive qualitative data available that can inform key systems issues such as structures and policies merits its usage in informing causal diagrams (12).

Design methods, too have the potential to impact wicked problems (13). The design disciplines have evolved from a product and artifact centric focus to one that is increasingly broader, and about issues such as experience, sustainability and transformation (14). A synergy between systems thinking and design is not a new concept and has been explored by different communities of research and practice, journals, and conferences at the intersection of the two fields. Design methods are rooted in and compatible with qualitative research broadly (15,16), with many design methods borrowing from other social science disciplines such as psychology, human factors, ethnography and sociology. We hence believe that qualitative approaches to generate causal diagrams are compatible with design's goals to address wicked problems and its methodological inclinations.

Yet, the methodological discussion about qualitative coding methods for the development of causal diagrams has been rather limited. A few studies have substantially developed such

qualitative analysis methods and critically considered the needs for it. Kim & Andersen (2) described a process for qualitatively coding purposive text data through tactics including detailed documentation of coding decisions, creating word-and-arrow diagrams, and maintaining references to underlying data sources. Yearworth & White (17) developed ways to use matrix queries in qualitative data analysis software to efficiently parse text sources for where potential causal relationships might exist. Turner, Kim & Andersen (18) developed a framework and corresponding research agenda around factors that influence the choice of a coding approach. They consider group characteristics, data collection characteristics and coder characteristics as three categories of considerations when choosing a coding approach. In relation to the infrastructure for qualitative analysis of causal diagrams, Farr et al. (19) proposed a data model for connecting different elements of information when qualitatively building simulation models with large sets of data, and developed a software application for this purpose.

Yet, there aren't canonical guidelines or practices on how to approach qualitative analysis for causal diagrams that are applicable for various types of projects. There also aren't standard practices for coding embedded in the capabilities of qualitative data analysis tools, such as there are for other more common methods such as grounded theory. This lack of common guidelines is also suggested in the detail of method description by studies using such diagrams. A scoping review of the usage of causal loop diagrams in public health found that description of methods was often lacking, often even when highly iterative methods were used, making it difficult to follow how the study went from data to diagrams (20). Similarly, an evaluation of transparency in reporting of qualitative causal loop diagrams by studies in the System Dynamics Review journal found that only 38% articles fully satisfied criteria of being overall discernible methods, and only 25% effectively identified the source of the information for the causal links in the

diagram (21). Qualitative causal diagramming practices seem to be in a nascent and experimental stage. Considering the limited development of methods and the lack of descriptiveness of methods currently used, there is a need to understand the current state of qualitative coding practices for generating causal diagrams.

Of particular interest to design and other intervention focused disciplines engaging with systems thinking, causal diagramming tools offer the potential to identify areas of leverage – high impact areas for intervention in a system (22). Perhaps the most frequently cited and accessible statement on thinking about leverage in systems is Donella Meadows' list of nine types of places to intervene in a system: going in increasing order of proposed effectiveness from constants, parameters, and feedback loops to the more deep-rooted aspects of systems such as goals, mindsets and paradigms (23). This way of thinking about leverage may be limited. Murphy (22) argues that prioritization of deeper leverage areas might not always hold true, and when systems are broken down into other subsystems, each may have its own leverage points, making it important to consider the layers of leverage. What is more, the latency of any leverage point may be different for different actors in the system (22) (e.g., different levels of influence, role and positions of any actor in the system also matter). Murphy and Jones (24) proposed the potential utility of graph theory to identify leverage points in a system by calculating measures such as degree, between-ness, connected-ness and reach efficiency of variables. This can suggest the roles a variable may play in the system such as being a high impact intervention point, a bottleneck, being volatile or stable, having high efficiency for propagating change, etc. Such approaches may also have limitations, as argued by Crielaard et al.'s (25) evaluation of two such measures – between-ness centrality and closeness centrality. They find problems with the reliability of the measures when the same system is represented with different inferred causal

diagrams, and other key gaps and problematic assumptions when such metrics are used. It would be beneficial to understand how studies have identified leverage and areas of opportunity, to maximize the potential of systems thinking and causal diagrams to enable action.

The visualization of causal diagram is an area that also deserves attention. Causal diagrams for complex systems can imaginably be very detailed and complex artifacts to use, whether for the research team itself or for group of broader stakeholders and audiences. Humans have inherent psychological limitations that impact the processing of causal diagrams (26). The limited number of variables that can be mentally manipulated also is challenging (26) specially when causal diagrams can often contain large sets of variables and diagram elements. Causal diagrams can be visually cluttered, and the challenges of interpreting the diagrams can reduce their wider acceptance (27,28). The visual treatment used for the diagrams matters. Stoyko (29) proposes multiple ways in which system diagrams can be ineffective from an information design standpoint, such as through false equivalence (equal treatment of unequally important items), and the all too common "spaghetti problem" (a jumble of connections being difficult to parse). Having inappropriate levels of abstraction and conflation of different levels of the system (e.g. of what happens at individual vs. environmental scale) can also be challenging (30). We anecdotally notice a great variety in visual practices adopted in systems thinking projects and there is a need to understand the ways in which these diagrams are visually presented. We also believe that this is an area where design can contribute to systems thinking and addressing wicked problems: by making visualization of causal diagrams more useful and usable to interact with, for various stakeholders.

Hence, we approach this study with the following primary research questions:

- How have different studies conducted qualitative coding of causal diagrams?
- What are the associated practices, conceptually, logistically, and technologically?

- What are the challenges reported by researchers conducting qualitative coding of causal diagrams?

The following are our secondary research questions:

- What techniques and tactics have studies used to identify leverage points or opportunity for action, from causal diagrams?
- What are the different ways in which causal diagrams have been visually presented?

Methods

We conducted a qualitative systematic literature review of published research that described their methods of qualitative coding of causal diagrams. We aimed to find studies involving the development of a causal diagram with either a methodological or empirical focus, or studies with general recommendations for the qualitative coding process. We sought studies across domains that focused on any type of causal diagram. Considering the limited development of the literature around qualitative coding methods for causal diagrams, an analysis of quality of each study was not deemed appropriate or necessary. Additionally, the varied types of studies included in the scope of this review, made it difficult to gauge quality by a common yardstick. Since there is limited agreement in the literature around a recommended process, it is not clear how to gauge rigor. Hence, we aimed to describe the variations and commonalities in current practices so that future research can critically review and evaluate such methods to generate better recommendations. It is also worth noting that extracting information about who does the coding, and how communication occurs, although important to inform methodological coding choices as discussed by Turner et al. (18), is outside the scope of this research.

Literature search

We conducted a literature search of the Web of Science and Scopus databases. Considering our cross-disciplinary approach, these two large databases that cover research from many disciplines were considered appropriate. We initially tested various combinations of search

strings that included terms under the search concepts ‘Causal Diagram’, ‘Qualitative Coding’, ‘Coding’ and ‘Systems Thinking’. After reviewing abstracts of studies that the initial search presented, we added additional useful search terms reflected in the abstracts and refined the string. We also consulted with an expert academic librarian to improve our search strategy. Lastly, the senior researcher (KHL) provided a list of studies that would fit our inclusion criteria. The abstracts of the studies were reviewed, and test searches conducted to check if the target studies were being captured by them. Accordingly, our search terms were expanded to ensure that the studies would be captured. Our final search string was a combination of terms under the following concepts: ‘Causal Diagram’ AND ‘Qualitative’ AND ‘Coding’. We searched for studies that were published between January 1, 2012, and September 2, 2022, accounting for little over a 10-year period of the literature. We only included English language studies through the search. The full search string can be found in Appendix A. The final pool of studies were imported into the systematic review management platform Covidence (31). Duplicates were automatically removed in Covidence.

Inclusion & exclusion criteria

We developed the initial inclusion and exclusion criteria with our focus on finding a broad range of studies with well-described methods of qualitative coding of causal diagrams. As we worked through the abstract screening process, additional criteria were added for full text screening. The following were our final inclusion and exclusion criteria. For inclusion, the study had to satisfy all of the following criteria:

- Must include either the development of a type of causal diagram OR a reflection, recommendation, or tutorial about the development of a type of causal diagram
- Causal diagram development process must include drawing on qualitative data (for example, interviews, literature, or other data sources)

- Must include a substantial description of methods of qualitative analysis and translation generating causal diagrams that enable replication of process. The documentation process must either be clearly explained and/or inferable from materials presented.
- If the study draws on a prior methodological source, it must describe adapting or changing the method (i.e. not just applying it)

We excluded studies that satisfied any of the following criteria:

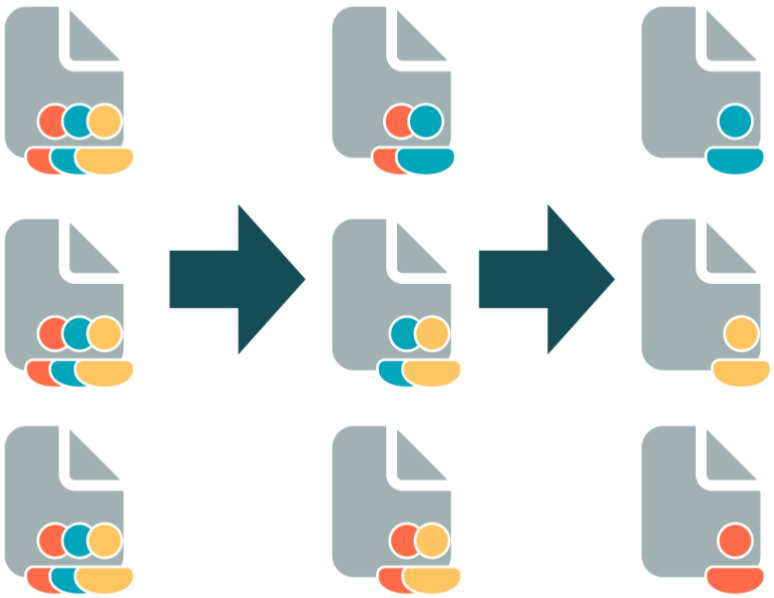
- Not in English
- Protocol papers
- Exclusively using participatory methods of building diagrams during interviews and/or focus groups (e.g. group model building)
- Exclusively focused on quantitative causal modeling or simulation
- Not including a substantial description of its coding methods to generate causal diagrams, in relation to its qualitative and non-contemporaneous components
- Dissertations or books

If a study drew on a combination of approaches, for example, combining a participatory modeling approach with the analysis of qualitative data, or combining qualitative and quantitative methods, as long as other criteria were met in relation to the qualitative coding component of the study, it was included. Whether or not a study drawing on a prior methodological source was substantially different was assessed with two considerations. If the study explicitly described that a methodological source was adapted in some way or if it did not describe how it was adapted, it was included as long as other criteria were met. On the other hand, if it explicitly described that a methodological source was used exactly as is, then it was excluded. We gauged whether a study is detailed enough in two ways. If the study included a clear description of its steps that enabled replication of the work and/or included images, figures, table, or supplementary materials indirectly suggesting a replicable description of its method, it was included. If the same author had multiple studies in our pool that overlapped or were related to one another, we did not exclude either of these studies for that reason.

Screening

The abstract screening was conducted independently by one researcher (RM) using Covidence, in consultation with the senior researcher (KHL). We expected that most studies would not clearly describe in their abstracts how detailed their method description would be. Hence, through this phase, we erred on the side of inclusion.

Figure 2.2. Illustration of phased approach used for full text screening, starting with greater overlap of studies (i.e. being screened by multiple researchers) and ending with greater amount of independent screening.



Full text screening was conducted by a team of four researchers (RM, KHL, HF and DK). To support a phased approach, to build consensus and shared understanding around our criteria, and to support flexibility in the process, the full text screening was conducted using spreadsheets. One researcher (RM) created independent screening spreadsheets for each screening team member to record their screening decisions, along with a comparison spreadsheet to compare screening decisions after each phase. Overall, the screening phases started with a greater overlap

of screened studies between two or more researchers, and more extensive and frequent discussion for building consensus (Figure 2.2). It ended with a greater percentage of studies being independently screened. Inter-rater reliability was calculated for each phase of screening, by calculating the percentage of votes screened equivalently, with a vote of 'maybe' counting towards an equivalent screening score, along with the study being discussed to resolve through consensus. Until 80% inter-rater reliability was reached, each study was screened by at least two researchers. Any confusing screening decisions were brought up to be discussed with the team and/or senior researcher. The detailed sequence of phases in which screening was conducted can be reviewed in Appendix B.

Extraction

The extraction spreadsheet was developed in two iterations. First, one researcher (RM) developed an initial extraction template based on the key themes that were discussed as a team and extracted information from three purposively selected studies including a method study and two applied studies. Then, the team discussed the output of the test extraction and accordingly some extraction fields were removed, additional fields were included, and additional details were added to make the extraction process more consistent. Two researchers (RM and HF) independently conducted data extraction for all studies and updated the extraction for the initial test extraction sample. Extraction was conducted using the finalized spreadsheet template, and a document to paste useful screenshots into. The output of extraction was discussed with the team, and any discrepancies were resolved with the help of a senior researcher (KHL). After extraction was completed, one researcher (RM) independently conducted a check for internal consistency of information across the extracted fields for each study. Types of information extracted included details about the type of study, coding activities and steps, tools used, ways of identifying

leverage points and visualizing causal structures, the value of the study in relation to the author's description of the usefulness of its methods, standards of research quality and efficiency, and any challenges addressed or unaddressed by the study team. Extracted information about steps and activities of qualitative coding included specific activities, along with the outputs of each activity and tools used, if described. Relevant quotes were also pasted into the extraction spreadsheet. Where processes were described as iterative, a general sequence as described was noted down. While some level of interpretation was necessary, we made the guidelines for extraction as detailed and explicit as possible. A description for the specific fields that inform this study is in Appendix C.

Analytic approach

For the types of studies in our sample, descriptive information was reported. Most components of the extracted data were summarized or grouped into meaningful categories and reported with a combination of descriptive text and figures. To report on the qualitative coding activities and steps of the studies, an additional level of analysis was conducted. Common categories of 'activities' were identified from the studies to form a typology or 'codebook' of methodological activities - examples of activities include coding of concepts, coding of causal relationships, and developing intermediate causal diagrams. This codebook was created in three iterations. First, one researcher (RM) reviewed a small, purposively selected subset of studies that were chosen for including many varied activities. Using this codebook of activities, each study was 'coded' for the activities it included, and for which steps in their sequence of their process when each of these activities were conducted. Second, a simplified version of the codebook was created by grouping and merging some of the activities, and the activities were coded again. In a third and final round of developing the codebook, all coding practices of all the

extracted studies were reviewed again to find any additional activities for inclusion in the codebook. The final codebook hence includes activities based on a combination of (a) their frequency across the studies (b) their uniqueness compared to other activities and (c) their importance based on our experiences as a research team.

The typology or codebook of methodological activities was then used by one researcher (RM) to code the activities that were conducted by each study and the steps in their sequence when these were conducted. Any studies that did not include substantial details about their specific sequence of activities were excluded from this part of our analysis. Details about the criteria for coding the activities and their sequence of steps can be found in Appendix D. The activities were described by reporting a table of activities and steps, along with a narrative description of each activity, including common practices, variations and unique processes or contexts within which any activity was conducted.

For reporting on the types of information that was coded in each study, we produced an inductively generated hierarchical chart to describe the variation of what was coded by the different studies.

Results and discussion

After removing 194 duplicates, the search yielded 371 records for screening. After abstract screening, 252 studies were included. Reports for 4 studies were not found. After full text screening, 32 studies were included. These studies were found to have substantial descriptions of qualitative coding practices for generating causal diagrams. The PRISMA diagram generated using PRISMA2020 is shown below in Fig. 2.3 (32).

Types of studies included

The pool included 7 methods studies and 25 applied studies. In addition to causal loop diagrams that were created in 21 of the studies, some studies also created - in their own usage of the terms - system(s) maps, causal maps, causal grounded theory process model, directed acyclic graph, qualitative mediation model, social ecological action situation configuration, and stock and flow diagram. One study involved the combination of a stock and flow diagram with a causal loop diagram (33). Figure 2.4 describes the characteristics of the included studies.

Figure 2.3. PRISMA flow diagram of screening & extraction process.

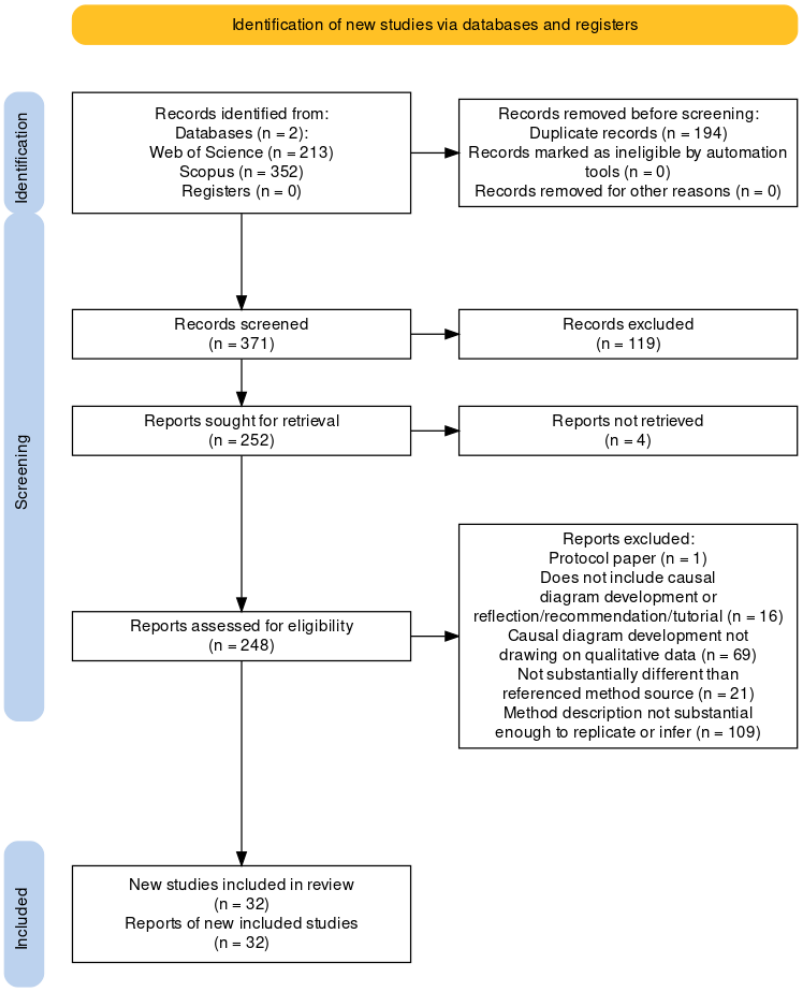
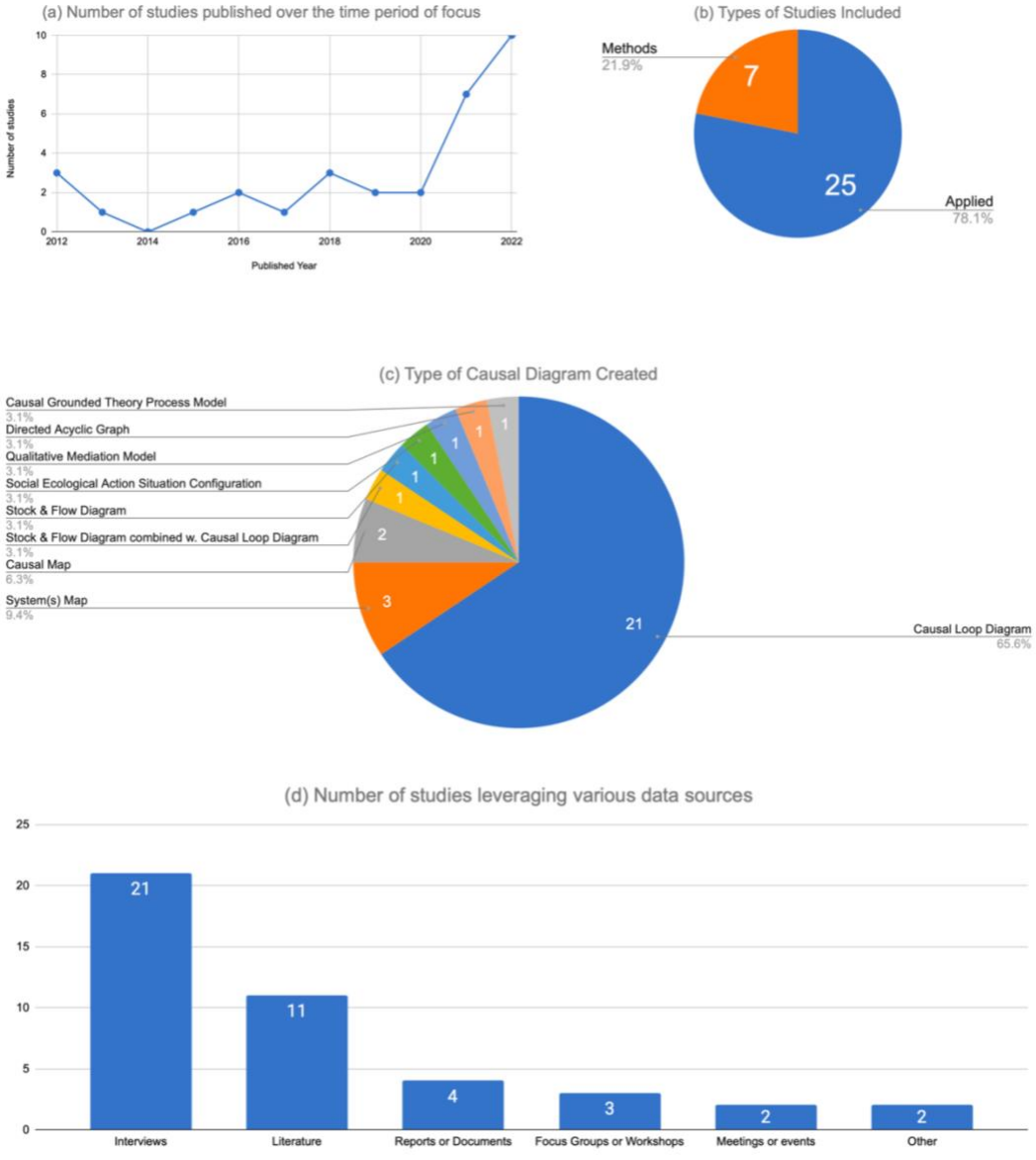


Figure 2.4. Characteristics of included studies.

Note: Types of causal diagrams created were reported as described by authors. If more than one type of causal diagram were created in sequence, the final diagram was included here. For data sources, memos or reflective artifacts were not included as these were considered analytical artifacts and not sources. If a data source was described as being used for a separate purpose than informing qualitative development of a causal diagram, it was not included here. Meetings, workshops and focus groups were only included if used as a data source that was analyzed and excluded if it was for contemporaneous generation or validation of insights.



Overall, we notice an increasing trend in the number of studies included in the pool. This would suggest that either more studies are involving qualitatively developed causal diagrams that are described in substantial detail, or simply that more studies are generating causal diagrams. This also suggests the increasing need for development of methodological recommendations. The various types of causal diagrams generated suggest that similar goals for describing complex causality may be shared across various types of tools and disciplinary practices, and there are opportunities for sharing practices across these.

Interviews and various literature sources - the most commonly used data sources - were leveraged by 21 and 11 studies, respectively. Yet, reports, documents, focus groups, workshops, meetings or events, and other sources such as archives, documentaries and ethnographies were also used. This highlights the various types of data that can be used for the qualitative generation of causal diagrams. In this regard, Kim and Andersen's (2) discussion of methods around the use of "purposive data" seems valid. They describe purposive data as that which arises from discussions with key decision makers or stakeholders, captures a causally and dynamically rich discussion, and a frank and unfeigned view of the participants' mental models. They propose that purposive data can be a by-product of existing discussions or be created specifically for the purpose of model-building.

Coding activities and practices of included studies

To synthesize our understanding of the coding practices of the included studies, we coded for the inclusion and sequence of coding activities conducted by the different studies. For our analysis, we define an 'activity' as any qualitative coding related practice conducted by the studies that was part of their transition from source data to causal diagram. While various coding activities were conducted by the studies, here we describe nine core activities that we coded for

and considered as central to the process for qualitative coding of causal diagrams across various studies based on a combination of reasons - frequency across studies, variation from other activities and our experience as researchers. We define a 'step' as one part of the sequence of any study's process that may include one or more activities.

Table 2.1 presents the coding activities for each of the included studies - showing which core activities the studies involved, and when in the sequence of their steps the activities were conducted. 30 of the 32 included studies described coding activities and sequence in enough detail for inclusion in this specific analysis. The two studies not included in this part of the analysis are included at the end of the table. One of the studies (34) included two separate methods conducted in parallel. In Table 1, these have been depicted as nested within the same study. In addition to the coding activities described here, some studies involved additional activities that are not described here. We now describe patterns and characteristics of coding activities conducted by the studies as described in the table.

Defining system boundaries

10 of the 30 studies involved defining system boundaries as an activity. Seven studies defined the boundary in parallel with another core activity. Defining boundaries was done alongside activities like coding (2,35–38), developing and reviewing analytic memos (33), converging individual causal diagrams or simplifying the system (39,40), and determining the depth or detail of the system (40). Some studies used specific inputs for the boundary definition activity - in the form of existing literature (36,41), an existing domain related framework (42), or an intervention's internal factors (37). The boundary definition activity resulted in defining the problem or scope (2,35,37,41), identifying relevant data (2), eliminating information beyond scope (38), determining endogeneity, exogeneity, inclusion and exclusion of system

Table 2.1. The coding activities undertaken by 30 of the studies.

AUTHORS & YEAR	QUALITATIVE CODING ACTIVITIES								
	Defining system boundaries	Developing a codebook	Coding of concepts	Consolidation of concepts	Coding of relationships	Consolidation of relationships	Building confidence in analytical insights	Developing intermediate causal diagram(s)	Developing final causal diagram(s)
Kim and Andersen, 2012	1	-	1,2	1,5	2	5	-	3, 4	5
Bate et al., 2012	-	-	1	2	3	3	-	-	4
Yearworth and White, 2013	-	-	1	2	3	4	-	-	5
Ghobadi and Mathiassen, 2016	-	1	3, 5	5, 9	4	6	2, 8, 10, 11	6,7	11
Eker and Zimmermann, 2016	1	-	1	2	3	-	6	4, 5	6
Xu and Mills, 2017	-	1,2	3, 4	-	4	-	-	5,6	6
Sarkar et al., 2018	-	-	1	-	3	-	2, 4, 6	-	5
Baugh Littlejohns et al., 2018	-	-	1	2	3	5	-	4,5	6
Kum et al., 2018	-	-	2	-	1	3, 4	-	-	4
Sewchurran et al., 2019	-	-	1	2	1	2	4	3	5
Liu et al., 2019	-	-	1	2	3	-	-	-	4

Table 2.1 (continued)

Eker and Ilmola-Sheppard, 2020	1	-	2, 3	-	3	-	4	5	6
Glenn et al., 2020	-	1	2, 3	4	2, 3, 6	4	7	5, 6	7
Sawyer et al., 2021	1	-	2	5	3	5, 6	4	3	6
Burrell et al., 2021	3	-	1	2	1	2	5	4	5
Gisladottir et al., 2021	-	-	1, 3	2	3	-	5	-	4
Zhang et al., 2021	1	-	1	2, 6	3	-	-	4, 5	6
Richards et al., 2021	-	1	2	4	2	5	5	3, 5	5
Sharma et al., 2021	-	-	1	2, 3	4	-	7	5	6
Boelsen-Robinson et al., 2021	6	2, 4	1, 3, 7, 9	1, 3, 6, 7, 8, 9	1, 3, 7, 9	6	8, 10	5, 6, 8, 9	10
Depasquale et al., 2022	-	-	1	2,3	1	2	-	-	4
Walters et al., 2022	-	-	-	2	1	1, 3	2	3	4
Herzog et al., 2022	M1: - M2: -	M1: - M2: -	M1: 1 M2: 1	M1: 2, 3 M2: 3	M1: 1, 4 M2: 1	M1: - M2: 4	M1: - M2: -	M1: 4 M2: 2, 3	M1: 5 M2: 5
van Heemskerken et al., 2022	-	-	1, 2	-	2	-	-	-	2
Lutete et al., 2022	-	-	1, 2, 3	-	4	-	-	-	5
Gudlaugsson et al., 2022	1	-	1, 2	-	2	4	-	3	5
Tobin et al., 2022	1	-	1	1	2	-	4	3	4
Tomoaia-Cotisel et al., 2022	-	-	1	-	1	-	-	2	3
Kiekens et al., 2022	-	-	1	-	1	5	6	2, 3, 4, 5	6
Kiekens et al., 2022	5	1	1	-	1	4, 5	6	2, 3, 4	5
TOTAL # STUDIES CONDUCTING ACTIVITY	**10**	**6**	**29**	**20**	**30**	**18**	**16**	**21**	**30**
ADDITIONAL INCLUDED STUDIES									
Videira et al., 2012	-	-	-	-	-	-	-	-	-
Aslani and Naaranoja, 2015	-	-	-	-	-	-	-	-	-

elements (33,36,37,39,40), identifying the main subsystem (35,36) and identifying other complex systems related to the core problem (40). 8 of the 10 studies defined system boundaries early into their process within the first three steps, either as its own standalone activity or in parallel with another activity. Kiekens et al. (40) described that defining the system boundary can happen throughout the process, and recommend not starting with a defined boundary. They suggest starting with representing as much detail as possible, so that no important factors are missed, and deeper insights are supported.

Developing a codebook

6 of the 30 studies involved developing or refining a codebook or thematic framework as an activity. As was expected, this was largely done early in the process: all but one study did this during their first step. The development of codebooks or frameworks ranged from being inductive to deductive for different studies. Inductive development involved reviewing data transcripts and development in parallel to or after preliminary coding were done (39,40,43). Richards et al. (44) developed a deductive codebook to categorize the literature they reviewed as per its methodological approach. Two studies also used a combined abductive approach. Glenn et al. (45) reviewed the literature and used their previously developed methods focused conceptual framework to develop a codebook. Xu and Mills (46) leveraged a domain related framework - in their case the World Health Organization categorization of health system building blocks - to analyze policy documents and develop a thematic framework. Multiple studies described updating of the codebook or framework through initial data analysis. Ghobadi and Mathiassen (43) iterated on their codebook by examining it for theoretical and logical relevance by comparing to existing frameworks and also by having an additional researcher assess its face validity and parsimony. As was also expected, coding of data was done by some

studies in parallel to this activity. Additionally, questions guides for data collection (46) and node structure in qualitative data analysis software (46) were also developed.

Coding of concepts

29 of the 30 studies conducted coding of concepts, themes, variables, factors, challenges, or effects (referred to as coding of concepts, for simplicity). For most studies, this was done early during the process: 22 studies coded concepts as their first step. This is expected since many qualitative approaches draw on principles and inductive steps from core qualitative methodologies such as grounded theory. 10 of the studies coded concepts during multiple steps in their process. This iterative nature was observed in a few different ways: returning to coding concepts with other activities in between, consecutively coding different types of concepts one after the other (e.g., first coding themes, and immediately afterwards coding variables), repeating a coding activity for the dataset after codebook stabilized, or coding concepts for multiple split parts of a dataset. Many studies coded concepts in parallel with another activity. Most commonly, 16 of the studies coded for causal relationships or chains in parallel to this activity.

While most studies inductively coded concepts, 10 of the studies included a deductive influence such as the usage of existing frameworks or literature to inform this activity. When described, the studies differed in the lengths of text segments coded e.g. line-by-line vs. paragraph by paragraph. One study described the usage of in-vivo codes (2). Some studies described using reflective and analytical notetaking practices while coding, such as memoing and annotation (2,33,38,47). In describing characteristics of good codes, Depasquale et al. (48) state that codes must be semantically rigorous and universally applicable across the dataset. Similarly, Eker and Zimmermann (38) described the importance of understanding context during this activity to enable coders to identify concepts not explicitly stated. For this purpose, they suggest

coding of information that may not directly feed into the causal diagram. Boelsen-Robinson et al. (39) described coding of concepts until saturation was reached. Some studies described specific ways in which the output of coding of concepts was utilized. Kim and Andersen (2) described identifying segments of data that reflect mental models of the system. Kum et al. (49) extracted segments of data during the coding of concepts, and used these data segments to identify relationships in later steps.

Two studies adopted unique practices for coding of concepts aligned with their studies goals. Depasquale et al. (48), in proposing a method to survey the state of literature in any problem domain – the PAD review protocol - code for each paper in their literature review, three categories related the paper's contribution to the domain being studied, i.e., problems it addressed, approaches used to address these, and developments or contributions that resulted. Tomoaia-Cotisel et al. (47) in their causal diagram validation-focused method called Rigorously Interpreted Quotation (RIQ) method record detailed information to analyze particular quotes for validating and updating a causal diagram already created in prior steps. They record data source, who said the quote, position of quote in transcript, word counts, underlining and extracting particular phrases in the quote that describe causal diagram elements (variables, delays, and feedback loops), causal chains identified as a result, implicit or indirect mentions of causal elements, and coder's interpretive notes. This is then used to compare the pre- and post-RIQ method causal diagrams.

Consolidation of concepts

20 of the 30 studies conducted grouping, merging, filtering, or simplification of concepts, themes, variables, factors, challenges, or effects (referred to as consolidation of concepts, for

simplicity). Seven of the studies did this during multiple steps of the process. Consolidation of causal relationships was done in parallel with consolidation of concepts for seven of the studies.

Concepts were consolidated for various purposes and in various specific ways. As is common during qualitative research generally, using hierarchical or tree structures for linking of concepts was described (17,38). Two studies' consolidation included addressing idiosyncratic ways of description across cases and company specific jargon (2,43). Consolidation included merging of similar items but also removing redundant items (43). Through this step, some studies described specific ways of filtering concepts: choosing to only include concepts that were the most significant, the most frequently described, and/or the most important to the scope of the study (33,34,38,45,50). One study described disassociating the variables with causal relationships they were coded within, prior to consolidating the variables (44). Depasquale et al. (48) used visual containers holding multiple related concepts into what they call super-categories. Ghobadi and Mathiassen (43) used a deductive approach using an existing framework for consolidating concepts.

Two studies described considerations or stepwise processes for consolidating concepts. Depasquale et al. (48) in their study uniquely focused on surveying the state of the literature in a particular domain, described steps helpful when consolidating a particular concept, such as seeking a concept that is similar in meaning, leaving ungrouped if none are found, and if found, naming the high level concept to be suitable for inclusion of both, and revising the scope of the concept as appropriate. Richards et al. (44) in their study spanning different geographic and temporal scales and granularity considered the level at which to aggregate concepts – in their case they opt for describing concepts at a national level.

Coding of relationships

30 of the 30 studies conducted coding of causal relationships, chains, or substructures (referred to as coding of relationships, for simplicity). Generally, this was done early during the analysis process: ten of the studies did this during their first step, and twenty-six did this during their first three steps. Three studies coded relationships during multiple steps. Additionally, Coding relationships was frequently done – for sixteen of the studies - in parallel with the coding of concepts.

In addition to coding relationships inductively, some studies described deductive variants. Eker and Zimmermann (38) used concepts that were aggregated in prior steps to code relationships. Bate et al. (51) approached this activity with a deductive predisposition based on their intervention model. While multiple studies coded relationships in pairwise fashion i.e. for cause and effect pairs, some studies coded multiple chains of cause and effect at a time, for example, from cause to effect to indirect effects (36,46,48,52). On a similar note, moderating and intervening relationships were also recorded (51,52).

Some studies described specific considerations and unique practices for coding relationships. One set of such practices focused on the *finding* of causal relationships in the data. Yearworth and White (17) used the matrix query feature in the qualitative data analysis (QDA) software NVivo (53) to find segments of text that were simultaneously coded with a pair of concepts more than a certain number of times. This was a strategy to quickly identify potential causal relationship for the researcher to investigate and determine significance of. Similarly Bate et al. (51) reviewed data included within linkages between similar concepts in the QDA software Atlas.ti (54) to identify specific relationships within. While searching for relationships, Lutete et al. (55) coded only focal quotes informing a causal relationship, and not the text preceding it for

context. Another set of unique practices focused on gauging the validity of relationships. Baugh Littlejohns et al. (56) used a specific set of criteria for evaluating potential relationships – Davidson's criteria for inferring causality (57) – such as "temporal precedence (i.e. establishing A before B), constant conjunction (i.e. when A, always B), and contiguity of influence (i.e. plausible mechanisms for linking A and B)". Bate et al. (51) used process induction, where they searched for causal relationships in one case and then tested this against other cases. Sawyer et al. (41) described how conflicting evidence regarding the presence or direction of a relationship, when occurring, was handled by choosing the relationship most commonly reported relationship among the sources.

As described in prior sections, two studies adopted unique practices for coding of relationships aligned with their study goals. Depasquale et al. (48), in proposing a method to survey the literature in a domain, coded data into three categories related to the state of the literature for the domain: problems, approaches used, and developments as a result. For each triad, they coded the relationships from problem to approach to development. Tomoaia-Cotisel et al. (47) in their causal diagram validation focused method called Rigorously Interpreted Quotation (RIQ) method recorded detailed information to analyze particular quotes for validating and updating a causal diagram. As described above, they recorded data source, who said the quote, position of quote during interview, word counts, underlining and extracting particular phrases in the quote that describe causal diagram elements (variables, delays, and feedback loops), causal chains identified as a result, implicit or indirect mentions of causal elements, and coder's interpretive notes. This was then used to compare the pre- and post-RIQ method causal diagrams.

Consolidation of relationships

18 of the 30 studies conducted grouping, merging, filtering, or simplification of causal relationships, chains, or structures (referred to as consolidation of relationships, for simplicity). Four studies consolidated relationships during multiple steps. A few other activities were frequently done in parallel with consolidating relationships: developing intermediate causal diagrams (six studies), developing final causal diagrams (six studies), and consolidation of concepts (seven studies).

The types of consolidation varied from decomposition, elimination, filtering, merging or categorization. Two studies decomposed relationships and/or identified implicit structures while doing this (2,35), for example, in a causal relationship between variable A and C, adding an intermediate variable B, so that the influence moves from variable A to B to C as implied by the context of the data. Two studies eliminated diagram elements by removing intermediate auxiliary variables in chains of relationships that might lead to an overly complex diagram or removed double pathways between concepts that might occur when coded differently by multiple researchers (17,40). Kiekens et al. (40) qualify this by stating the importance of considering whether an intermediate variable is crucial to understanding of the problem. Similarly, multiple studies filtered relationships in different ways: to the most valid, significant, or frequently discussed relationships, to relationships most central to the topic and through setting system boundaries (33,34,36,40,45,50). Two studies merged relationships using merged concepts identified in previous steps of their process (35,43). Two studies identified causal loops that contribute to the same overarching mechanism or theme to simplify the diagram (40,58). In the process of merging, Kum et al. (49) used labels assigned to data segments in prior steps as filters, to aid in the process of generalizing the relationships. Studies also conducted various types of

categorizations without condensing causal structures. Baugh Littlejohns et al. (56) in a form of triangulation, labeled themes and feedback mechanisms as dominant if they were present in both data sources they used. Boelsen-Robinson et al. (39) grouped sub-systems in causal structures by color codes. Walters et al. (59) labeled causal relationships as representing 'challenge' or 'solution' and these fed into two corresponding types of causal diagrams created.

Some studies described unique considerations and practices for consolidation of causal relationships. Herzog et al. (34) used Inam's six steps for merging of diagrams (60). A few studies started the merging of intermediate causal diagram with one diagram and then progressively incorporate elements from other diagrams (34,39,44). In this case, Herzog et al. (34) started with the most complex of all the intermediate causal diagrams, and progressively layered in other diagrams. Kiekens et al. (40) suggest merging concepts if there is not significant differences in nuance in the contents of the two, and if they don't have different relationships to other elements, and to consistently apply the process for the whole system.

Building confidence in analytical insights with new information

16 of the 30 studies conducted activities to build confidence in analytical insights with new information. We defined this to include any information external or new to the project prior to this activity being conducted (e.g., member checking, validation with stakeholders or comparison to external information or framework). This was frequently done in the final steps of a process: all of these 16 studies did this activity during their last three steps. Three studies did this activity during multiple steps. This activity was frequently done – for eight studies - in parallel with the development of final causal diagrams.

This confidence building was of two types: comparison to existing literature or frameworks, and engagement with participants or stakeholders. Eight of the studies compared

their insights to the literature or existing frameworks. Eleven studies engaged with participants, stakeholders, or other key informants to build confidence in insights. Two studies asked participants to identify missing factors, relationships and/or describe whether any relationships were inconsistent with experiences. Following this, Boelsen-Robinson et al. (39) checked if newly identified relationships are indirectly present through other variables in their diagram. Studies also conducted group model building, interviews, or sent insights to participants for approval.

The confidence-building activities led to various outputs, including different types of validation, reconceptualization, and additions. Ghobadi and Mathiassen (43) checked for theoretical and logical relevance of their coding scheme. Three studies deductively renamed concepts or variables using this activity (42,52,59). Six studies validated or extended insights in their causal diagrams. Ghobadi and Mathiassen (43) validated interpretive accuracy and trustworthiness of diagrams. Herzog et al. (34) checked and expanded on diagram elements constituent to the problem of interest. Gudlaugsson et al. (36) validated and confirmed selection of causal relationships in a process seemingly akin to filtering. In addition to validity, one study also examined the application and usefulness of the diagram (43).

Developing intermediate and final causal diagrams

As per inclusion criteria, all of the 30 studies involved developing a final causal diagram. For four studies, developing final causal diagrams was followed by building confidence in analytical insights with new information. 21 of the 30 studies involved developing some type of intermediate causal diagram. This was largely conducted towards the later stages of processes: 19 studies developed one or more intermediate diagrams during the last three steps of their process. 12 studies developed intermediate diagrams during multiple steps in their process.

Considered together, development of intermediate or final causal diagrams was frequently done in parallel with consolidation of relationships and building confidence in analytical insights, by ten and eight studies respectively.

Aside from the manual generation of causal diagrams through one or the other drawing tool, one study described an automation of uploading codebook to the tool Kumu (61) to automatically generate a causal diagram (40). The studies involved creating various types of intermediate causal structures. Word-and-arrow diagrams were used by multiple studies (2,35,56), and based on their limited descriptions seem to be miniature causal diagram substructures, corresponding to individual data segments. These diagrams are transformed from text with the purpose of building causal structures consistent with the language of system dynamics (2). One study developed individual feedback loops as intermediate diagrams (56). Two studies involved creating a causal diagram corresponding to a single quote or segment of data (2,47). Seven studies developed diagrams for individual participants or data sources (33,34,39,40,43,44,58). Three studies developed diagrams corresponding to specific roles or groups (35,38,43). Two studies developed intermediate diagrams for particular subtopics or issues (42,45). Intermediate diagrams were also used as draft versions of final diagrams.

Some studies adopted specific practices for transitioning from one causal diagram to another. This included processes such as collapsing generalized relationships, adding intermediate structures, re-evaluating relationships, refining variables, and revisiting source coding (46,49). One study added additional elements to diagrams based on logical inference (46). In transitioning between causal structures, two studies adopted approaches to color code or alphanumerically code, and to visually segment parts of diagrams, in order to visually map the correspondence between the two stages of diagrams (34,44).

Some of the studies included unique or multiple purposes for developing causal diagrams. Kiekens et al. (40) developed multiple diagrams with different spatial arrangements and encodings to communicate the system in different ways. For example, one version of their diagram groups variables in radial layers representing different layers of the system ranging from micro to macro layers, while another version clustered the variables into thematic groups. Other practices included diagramming counter-intuitive aspects or unintended consequences (45), and separate and integrated maps for challenges, solutions and interventions (46,59). One study created an intermediate diagram that was then simplified for communication with external stakeholders (40). As discussed earlier, Depasquale et al. (48) for their study on surveying the state of literature in a particular problem area – in a process they refer to as the PAD review protocol – developed a three layered directed acyclic graph and other complementary causal diagrams to demonstrate the movement of research in a field from problems to approaches to developments.

What types of information were coded

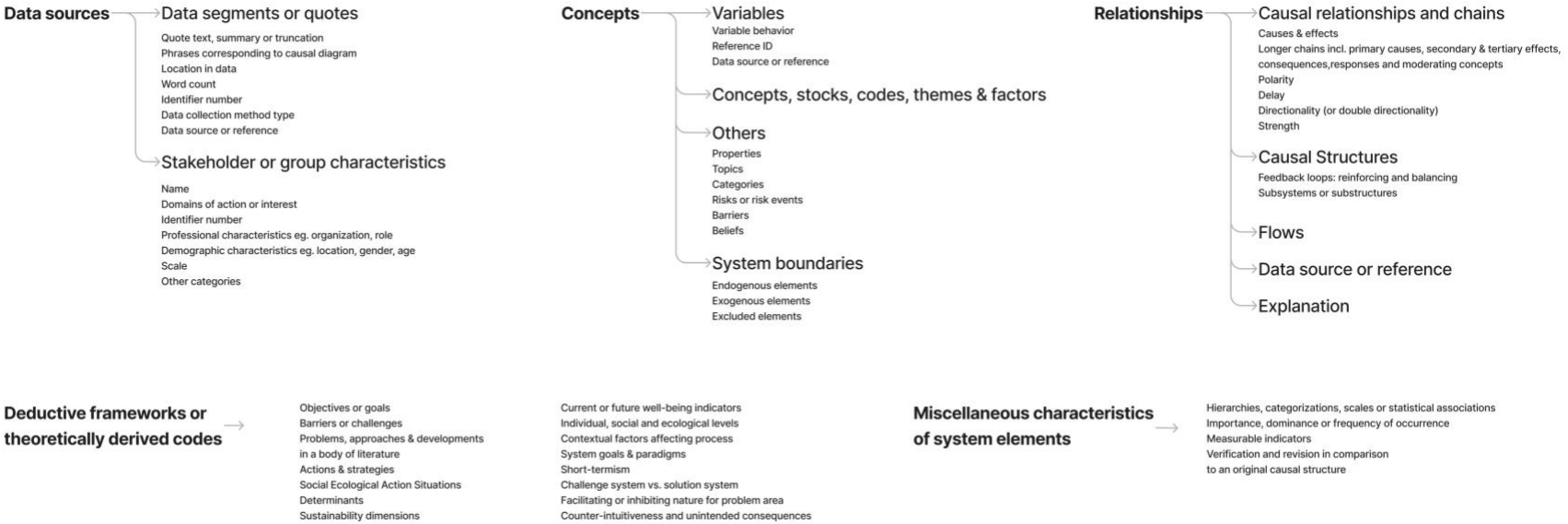
Types of information coded in the studies included various types of codes such as elements, themes, factors, variables, causal relationships, causal chains, and more complex structures like feedback loops and archetypes. We also report on various characteristics of the codes that the studies also recorded (e.g., categorization of variables such as being endogenous, exogenous, or excluded from diagram). Theoretically-driven and domain-relevant frameworks also influenced coding for some studies. Figure 2.5 illustrates a hierarchical description of the different types of information coded across the studies.

Artifacts and documentation supporting the coding process

The studies used artifacts and specific types of documentation to support the coding process. This was broadly used to record analytical insights and process, as well as to maintain connection between causal diagrams and underlying data. Some studies used a coding chart per argument or quote for its rigorous interpretation by recording detailed information on coding decisions and data corresponding to it (2,47). Most studies used some form of a table or spreadsheet to record variables and/or causal relationships, along with corresponding supporting information. One study used matrices to record causal relationships with quantitative information included (41,43). As mentioned earlier, some studies also used unique features of qualitative data analysis (QDA) software for finding potential causal links, for example, using NVivo's (53) matrix query or for recording causal relationships using the relationship feature of QDA software (17,38). Technical reports and narrative descriptions written up after conducting interviews were also used (e.g., to enable the research team to fully comprehend the data prior to qualitative coding) (40,51,58).

Some of the studies included a mechanism to support linking source data to the causal map, either fully or partially. One variety of methods for such linking included using identification numbers for specific research elements such as data source segments, diagrams, coding charts and sources. Tables were frequently used for recording linkages between data and diagrammed structures (e.g., causal linkages, feedback loops). One study used a data source reference table to connect identifier numbers associated with quotes and with maps (2). One study used adjacency tables to describe which variables correspond to particular diagrams (62). Another common tactic involved documenting specific quotes, sources, or identifier numbers adjacent to corresponding elements in a table or coding chart recording variables or causal

Figure 2.5. Types of information coded across the studies.



relationships (2,33,35–37,39,40,42,46,47,49,55,62–67). Some studies that used qualitative data analysis software such as NVivo or Atlas.ti used the querying capabilities to review underlying codes or data (17,38,51). One study used a particular naming convention for diagram elements which included unique identifiers associated with codes, hence supporting linkage (48). One study described sequencing and maintaining an interpretive trail to link diagrams to empirical evidence (41). As described above, in transitioning from one causal diagram to another, two studies used color codes and alphanumeric corresponding to parts of causal diagrams, in order to visually map the correspondence between the causal diagrams (34,44). This serves to maintain some linkage to underlying data. One study used interactive and data driven capabilities of diagram generation using the software Kumu (61) to record quotes corresponding to diagram elements.

Different software tools used for coding, documentation, diagramming, and presentation included NVivo, MaxQDA, Atlas.ti, CMAP2, MS Excel, Airtable, MS PowerPoint, Vensim, STICK-E, and Kumu. In this list, we do not include software used for quantitative calculations.

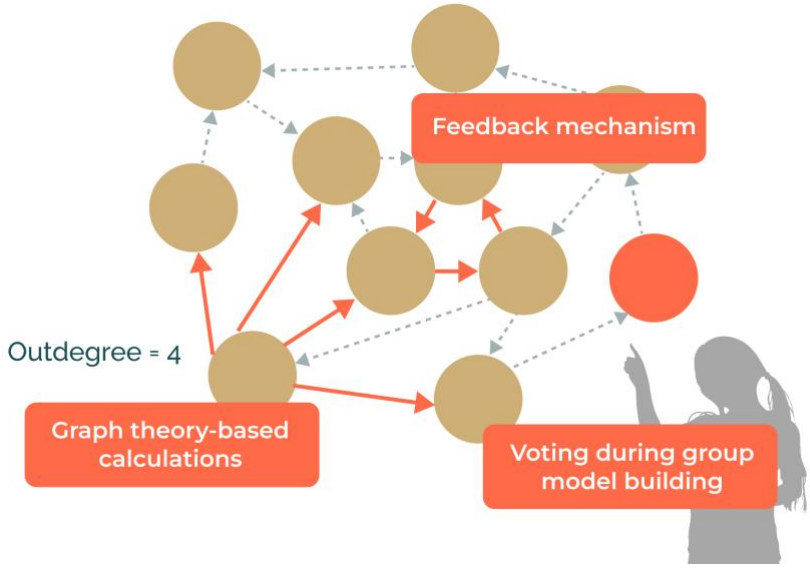
Strategies or methods to identify leverage points

14 of the 30 studies included some description of how leverage points were identified. Figure 2.6 illustrates a selection of these approaches.

Here, we define leverage points broadly as any area of opportunity for system improvement identified based on a diagram, depending on the goal of the study. Some studies identified leverage points through structural aspects of the causal diagram. Two studies considered feedback mechanisms or sub-systems within a causal structure as ways to find leverage points (56,58). In one particular study, balancing feedback loops were stagnating and

problematic in preventing a system from changing, hence the authors considered these balancing loops to be leverage points (45).

Figure 2.6. Illustration of a selection from the set of approaches the studies used to identify leverage points.



Three studies identified leverage points through calculations based on graph-theory (40,59,67). Van Heemskerken et al. identified leverage points by calculating the centrality measure of the variables (67). Kiekens' (40) study identified leverage points in elements in a causal diagram that have a high out-degree (number of outgoing connections) and low in-degree (number of incoming connections), indicating elements having higher influence on elements in the system, but being less influenced by them. In a very similar fashion, Walters et al. (59) generated influence maps on a two-by-two chart that visualized the influence and dependence any particular variable has, and identified leverage points in the variables with high influence. The same study also used the weighted eigenvector centrality of variables as a measure of leverage. They share a word of warning about how identifying leverage points through such metrics must be approached carefully as it is highly dependent on coding choices made in previous steps. This is consistent with two other studies describing the importance of interpretation in identifying

leverage points (40,45). Another quantitative approach was Bate et al.'s (51) statistical mediation analysis to complement their qualitative mediation modeling study. Walters et al. (59) developed separate challenge and solution maps, as described in earlier sections. In structurally comparing these maps, they assessed leverage in two additional ways. One, in 'overlay' interactions that were strong drivers mentioned in both maps. Two, they also described where they think there *isn't* leverage – considering the discrepancy and structural differences between the two maps, they suggest that there would not be leverage in addressing all factors or in strengthening existing weaknesses. Beyond data-focused analysis methods, one study identified leverage points through group model building sessions involving voting done by participants (62).

Some of the studies sought very specific types of leverage points, or areas of opportunity, based on their problem of focus. Ghobadi and Mathiassen's focus was on comparing mental models of different stakeholder groups to improve communication and collaboration across the groups (43). They identified areas of overlap and difference between the mental models through a causal comparative analysis (68) of causal diagrams for each stakeholder. Depasquale et al. (48) in surveying the state of literature in a particular problem area, visualized a directed acyclic graph of pathways from problems to approaches to developments. They use frequencies of pathways between problems, approaches, and developments as an indicator of maturity. They visualize this frequency of pathways using line thickness to understand fecundity of pathways. Additionally, they calculate multiple other metrics. Sewchurran et al. (50) in developing a business plan and investment programme, conducted surveys and facilitated sessions with participants to identify business capabilities that had been underinvested in, to identify gaps to address. Gisladottir et al. (65) used Ragin's approach to case-oriented inquiry to identify commonalities across different cases that led to a similar outcome. Although the authors didn't

explicitly describe this in terms of leverage, a similar process could arguably be used to identify important root causes of an issue across different cases. For a multi-stakeholder problem, Boelsen-Robinson et al. (39) suggested that their causal diagram can be used to identify closely linked factors that are under a particular stakeholder group's domain of action/sphere of influence. One study found leverage points through domain-specific theoretical categorization of diagram elements - in their case they identified "three-layer relationships" including operations, supply chain risk, and corruption's modifying impact on risk effects (64).

Visualization and presentation of causal diagrams

The studies used various visual tactics for presentation and to support different types of analysis. A commonly observed practice used by ten of the studies was dividing the causal diagrams into different sub-diagrams or visually segmenting different sub-systems within a single diagram. In a related manner, some studies presented versions of causal diagrams to emphasize specifics such as key relationships, and described the system at varying levels of granularity (41,55,66). Two studies used bounded dialog boxes to emphasize and detail a selected part of a causal diagram (47,64). 24 of the studies used variations and combinations of shapes, colors, line thickness, node sizing, font, and other visual encodings to categorize or emphasize particular elements, or to visually communicate quantitative aspects of information (e.g., using particular colors to emphasize key variables or loops or line thickness variation to indicate the relative strength of relationships). Walters et al. (59) used an additional tactic of including miniature diagrams to depict the key or legend of visual encodings they used in their main diagrams. Some studies used additional graphic elements or codes overlayed on causal diagrams to describe additional information, such as happy and sad faces for facilitating and inhibiting factors for a problematic variable (56), or text bubbles to describe additional

contextual information about different parts of the causal diagram (50). Similarly, some studies also visualized interventions or intervention points on the causal diagrams. Some studies created additional supplementary diagrams to represent additional aspects of causal complexity. In addition to the multiple studies using tables, other types of visuals used included systemigrams (36), bar charts (62,67), line chart (64), influence maps (59), sub-system diagram (63), stakeholder maps (65), and policy structure diagram (63). In some such cases, the additional diagram was intentionally placed adjacent to a corresponding causal diagram. Five studies used placement, clustering, and grouping of diagram elements in theoretically useful ways (40,43,48,58,59), for example by radially placing variables in different biological, social and ecological levels. Ghobadi et al. (43) presented metrics corresponding to diagram elements overlayed on the causal diagram. Two studies progressively increased the scale and complexity of diagrams as they revealed it through the narrative and description of results, seemingly to facilitate accessibility or comprehension (i.e. starting with a core diagram and progressively expanding to facilitate accessibility) (65,69).

Challenges in qualitative coding of causal diagrams

We report the challenges described by the various studies, specifically the ones that were unaddressed by the studies per author descriptions. We focus on aspects related to coding and do not report on challenges related to analysis of causal diagrams post development. The following list described the challenges discussed:

- Efficiency and cost
    - The qualitative systems thinking and coding process can be time, labor, and resource intensive (2,67). This can depend on various factors such as data volume, clarity of conversation, coder familiarity with data, degree of iteration and desired degrees of confidence, hence requiring consideration of purpose of generating causal diagram (2). Time intensiveness increases when participatory stakeholder engagement are desired (37).
- Tool limitations

    - The inability to interact with a causal diagram in qualitative data analysis tools leads to inefficiency, and limits monitoring of coding progress (17,38).
- Paradigmatic considerations
    - Theoretical integration of systems theory with qualitative approaches leveraged such as grounded theory, is needed (35).
- Validity
    - Treating conflicting information in coding process and visualizing corresponding uncertainty in causal diagrams is challenging (2,38).
    - Subjectivity of researchers and risk of bias can negatively affect validity (35,38,45,65).
    - Comprehensiveness and generalizability of insights is difficult to achieve (45). Comprehensiveness is further challenged when system boundaries are set early in process (33) or when boundaries are determined by choice of data source (39).
    - There can be ambiguity of meaning in description of variables (67).
- Diagram communication
    - Communicating with causal diagrams to those with limited experience in diagram usage is challenging, and can lead to limitations in the ability to validate diagrams with participants (46). There is a need to make methods more accessible to practitioners and stakeholders (59).
    - It is challenging to represent specific nuances of causal complexity in diagrams: representing geographic levels – local, regional or national – at which interactions happen (34), state of minds of system actors (34), and situations when the level of a variable can lead to different pathways (67).
    - It is also challenging to represent dynamic qualities of causality such as time components (34), sequences of narratives (39), initial conditions (39), and dynamic aspects such as non-linearity, emergence and non-intuitive results with the qualitative and static nature of causal diagrams (44).

Implications

Our contribution presents a comprehensive picture of the different ways in which causal diagrams have been qualitatively developed. We report on the types of coding activities conducted as well as various specific practices within these. These practices can be considered akin to Lego blocks (Figure 2.7). We believe that researchers can use our analysis of coding practices by considering them as modular components that can be combined to develop coding processes suited to a particular project. There is a need to develop qualitative coding methods to balance what may be sometime competing needs such as rigor, efficiency, usefulness, and practicality of findings, etc. Based on the needs, resources and constraints within a particular project, the processes described in the literature can be combined to reach useful compromises.

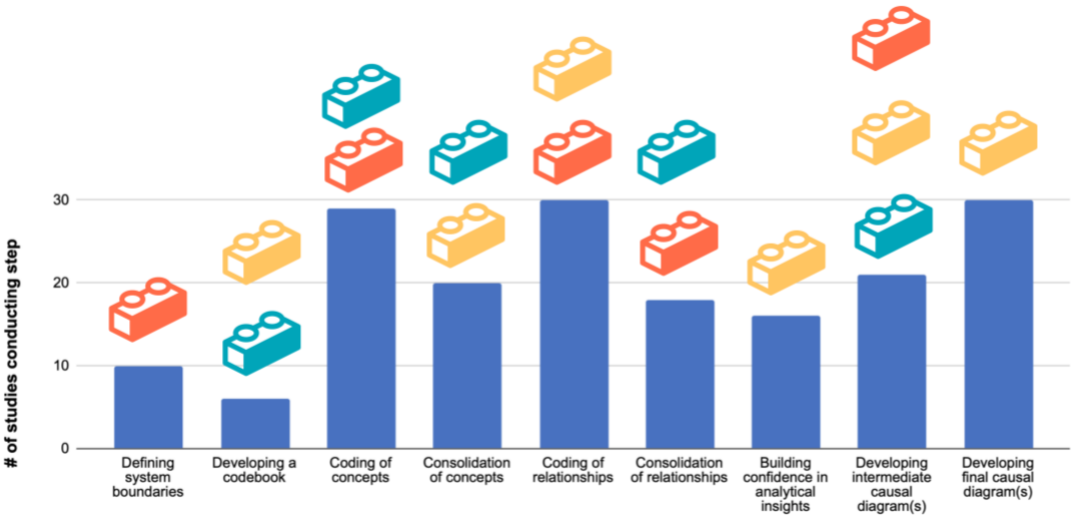
For example, if a team needs to balance rigor with efficiency, they might consider combining practices that use literature sources to build confidence in insights while using data management practices and tools that make the coding activities less resource intensive. We believe another contribution of this study is in building a conceptual vocabulary of ideas useful for qualitative development of causal diagrams, for example, to learn of different ways in which causal relationships could be reconciled. We found a rich variety of practices, and considering the suitability of methods would depend on various project relevant factors (18), there is a need for researchers to experiment with different ways of working. An area where future research is needed is the critical reflection and empirical evaluation of different coding practices for qualitative generation of causal diagrams. We believe that our analysis can be used as a framework for such efforts. For example, are certain sequences of coding activities more fruitful than others? Do particular tactics within coding approaches such as using particular criteria for causality (57) lend themselves to better quality output? There is also a need to reconcile our findings with frameworks with different foci, such as Turner et al.'s (18) framework for considerations when choosing a qualitative approach.

Our findings suggest the need for better tools to support qualitative coding and analysis practices. The insights here can be used by methodologists and developers of qualitative data analysis software to better cater to the requirements of such methods. Development of effective tools or the development of creative ways to use current tools is another area ripe for future research. This is an area of opportunity for design methods and particularly rapid prototyping practices to contribute to systems thinking practices.

The field is also in need of clearer reporting standards for which Jalali and Beaulieu (21) have made some progress. This is echoed in our findings considering that 109 studies out of 248

in our full text review phase did not include substantial descriptions of methods. Our findings can be used to extend reporting standards in future research.

Figure 2.7. Metaphorical illustration of how researchers can use the coding practices described within the coding activities by considering them akin to Lego blocks that can be combined based on one's project's needs.



Murphy (22) has proposed that we need a modern theory of leverage. We found a limited number of studies adopting specific techniques to identify leverage points and/or assess leverage of elements within a causal diagram. There is a need for future research to enhance such techniques, empirically test them and to experiment with combined leverage approaches such as using techniques from graph theory with interpretive or participatory approaches.

The various challenges described by the researchers highlight other areas where work is needed. One such area is the communication and visual presentation of causal diagrams. There is a need to develop visualization practices that are useful to diverse stakeholders and communicate additional nuances of causal complexity such as levels of a system and temporal characteristics. This is an area of opportunity for design methods and particularly its visualization practices to contribute.

There is clearly a need for more cross-disciplinary discussion and reflection of ideas to address these challenges. Challenges faced by one sub-discipline may have already been resolved by another. Our work begins to develop ground for such cross-disciplinary work by describing causal diagramming practices across various disciplines.

Limitations

This study has two central limitations. First, our sample of studies is limited by the time period of focus, and the two databases that were used. As discussed, causal diagramming is a practice of interest to many different fields. In the process of this project, we learned about additional types of causal diagrams that we were not aware of when conducting this search for studies. We would not be surprised to find yet more types of causal diagrams. As a result, we may have missed important studies from other time periods, other disciplines or those developing alternative types of causal diagrams. When conducting the full text screening, we also found studies that were referenced by the screened studies and might be relevant for inclusion. These were not included for practical purposes of the scale of the analysis, which as another related limitation.

Overall, we adopted a rigorous process and have reported our methods in detail. Yet, as we described, in some stages screening, extraction and analysis were conducted individually. While we were mindful to maintain an audit trail and resolve discrepancies through consensus, this may still limit reliability and validity of decisions we made.

Conclusion

We have conducted a comprehensive systematic review of qualitative coding practices for generating causal diagrams in various disciplines. Our analysis offers a description of various possibilities of causal coding approaches. We have identified challenges that suggest the need for

future research and cross-disciplinary sharing of practices. We have identified practices in qualitative coding for design researchers interesting in complex problems to benefit from, and areas of opportunity for design to contribute to systems thinking.

Chapter 3

Applying systems thinking to holistically understand postpartum hypertension health education experiences

Abstract

The postpartum period is particularly important in the challenging maternal health landscape in the United States, being a window of opportunity impacting long-term maternal and infant health. A large portion of pregnancy-related deaths occur during the postpartum period, and hypertension is a major clinical cause. Critical health education is provided during the postpartum period to prepare patients, but multiple studies find that postpartum health education has shortcomings that reduce its effectiveness and that it can be an overwhelming experience for patients. Various factors impact the effectiveness of health education. There is a need to study the complex drivers of postpartum health education experiences holistically. Adopting a systems thinking perspective, the researchers analyzed a focus group of postpartum birthing persons who experienced care at a large Southeastern hospital in the United States using purposive secondary data. A causal loop diagram was developed that presents a dynamic hypothesis of drivers of health education experiences and patient health. The results describe the drivers for three key pillars of patient health: patient knowledge and skills, care mishaps, and care monitoring. Balancing feedback loops – those that describe cyclic effects within the system that keep it in check or resist change - describe the negative impacts of early-stage patient health on effective education hence affecting patient health in later stages. Involvement of alternative care teams, patient involvement, support person(s) involvement, care team's time spent with patient and continuity of care interactions may be fruitful leverage areas for systemic interventions. Systems thinking methods are a promising way to understand complex problem spaces, and for finding opportunities for action.

Relevance for design & systems thinking:

Applying and testing a method to identify areas of leverage or action in a complex problem space through a qualitative method

Relevance for postpartum healthcare:

Developing a holistic and dynamic understanding of the drivers of effective and poor experiences with postpartum health education and how this drives patient health

Introduction

In the United States, maternal mortality has unfortunately been on the rise - between 2000 and 2020, maternal mortality has more than doubled (70,71). Sadly, this is the case even considering that 60% maternal deaths may be preventable (72). There are persistent disparities when comparing the maternal mortality rate for people with different socioeconomic characteristics. In 2020 - consistent with a tragic century-long trend - non-Hispanic Black women had the highest rates of pregnancy-related deaths: 2.5 times as many pregnancy-related deaths per live birth when compared with non-Hispanic White women and Hispanic women (71). These worrying statistics underscore the importance of attention and interventions in this domain of healthcare. Additionally, pregnancy is seen as a window of opportunity impacting long-term maternal and infant health (73), making it a key time period to understand from a life-course perspective.

The postpartum period is of particular importance when considering maternal health experiences. A large proportion of pregnancy-related deaths occur in the early postpartum period - 18.2% of these deaths occur between 1-6 days postpartum and 13.2% occur between 7 and 41 days postpartum (74). Hypertension is one of the major clinical causes of maternal mortality during the postpartum period (70). Maternal hypertension is a condition with inequitable impacts on certain populations: for example, the prevalence is higher in American Indian/Alaskan Native (8.9%) and non-Hispanic Black (9.85) than White birthing persons (75).

In the United States, since a large portion of deliveries occur in settings such as hospitals and birthing centers, the transition from discharge to home is critical. As families are prepared

for discharge, key risk factors are identified, physical examinations are conducted, the mother and child are cared for and observed, and education is provided on important topics (76). In the United States, the average length of postpartum stay has approximately halved in recent decades - from 3.9 days for vaginal births in 1970 (77) to 2 days for vaginal singleton births in recent years (78). As a result, the postpartum hospital stay may have a lot of activities packed in a short period of time. Even through the postpartum discharge transition, racial disparities are present. For example, barriers to care due to insurance coverage disproportionately impact Black women, and women with low incomes, limited English proficiency, and Medicaid coverage (79,80).

During the postpartum hospital stay, education is provided to families across multiple time points and in multiple formats. Suplee et al.'s (81) study found that education provided is typically a combination of individual interactions through the postpartum stay, along with providing written and audiovisual materials. The interactions may involve a dedicated 15–30-minute session with a 'discharge nurse'. A discharge education sheet is provided, that is reviewed and signed by patients before discharge. While postpartum education covers a large range of topics, the priorities of nurses and patients differ, with nurses prioritizing safety (e.g. safe sleep, preventing infant falls, decreasing infection), screening for postpartum depression and avoiding adverse outcomes, and patients prioritizing self-care, pain management, infant care, and parenting (82).

Postpartum educational practices have their shortcomings in effectively equipping families. Education and materials provided by nurses during the postpartum period may not be effective, particularly when it comes to warning signs (81). During the postpartum stay, warning signs for maternal mortality and morbidity are often not discussed until the day of discharge and may not be the primary focus, in addition to being taught inconsistently by different nurses (83).

Suplee et al.'s (84) survey of registered nurses found that 67% of participating nurses spent less than 10 minutes teaching patients about warning signs of potential complications on the day of discharge. The same study also reported that the nurses weren't current on rates and timing of maternal mortality and did not always provide comprehensive education to all women prior to discharge.

Various contextual factors can also impact educational experiences. Patient literacy, comprehension and language barriers make effective discharge education a challenge (81). Distractors and stressors during the postpartum stay, cultural traditions, previous birthing experiences, and overwhelming postpartum experiences can impact educational interactions (82). Unsurprisingly with the short duration and overwhelming postpartum stay, Mazloomy Mahmoodabad et al. (85) have found that education in the prenatal period - in their study, specifically for weight management - can have lasting benefits through the postpartum period. While there may be benefits to individualizing education tailored to a birthing person's unique experience, nurses find it difficult to individualize education due to timing constraints and staffing issues (82). Women also report their educational experiences being impacted by limited nursing time (83). Education before the postpartum discharge from the hospital - sometimes known as 'discharge teaching' - is one area with conflicting evidence on optimal teaching strategies. For instance, content delivered in excess of the mother's needs is associated with greater discharge readiness (86). At the same time, studies show concerns about postpartum education being an overwhelming experience (82). Quality of discharge teaching - both in content and delivery - is found to have the greatest impact on discharge readiness (86).

Multiple studies have evaluated the impact of education styles and interventions on outcomes including patient satisfaction, efficiency, and feasibility (82,87,88,88–92). There is a

lack of consensus on the ideal ways to conduct postpartum education. While the goals of the listed studies vary, it is unclear what teaching styles (e.g. one-to-one vs. group) and mode of delivery (e.g. using videos or educational booklets) have are most impactful. Successful interventions include the Association of Women's Health, Obstetric and Neonatal Nurses (AWHONN) postpartum education initiative 'Empowering Women to Obtain Needed Care' consisting of a Discharge Education Checklist for nurses to use, along with a flier for patients about warning signs and relevant actions for different postpartum life threatening conditions (93). This intervention was found to successfully increase patient knowledge. Digital health interventions have led to some level of success in supporting patient education in the postpartum period and across pregnancy generally. Jaynes et al.'s (94) systematic review of the impact of digital interventions on maternal outcomes in the postpartum period found a positive effect of interventions on mental health, weight loss and breastfeeding outcomes. Similarly, Schnitman et al.'s (95) review of digital patient education for maternal health found benefits reported in the studies for improved knowledge, emotional/attitudinal benefits, and improved behavioral/clinical outcomes. Logsdon et al. (96) reported significant improvement in postpartum patient knowledge by providing access to educational video in addition to printed materials.

Literature about postpartum and maternal health information seeking echoes some of the challenges of postpartum education practices described earlier. Henshaw et al.'s (97) study of parents through the first 6 weeks postpartum reports gaps in knowledge about things they didn't know and difficulty retaining information received at the hospital. Loudon's (98) work on information seeking for first time mothers reveals experiences of information overload and difficulty finding time for information seeking.

Poor experiences with clinicians or healthcare information sources may de-motivate health information seeking. For first time mothers, conflicting information received from different sources and care teams can lead to hesitation to seek information in the future and to connect with the care system (98). Additionally, guilt can play a large role as well, with the fear of judgment for asking about their own health holding mothers back (97,98). Conrad's (99) review of literature on pregnant women's information seeking behaviors on the internet reports that women hesitate to 'burden' or 'bother' providers with simple questions, suggesting the need to consider the power dynamics and perception of clinicians by patients.

Different sources of information can have different levels of perceived utility based on personal characteristics and goals. Academic or government websites are used less often than commercial sources by pregnant women in spite of providing the most accurate information (99). Many pregnant women don't review online information shared by their clinicians (99). Burleson et al.'s (100) study with low-income African American pregnant women in Detroit found that equal trustworthiness is placed in formal and informal sources, with timeliness of responses also impacting trust. Similarly, first time mothers may value advice from other family members trusting their shared concern for the child rather than a wider policy or product-driven agenda (98).

In summary, postpartum and maternal health in the United States is in a crisis with rising mortality rates and wide disparities between different socioeconomic groups, making it a problem area demanding urgent attention. Health education during the postpartum period is key to supporting healthy and successful outcomes for birthing persons and families after discharge, yet there is evidence to suggest that health education during the postpartum hospital stay is

overwhelming, and not supporting families to be meaningfully ready before discharge. Providers are constrained by policies, tools, and time. Patients are overwhelmed by the experience.

Methods

Considering the complexity of this problem space and inter-relations between various drivers of postpartum care suggested by the literature, there is a need for holistic inquiry. This study hence aims to understand how various drivers of health education - generally and around hypertension - in the postpartum period impact patients' experiences and health outcomes. The following are the research questions:

- RQ1: What are the experiences and challenges of birthing parents receiving care at a Southeastern U.S. hospital in obtaining, understanding, and applying hypertension education during the postpartum hospital stay and after discharge?
- RQ2: What are the experiences and challenges of birthing parents receiving care at a Southeastern U.S. hospital with managing hypertension-related health after discharge to home?

This study was part of a larger project and research collaborative called Postnatal Patient Safety Learning Lab (PSLL) to improve postpartum care experiences and was funded by grant R18HS027260 from the Agency for Healthcare Research and Quality (AHRQ). As part of the project, the lab's research team conducted multiple focus groups with patients and care team members, with a focus on studying experiences with hypertension, postpartum healthcare, health education, and developing interventions. For this specific study, the researchers analyze a focus group with birthing persons discussing health education and hypertension, through the lens of systems thinking to develop a causal loop diagram and to identify areas of leverage. This study hence utilizes a component of data collection from the lab's efforts as secondary data and is approved by NC State University's Institutional Review Board (protocol #2672).

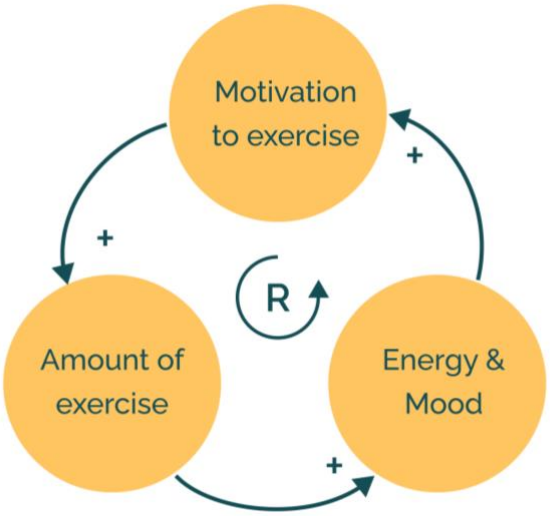
Theoretical perspective: systems thinking

To understand the complexity in this problem space, the researchers applied a systems perspective. Systems thinking (also referred to more generally here as a systems view) is a theoretical perspective of reasonable breadth and possibilities - it has been applied to a wide range of disciplines (1). At its core, is holistic and integrative thinking - the sum is greater than its parts, and hence cannot be understood merely by dissecting the system and isolating its parts (1). The emphasis is on understanding a system's behavior, and the source of this is in the structure of the system and understanding relationships and flows between elements (5). A systems view is simultaneously a paradigm, a language, and technology - it can be a way to think about the world and relationships, a way to diagram systemic understanding, and as technology for modeling and simulation of systems (6).

The language of systems thinking is key to communicating complexity through its various visual and analytical tools, a subset of which are causal diagrams. Causal loop diagrams are one such tool (1,7), as shown in a simple example in Figure 3.1. A causal loop diagram consists of a network of causal relationships between variables, represented by variables and arrows/linkages between them. Arrows indicate causal linkages wherein a change in the first variable will trigger a change in the connected variable, all else equal. A '+' or 's' sign corresponding to a link is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding increase (decrease) in the connected variable, or that they move in the same direction. A '-' or 'o' sign is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding decrease (increase) in the connected variable, or that they move in opposite directions. This sign is also referred to as the polarity of the relationship. Chains of arrows that close a circle (and thus repeat) are important

structures and can be of two types. A reinforcing feedback loop is like a 'vicious cycle' or 'virtuous cycle' (depending on whether results are desired or not), where an increase in one of its variables leads to its own continued increase over time, or a decrease in the variable leads to its continued decrease over time. Reinforcing loops are powerful and drive exponential change. A balancing feedback loop on the other hand 'keeps the system in check', where an increase in a variable is balanced by a decrease in it over time, and vice versa. Balancing loops are also important in that they resist change.

Figure 3.1. Example of a simple causal loop diagram.



Sampling and data collection

A total of six participants (n=6) took part in a virtual qualitative focus group discussion with five researchers and facilitators. The focus group took place in January 2020. The goal of the original data collection of the workshops was to understand birthing persons' experiences of feeling informed during maternity care, what they know about hypertension in relation to pregnancy, and how they would want to learn about this information.

Participants were selected using a purposive and variation-based sampling approach. For inclusion in the study, participants had to have experienced care at the hospital in consideration in the prior 12 months. Variation was sought through recruitment to include participants with various levels of experience with hypertension and preeclampsia. For recruitment, a research assistant screened potential participants via electronic health records at the hospital, and approached participants in person and via phone, with eligibility screening conducted over a survey using Qualtrics (101).

A facilitation protocol was used to guide the focus group discussions (Appendix E). This included questions about the participants' pregnancy journey, what education was (or was not) provided to them about hypertension, and what made them feel prepared or unprepared in relation to hypertension and their health. In preparation for the focus group, participants were asked to complete a journey map. On this journey map, participants plotted the positive and negative aspects of their maternal care journey through its different phases, using photos from a provided set to represent their emotions, in a manner like a collage. An example of the journey map created by a participant is shown in Appendix F. In the first activity during the focus group, participants were asked to explain their journey map, followed by question-guided discussions. The activity was conducted during the evening time over the video conferencing software Zoom (102) anticipating difficulties for participants to join during working hours. Participants were encouraged to not hinder other activities such as childcare responsibilities and told that they were welcome to have their children around them or in the frame for the video call. Some participants joined the focus group with their cameras off. Researchers weren't certain whether the participants had other family members around them, yet participants appeared to share their experiences in a candid manner.

The discussion was recorded and transcribed automatically by Zoom's built-in feature. The transcript was manually reviewed by two researchers and edited for accuracy.

Data analysis

One researcher (RM) conducted the coding and analysis. The analysis incorporated multiple best practices of qualitative causal analysis drawing on the systematic literature review in Aim 1 of this dissertation. Theories of health behavior were reviewed by the researcher conducting causal coding, as sensitizing concepts. The data analysis began with an open-ended review of the transcripts. While reviewing the transcripts, annotations and memos were made regarding potential causal connections, analytical insights, and ideas. Additionally, drawing inspiration from a tactic developed by Tomoaia-Cotisel et al. (47) in their Rigorously Interpreted Quotation Analysis method for validating causal diagrams, while reading the transcripts, key phrases were underlined that indicated the presence of potential variables in a causal connection or chain. Segments of data that contained causal information were highlighted. Additional variables were underlined for context about participant experiences. This initial review of transcripts was then used for a more thorough coding process.

Qualitative causal coding was conducted using a spreadsheet in Microsoft Excel (103). For the first round of coding, open coding was conducted to document causal connections between pairs of variables. The spreadsheet included fields to record participant ID, quote, from/cause variable, to/effect variable, polarity, and variable behavior (whether it was described in the focus group as increasing or decreasing; Table 3.1). Noting variable behavior was a simplified adaptation of coding practices of Kim & Andersen (2). Additional comments were made to note links requiring validation or discussion. Comments were used to describe causal links that were only implicitly described, or more complex descriptions involving meandering

conversations (47). Memoing was used during the coding process to note key analytical insights or patterns, potential feedback loops and intervention points, and variables to consider merging, adjusting, or splitting. Another spreadsheet was used to note insights around participants' levels of knowledge and of being informed about hypertension and postpartum preeclampsia.

Table 3.1. Excerpt from template used for open causal coding.

Participant ID	Quote	From	To	Polarity	To variable direct
F018	My doctors made me feel considered. They helped with giving me information to feel educated. They were receptive I had the same doctor for both of my children when I was getting prenatal care, so there was a good amount of trust there between the two of us. I had a great health care team, I felt like. And I was pretty optimistic going into the pregnancy itself and getting ready to have birth.	Continuity of care team	Trust between patient and care team	+	Inc ↑
F018	And then, for, like some of the things dealing with like mental health doctors or you know [to/for] helping with controlling the medicine, it's hard to have those appointments virtually. So not having an option to go in, because I had no privacy. And trying to speak to a doctor about those types of issues of like depression or postpartum things when you have an infant grabbing you, a toddler trying to pull on you and you have no privacy at work or something to have private conversations, it's very hard and it doesn't help when you re trying to talk about things like that.	Patient privacy during virtu	Virtual appointment success	+	Dec ↓

The next step involved abstracting and merging variables. A list of each unique variable from the previous step was created. Counts of the number of times a variable was mentioned by each participant, and the total number of participants mentioning a variable were reviewed. A matrix was then created in Excel for the abstraction and merging process (Table 3.2). Filtering and conditional formatting rules were applied to the data from the open coding stage to easily find and examine relevant causal connections. Additionally, a draft causal diagram was created using the mapping software Kumu (61) for reference during this stage. Each variable from open coding phase was reviewed systematically through constant comparison to other variables, to the draft causal structure, to causal connections it was mentioned as part of, and in some cases, other

related causal connections mentioned in the same quote. Variables were then either merged with another variable, renamed, excluded for being out of scope, or left unchanged and included. The rationale for merging and exclusion decisions was recorded in the matrix. Categories of reasons for merging variables included being conceptually similar or overlapping, having similar connections into or out of the variable in the model, or being the same concept at different time points (e.g. at different stages of pregnancy). Auxiliary chains with intermediate variables that could be merged with either preceding or succeeding variable were also simplified. The matrix was used to map the abstracted and merged variables to the open coding variables. While going through this process, definitions for each included abstracted variables were recorded to generate a codebook. Minor changes were also made to the open coding because of the further detailed review occurring in this step.

Table 3.2. Excerpt from matrix used to abstract and merge variables.

UNIQUE FUNCTION to identify unique variables	# of participants mentioning variable	F001	F006	F009	F014	F015	F018	Variable merging/exclusion status		New	Patient health	Continuity of care interactions	Covid 19	Care team with differing views	Staffing shortages	Alternative care team involvement	Care mishaps	Unwelcome traffic in patient's room	Information overwhelm	Support person(s) involvement	Patient advocacy	Continuity of care provision	Infant health
										Defir	Health stat	Having coi	Occurrenc	Patient's care	Capacity of	Involvement of	Errors, misha	Diff are team	Large amount	Presence and	Patient's n	Continued ca	Health status
										Mer	Same cent	Both get at	aspects of	experiential	continuity	Having similar c	Conceptually	Research stud	Volume of info	feeds into	educational	overwhelm;	time for processin
Continuity of care team	3	0	0	1	0	1	3	Included				x											
Covid 19	4	1	1	2	0	0	2	Covid parking															
Fast changes in hospital information	1	0	0	0	0	0	2	Covid parking															
Care team with differing views	3	0	1	1	0	0	1	Included						x									
Patient privacy during virtual appointments	1	0	0	0	0	0	3	Parking lot - s															
Childcare responsibilities	1	0	0	0	0	0	1	Parking lot - s															
Privacy at work	1	0	0	0	0	0	1	Parking lot - s															
Staffing shortages	1	0	0	0	0	0	1	Included							x								
Doula or midwife involvement	3	0	2	6	0	0	1	Included								x							
Delay in received care	2	0	0	0	3	0	3	Included									x						
Research study requests	1	0	0	0	0	0	1	Merged but li										x					
Volume of information	2	0	1	0	0	0	1	Included - deli											x				
Support person(s) involvement	5	2	3	2	1	0	1	Included												x			
"somebody there that can speak for me"	3	2	0	6	0	0	1	Included													x		
Unwelcome traffic in patient's room	3	1	0	1	0	0	1	Included										x					
Patient health	6	6	3	17	4	8	1	Included			x												
Restrictive NICU policies	1	1	0	0	0	0	0	Parking lot - fi															
Alternate support organizations	2	2	0	2	0	0	0	Included								x							
Continuity of care provision	2	2	0	1	0	0	0	Included														x	
Delayed understanding of patient health	0	0	0	0	0	0	0	Excluded - spl															
Infant health	1	0	0	5	0	0	0	Included															x
Care team understanding of patient health	2	0	0	8	3	0	0	Included															
Prior pregnancy experience	5	3	0	2	3	1	1	Included															
Patient involvement (listening + leveraging self knowledge)	3	0	0	8	1	1	0	Included															
Patient desire to be in hospital setting	2	0	0	3	0	0	1	Included															
Early pregnancy health	2	0	2	1	0	0	0	Included			x												
Time for processing	1	0	4	0	0	0	0	Included - deli											x				
Information overwhelm	2	0	2	0	0	0	4	Included											x				
Asynchronous learning (eg. online)	1	0	1	0	0	0	0	Included															
Synchonous learning (eg. appointments)	1	0	1	0	0	0	0	Included															
Patient knowledge	6	10	6	10	3	10	6	Included															
Patient self knowledge	2	4	0	4	0	0	0	Included															
Patient monitoring of health	4	3	5	3	0	0	2	Included															
Firefighting to protect health	1	0	0	2	0	0	0	Included															
Health before pregnancy	4	1	0	0	1	1	1	Included			x												

After abstracted variables and the codebook were created, the connections in the initial coding were updated to reflect updated variables. Care was taken to ensure accurate direction of causal connections was updated if a variable was abstracted in a way that would change the

direction of a connection. This process hence generated duplicate connections of two types: (i) if concept A & B were merged, links from A>C and B>C were made redundant (ii) if concepts A & B were merged, links from A>B were made redundant. These redundancies were reviewed and deleted.

The links from the previous steps were then merged, maintaining the abstracted variables, quotes supporting the connection, and the total number of participants from the sample mentioning the link. The final coding spreadsheet was then uploaded to the mapping software Kumu (61) again to generate the integrated causal loop diagram. Emphasis was added to variables based on interpretation. The link thickness of causal relationships was made variable based on the number of participants who mentioned something that supported the connection. As the diagram was reviewed in Kumu, discrepancies found were verified and resolved. At this stage, the diagram was further simplified by concealing or pruning a few additional variables that were determined to be out of scope of study or being secondary outcomes not driving any primary outcome or important factors inside the system. Vensim Personal Learning Edition (104) was used to draw sub-structures and loops for reporting. Quotes reported along with results were edited for concision and clarity, primarily removing filler words.

Overall, coding was an iterative process and the multiple stages of review enabled resolution of coding inconsistencies along the way. After generating the diagram, Kumu (61) was also used to identify feedback loops and calculate leverage metrics. Of particular interest to design and other intervention focused disciplines engaging with systems thinking, causal diagramming tools offer the potential to identify areas of leverage – high impact areas for intervention in a system (22). Perhaps the most frequently cited and accessible statement on thinking about leverage in systems is Donella Meadows' list of nine types of places to intervene

in a system: going in increasing order of proposed effectiveness from constants, parameters, and feedback loops to the more deep-rooted aspects of systems such as goals, mindsets and paradigms (23). This way of thinking about leverage may be limited. Murphy (22) argues that prioritization of deeper leverage areas might not always hold true, and when systems are broken down into other subsystems, each may have its own leverage points, making it important to consider the layers of leverage. What is more, the latency of any leverage point may be different for different actors in the system (22) (e.g., different levels of influence, role and positions of any actor in the system also matter). Murphy and Jones (24) proposed the potential utility of graph theory to identify leverage points in a system by calculating measures such as degree, between-ness, connected-ness and reach efficiency of variables. This can suggest the roles a variable may play in the system such as being a high impact intervention point, a bottleneck, being volatile or stable, having high efficiency for propagating change, etc. Such approaches may also have limitations, as argued by Crielaard et al.'s (25) evaluation of two such measures – between-ness centrality and closeness centrality. They find problems with the reliability of the measures when the same system is represented with different inferred causal diagrams, and other key gaps and problematic assumptions when such metrics are used. In this study, we analyze leverage using three graph theory based measures drawing on Murphy and Jones' (24) leverage analysis method:

- In-degree: The total number of connections into a variable, representing elements that may be highly sensitive or stable.
- Out-degree: The total number of outgoing connections from a variable, representing elements with high impact on many other elements, and being potential leverage points.
- Betweenness: Frequency of participation in the shortest path between two other elements, representing gatekeeping or being a bottleneck, where change strategies should consider bypassing or preventing blocking.

These leverage measures and the key roles of different variables they indicated were then interpreted qualitatively considering other considerations such as modifiability and the stories describing the variables shared by the participants.

Results

Six postpartum birthing persons participated in the focus group. 5 of the participants had experienced a hypertensive disorder, including one who experienced preeclampsia. Of the participants, three identified as Black, one as White, and one as biracial. Through open coding, 193 causal relationships were initially identified, that consisted of 82 variables. After merging, consolidation and removing variables that were secondary or out of scope, the final causal diagram consists of 41 variables and 75 causal connections. The codebook for the included variables is in Appendix G.

Figure 3.2 presents the integrated causal loop diagram describing causal drivers of health, health education and patient experiences. In the diagram, we identified a total of 26 causal loops. After comparing the loops, we found multiple loops that were describing similar mechanisms through variation in specific pathways and "detours". After selecting and condensing multiple of the loops, we identified three key loop substructures that describe the cyclical mechanisms at play in the system. Figure 3.3(a) presents a balancing feedback loop describing the negative impacts of healthfulness in early stages on later stages of health, via patient's education, knowledge, and skills. Figure 3.3(b) presents a reinforcing feedback loop describing the negative impacts of poor health leading to further deteriorating health, via patient education, knowledge, and skills. Figure 3.3(c) presents a balancing feedback loop describing the effects of patient health on the monitoring of the patient's health which in turn impacts the patient's health.

Upon conducting leverage analysis to identify the variables with highest out-degree, and after filtering out variables with out-degree value being lower than 3 and variables that did not represent modifiable factors, 5 variables were found to have the highest out-degree: alternative care team involvement (out-degree = 6), patient involvement (out-degree = 5), support person(s)

Figure 3.2. Causal loop diagram (CLD) of drivers of patient health, health education and experiences in relation to the postpartum period and hypertension.

Note: Variable colors have been added for emphasis to key variables. Thickness of causal connection arrows represents the number of participants mentioning the causal connection. '+' and '-' signs indicate causal relationships where variables move in same and opposite directions, respectively.

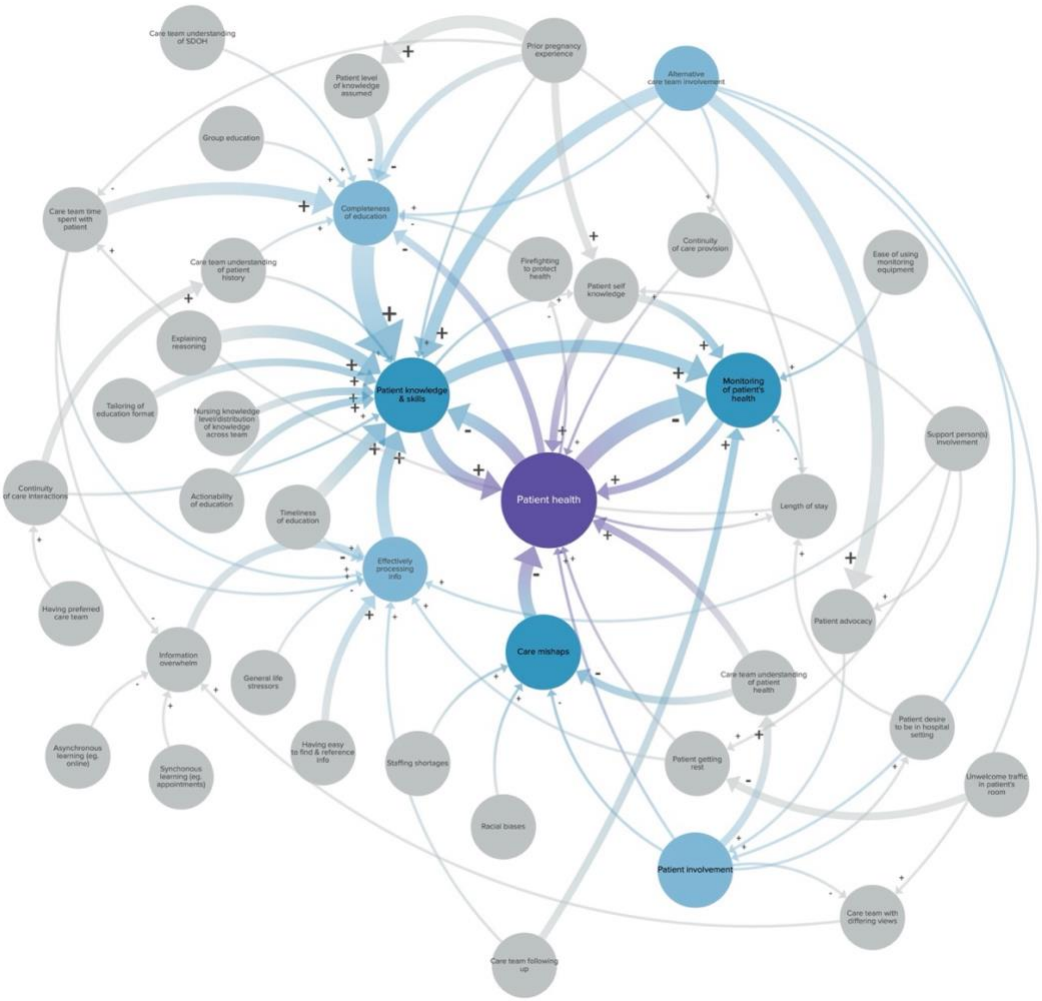
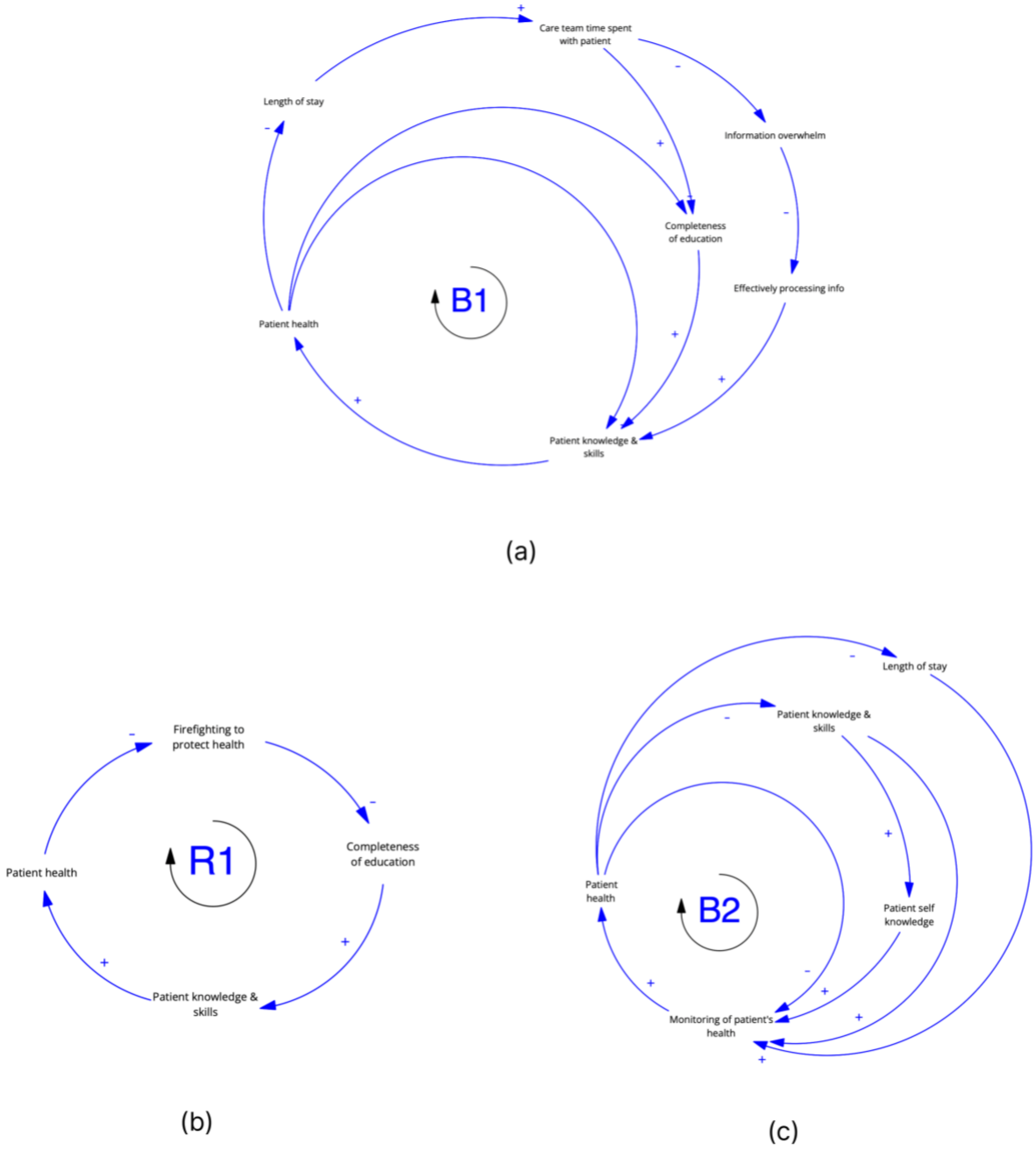


Figure 3.3. Feedback loops describing primary mechanisms in causal diagram.



involvement (out-degree = 4), continuity of care interactions (out-degree = 3), and care team time spent with patient (out-degree = 3). Patient health (betweenness = 0.131) and patient knowledge and skills (betweenness = 0.111) were found to have highest betweenness values.

Discussion

The following paragraphs and figures describe the key loops, stories and sub-structures we interpret from the generated causal loop diagram (CLD). Based on the descriptions of participants, and the small degree of separation to central variables, we consider the following to be key pillars to patient health: patient knowledge & skills, monitoring of patient's health and care mishaps. These were frequently described by participants from the sample.

Patient knowledge and skills

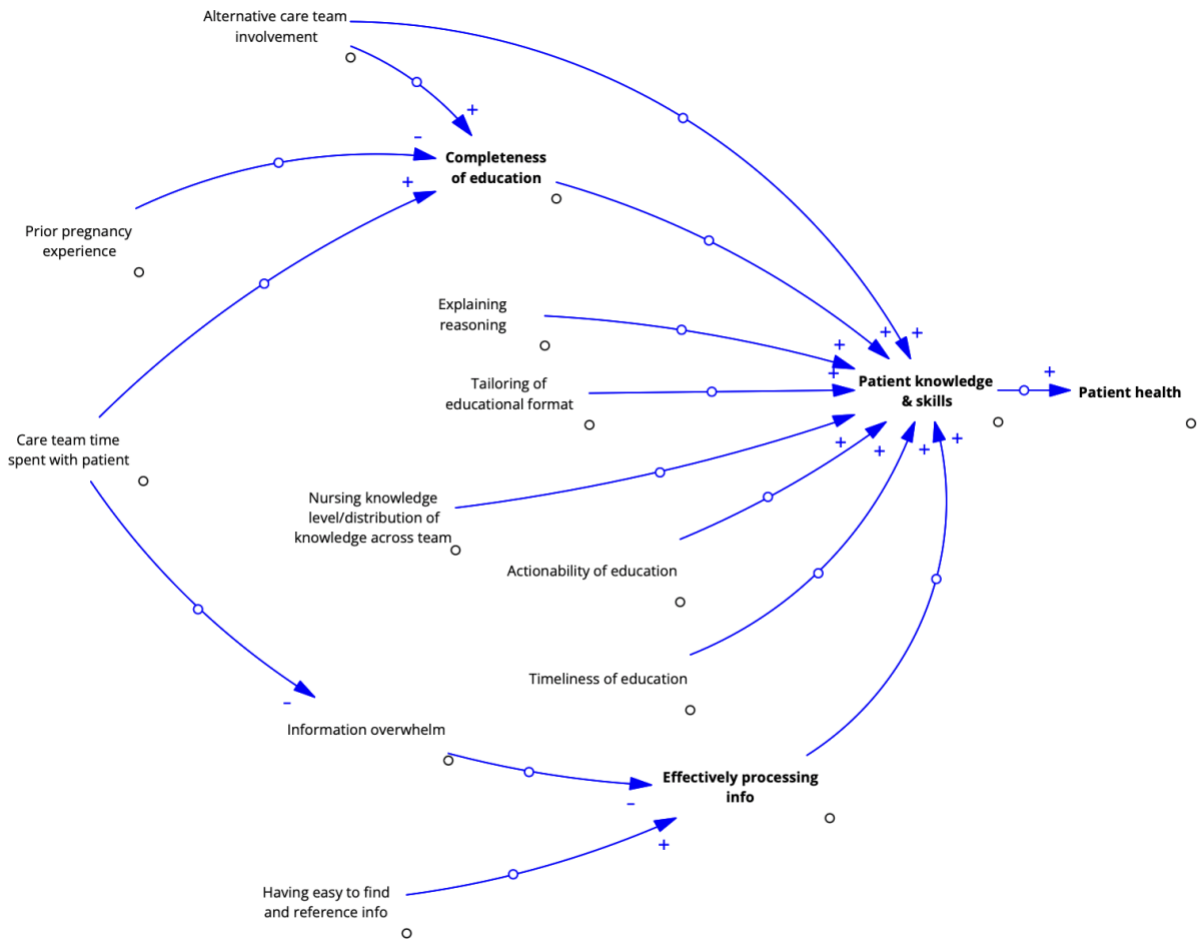
Patient knowledge and skills is a variable with high in-degree (value = 12, rank = 1) and high betweenness (value = 0.111, rank = 2), meaning it may be highly sensitive or resilient and may be a bottleneck for change. It is closely connected to patient health.

Figure 3.4 presents key variables and interactions associated with patient knowledge and skills. Two major drivers of this are the completeness of education and the effective processing of information. Multiple participants described not being aware or informed of postpartum hypertension and preeclampsia, associated risk factors and what to look out for, and described that having prior experiences of pregnancy meant the care team didn't educate them effectively.

> *"You know, they think because you have multiple pregnancies or multiple deliveries, that you should know everything you need to know. I mean every pregnancy is different, so you don't know when a new thing is going to happen. And then they just give you less information when something new comes up. So I felt like with my experience, too, they could have gave more information when the new symptom came up during the pregnancy, instead of just ignoring it.*"

The time spent by the care team with patients and inolvement of alternative care team such as midwives, doulas or other organizations was described by multiple participants as being effective at equipping them. Being overhwhelmed by a lot of information being covered over a short burst of time during synchronous interactions and not having information that is easy to

Figure 3.4. Patient knowledge and skills sub-diagram with selected variables and relationships included.



find and reference were described as problematic by multiple participants, as this can negatively affect how they are able to process the information.

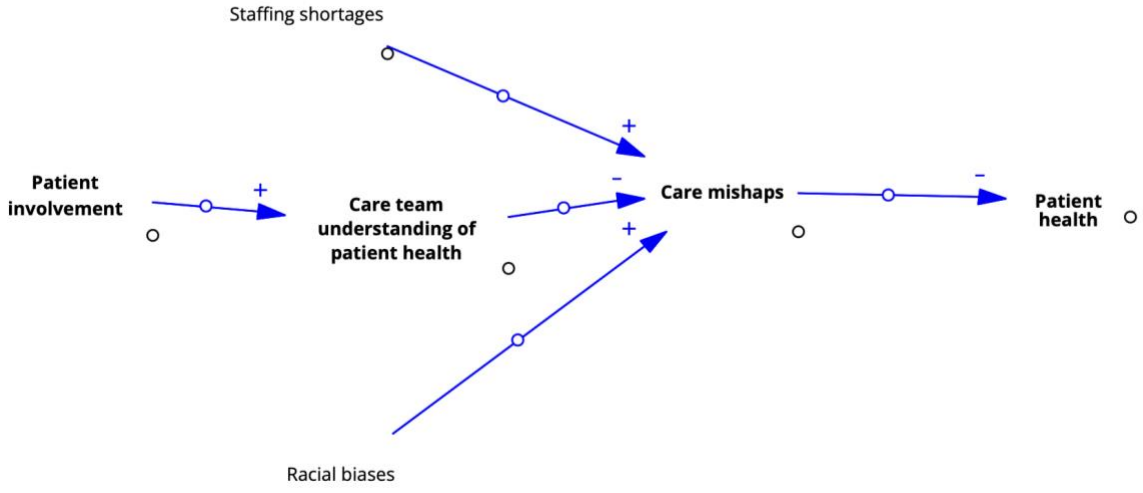
> *"Most of my research is online.. like the appointments, they're helpful for some things, but then, I don't process it right away. So I forget a lot of stuff. I forget a lot of details. I knew about induction.*
> *But I will say the least prepared [I felt] was when I was getting discharged. I know the first time that they kind of made me feel like they wanted me out of the room quickly. They were just trying to push me out and it was like, it just kind of made me feel rushed getting out of the hospital. And it was at the very last minute, everybody starts running in and it's like everyone's trying to squeeze in to see you before you leave. So it's just back to back to back doctors are throwing so much information at you….*
> *… You know and I'm taking it in at the moment but you're so tired, you know you're sleep deprived, your partner, you know, he can't take in all that information."*

Participants described other attributes of a good educational experience such as being explained the reasoning of an action or recommendation, tailoring of education format (e.g., some patients may prefer reading, some may prefer videos, some may prefer face-to-face discussions), being provided information that they can take action on to take care of themselves (as opposed to just being told when to reach back out to their care team), and occurring at suitable timing so patients are prepared well in advanced and at a time when they can effectively process the information.

Care mishaps

Errors, mishaps, and delays (Figure 3.5) in care provision that negatively impacted the patients' health were also described by multiple participants. A common concern here was of the patient's voice not being heard, and of their expectations, needs and perspective not being understood which leading to mishaps in care. Racial biases and staffing shortages were also discussed as drivers of this.

Figure 3.5. Care mishaps sub-diagram with selected variables and relationships included.



Balancing loop 1: Healthfulness in early stages negatively impacting education & knowledge

Being healthy during stages prior to postpartum was described by multiple participants as negatively affecting their experiences, particularly how prepared they were in terms of knowledge and skills and the education they received, which can lead to worsening health over time. Figure 3.3(a) described this balancing loop that influences their health by 'keeping it in check' for the worse. One participant described not being given adequate information prior to delivery because they hadn't experienced any negative symptoms or health consequences at that stage.

> *"I don't feel like I had any good experience with the information. I guess, because I wasn't experiencing all of this prior to the delivery. I would say the hospital didn't give me adequate information, besides "if it's this number give us a call back,". I feel like they could have addressed it a little bit more and gave me things that I could have done to try to work on lowering my blood pressure. If it happened, I just feel like they just felt like "Oh, this is her fourth baby, she knows what to do, let's just send her on home." That's just how it was given to me while I was in hospital."*

Another participant's experience suggests not expecting issues or being prepared since they hadn't experienced high blood pressure prior to pregnancy.

> *"I never had issues [with] my blood pressure prior to being pregnant and I didn't know it was a thing until being pregnant. I just want to give you a heads up. But you know it happened, so now I'm more aware of it with the blood pressure, how can rupture your liver….*
> *…. But I wasn't taught or explained, like these are the effects from your blood pressure being so high from someone that's always been healthy throughout my pregnancy"*

Similarly, patient health during the postpartum period may lead to a correspondingly shorter length of postpartum stay, limiting time spent with care team during the stay, and leading to overwhelming experiences of education around discharge that the patient may not be able to effectively make sense of.

Reinforcing loop 1: Poor health negatively impacting education and knowledge

Interestingly, health status of a patient can negatively impact their experiences with education and being prepared in more ways than one, as described by one participant (Figure 3.3(b)). In addition to previously described balancing loop, a reinforcing loop may be active when the patient's health is particularly in a state of crisis, in what we describe as 'firefighting to protect health'. In such a case, the care team's may be heavily focused on addressing short term crises to protect the patient's health, and as a result, preparing the patient through health education may be deprioritized and lead to further negative health impacts later.

> *"They just told me a little bit, but they didn't really explain much, you know, the signs that I was supposed to look for preeclampsia. So, I didn't really get much information because they were too busy, [I] guess, trying to keep my blood pressure down for the baby's sake,*
> *so, they really didn't help me with that information. I learned more from my doula then I did from the actual healthcare team."*

Balancing loop 2: Patient's health impacting monitoring of health

The degree of monitoring of patient's health that occurs may inversely depend on the status of their health (Figure 3.3(c)). Participants described how they were not asked to monitor their health, or it wasn't effectively monitored by the care team, until it got much worse, or they were diagnosed with a condition, after which monitoring became a priority. The patient's health may also be monitored less by a care team because of a shorter postpartum stay. Again, it seems that health during earlier stages may indirectly impact health in later stages: in this case, via the degree of monitoring.

> *"I don't really understand the readings. I'd like to go into detail about that and figure it out, but I didn't understand why it was important to pregnancy, that was not explained to me.*
> *And 1 wasn't really given signs until I got that diagnosis and then the midwives are very on top of [it]. Like, "watch out for headaches", and I was actually admitted overnight"*

"When I was induced into the hospital [I] had high blood pressure readings. They really didn't check my blood pressure when I had her, until I was admitted into the emergency room six days after having her for having super high blood pressure readings and I also had pneumonia."

Leverage points and bottlenecks

Calculating the leverage measures of variables offers a useful yet imperfect heuristic of what the role of different variables is. We calculated leverage measures of out-degree and betweenness to identify areas of leverage and bottleneck, and reviewed the highest-ranking variables associated with these measures. It is important to consider these measures carefully through an interpretive lens (40,45), and hence we excluded variables that would not be directly modifiable (e.g. patient health, prior pregnancy experience, etc.).

As described in the results, we suggest the following five variables may be potential points of leverage. These are mapped to visualize their key impacts on patient health in Figure 3.6.

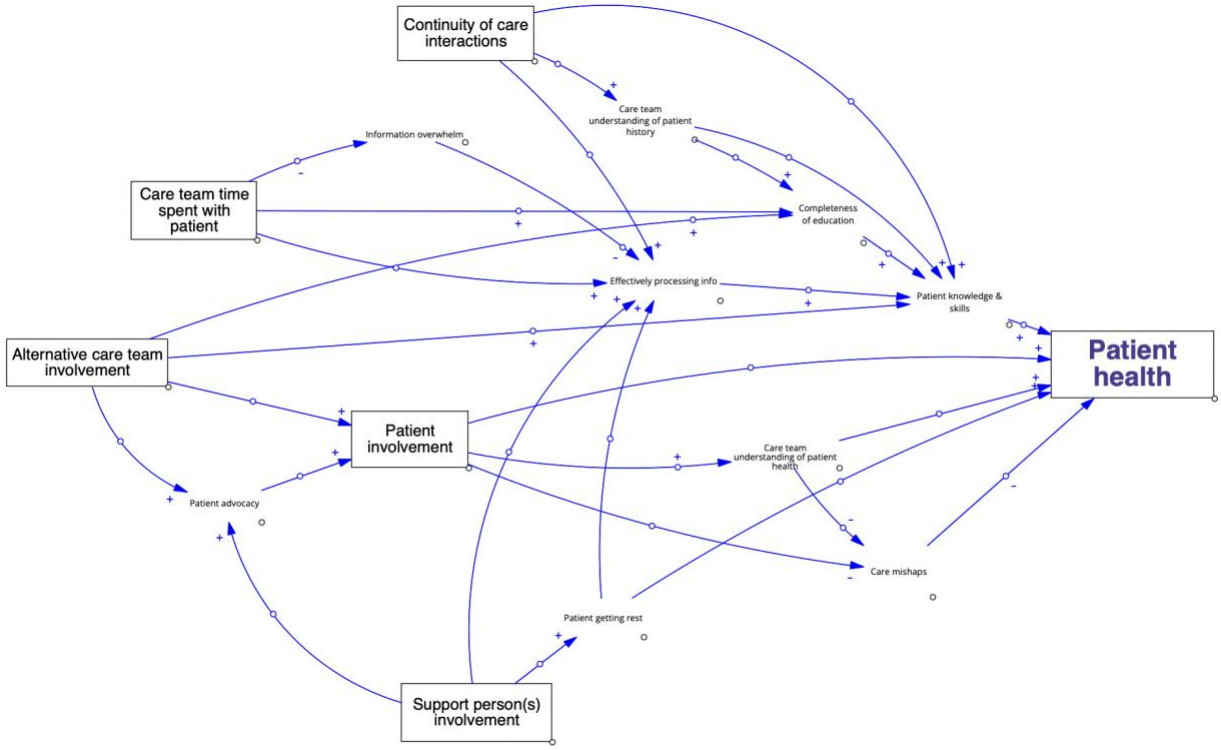
Alternative care team involvement (outdegree = 6)

Multiple participants described the positive experiences they had with alternative care team members such as doulas, midwives, and other organizations. They played roles such as advocating for patients and ensuring patient's voices are heard, continuity of care provision and providing detailed education to support the patient's knowledge and skills.

"I did have a doula with my third pregnancy, and she helped me out tremendously. You know, she walked me through a lot of things. We made a birthing plan, we talked to some of the healthcare team, just to make sure they was on the same page as we were"

"I really liked having the doula - we didn't expect to have her this time with all the Covid stuff. But the fact that she's able to go back there with me when they put in the spinal tap and everything. That made me feel really good - having somebody there that can speak for me and like, kind of hold your hand when you're crying, going through the pain of having that stuck in"

Figure 3.6. Potential intervention points and a selected set of their impacts on patient health.



Patient involvement (outdegree = 5)

Involvement of patients, among other ways, can increase the care team's understanding of the patient's health and reduce mishaps occurring, as discussed in earlier sections, as well. One participant described the experience of switching doctors because of not being listened to, and an improvement in their experience and health after they did that.

> *"And so, they was like playing games about getting me on the medication I needed to be on... the insulin that I need to be on that was for the baby. They was just pretty much not listening. So, I ended up having to switch to a different doctor, because I needed the doctor that was going to actually listen. So, once I switched to a different doctor, they was helpful. They listened and they got me on the right medication and on the right track and stuff to keep my blood sugar level down"*

Support person involvement (outdegree = 4)

The involvement of a support person was helpful in ways such as advocating for the patient's needs, enabling the patient to get rest, and supporting effective processing of

information. One participant described wanting to have a support person with them when during an appointment, a challenging transition in their plans occurred and the amount of information provided was overwhelming.

> *"Once I got that I was high risk and that it meant hospital birth, it meant induction, it meant I couldn't go to 40 weeks. Like, basically everything that I had planned was no longer. And she gave me that and she took me downstairs for a non-stress test. And she gave me all this information, but because no one was there with me, I walked away just feeling like 'What just happened!?'"*

Care team time spent with patient (outdegree = 3)

The amount of time spent by a care team with patient can impact how detailed the educational information provided to the patient is, as well as how effectively it is processed. One participant described a positive experience of regular and long conversations with a care team member during pregnancy appointments that increased their understanding of the induction process and enabled them to ask questions.

> *"I was going in weekly for non-stress tests and it gave me 10-15 minutes with a midwife. And we sat and those visits I feel like helped really understand what that process was going to be ....*
> *.... Having a chance to like sit down [for] 20-30 minutes and for me, having that chance to sit and like think about stuff and ask questions as it came to my head was really helpful and so I knew what the numbers were going to be and what would cause the things to cascade if they're going to. So, I felt really prepared for my induction going into it."*

Continuity of care interactions (outdegree = 3)

We define continuity of care interactions as patient's experiencing care with the same care team or with a care team member for multiple health interactions over time, or the repeated discussion of topics or skills. This can impact patient's knowledge, through care team's understanding of patient's history as well as increasing the effectiveness of processing of information. One participant described the experience of consistent interactions with a care team

member that they liked and who over time understood their history, in preparing them for a c-section birth.

> *"I think what made me feel the most prepared was I took control of who my provider was going to be …*
> *I found the lady that I liked so much. And I would try to make an appointment. They kept telling me 'Well, you never know who's going to be your doctor, it's good to see everybody', but not everybody made me feel so comfortable like she and I just clicked. She switched from [institution name] are from [city] to the [other city] location, so I would drive an extra 20 minutes, just to see her because she made me feel calm. And you know, after she got me, she was the first doctor that I saw at the hospital. Both of ours were on birth control, so they were both surprises, so I was going through that shock of 'Okay I'm on the pill, now I'm pregnant, now I'm on an IUD and I'm pregnant again.' So, so she walked me through everything. I felt very comfortable. She knew my history and she knew that I had to have the first C section she walked me through."*

Bottleneck areas

Betweenness measures suggest variables that are potential bottlenecks in a network. Patient knowledge and skills (betweenness = 0.111) was the highest-ranking variable in this regard (aside from patient health itself). One way to interpret this is that patient health is highly reliant on patient knowledge and skills. This makes sense in the light of the shorter discharge times and limited alternative and social forms of support for patients. Systemic solutions should evaluate and ensure patients are well equipped and prepared, and to reduce the reliance on patient's individual knowledge and skills, through additional social support and monitoring of patient health.

While not suggested by betweenness measures, having prior pregnancy experiences was a non-modifiable element with high out-degree (outdegree = 6). Multiple participants described the negative impact having prior pregnancy experiences had in the education they were provided. This inequity in experience should be mitigated and avoided in any potential interventions.

Conclusion

In rigorously analyzing focus group data for birthing persons experiencing care in a large southeastern hospital in the United States, this study identifies inter-related drivers of health education experiences and patient health. The findings are consistent with parts of the literature and add further nuance by describing inter-relationships between key drivers. Consistent with Suplee (84), this study finds multiple activities being packed into a short period of time for participants, and being an overwhelming education experience (82). Various factors can play a role in the educational experience such as general stressors and prior birth experiences (82). This study describes the role of various additional factors such as the type of information provided (e.g. actionability, and explaining reasoning) and timeliness of education, in quality of discharge teaching from the participants' perspectives.

This study presents a preliminary dynamic hypothesis of the drivers of health education experiences for postpartum care, with a focus on hypertension and postpartum preeclampsia. The findings are not generalizable, and the study sample was small. This is a key limitation of the study. The study offers only a preliminary model meant for iteration in further research and for comparison to related systemic models in the maternal health and health education domains. Future research can extend this work through extended qualitative research involving other key stakeholders including and beyond patients for building a well-rounded picture. Quantitative validation for external validity can be supported by methods such as surveys and quantitative modeling.

As described earlier, the coding and analysis for this study was done by one researcher from an inductive approach. Additionally, the author's relation to this study is from an etic viewpoint. This may impact the findings of the study through the types of codes generated and

assigned, boundary considerations made and particularly the interpretations of the results. Future research to extend this work should include diverse team members and stakeholders, particularly those with different positionalities to the topic.

The usage of secondary data for this analysis may be a limitation. As described, the original data collection had different aims from the analysis in this study. Through an initial pilot analysis study, we found the data to be purposive and including rich descriptions of participant experiences and causal drivers (2). Yet, if data were collected with the intention of such analysis, it may reveal additional or differing insights and may increase the validity and comprehensiveness of the dynamic hypothesis of causal drivers.

Aside from the limitations of this study, the researchers also found that the rigorous process led to fruitful insights from a data source that wasn't collected with this study in mind. Before analyzing this data, the researchers believed the data met the criteria of being purposive and suitable for a systems thinking driven causal analysis, and containing detailed and rich stakeholder perspectives (2). A preliminary analysis using only part of the data was promising, but the researchers only found the depth of insights that were in the data when conducting the complete analysis using a combination of best practices and a detailed analysis process. As a result, the researchers discovered that there were much more analytical insights in the data even than they had initially expected.

Design as a field is interested in increasingly complex problems (14). Design researchers may find much benefit from systems thinking's various methods. Ways of thinking about leverage such as intervention areas, connectivity, and bottlenecks may usefully complicate design's approaches to identifying opportunity areas, through techniques such as design criteria and requirements, and user stories. This offers additional opportunities for future research.

Chapter 4

Causal Loop Journey Maps & Causal Loop Storyboards: Systemic Design Diagrams for Stakeholder Engagement and Narrative Representation

Abstract

It is often an implicit assumption in any design research activity that what we see, and how we see it, makes a big difference on how we act and create. The complexity of wicked problems of the day makes it important for designers, other disciplines interested in complexity, and inter-disciplinary collaborations to be able to effectively visualize complex causality. The field of systems thinking offers tools and visual frameworks that represent the interconnected ways in which systems function and is especially helpful at understanding the complex workings of cause and effect through tools such as Causal Loop Diagrams and Stock-and-Flow Diagrams. While such tools are powerful at representing the layers of the system and complex causality, they often miss the trees for the forest – they can be hard to interpret, overwhelming for viewers, and additionally, they may not communicate additional important qualities and nuances of causally complex problems. Causal diagrams from various discipline and conventions each have their limitations and challenges. Recent innovations in the causal visualization offer ways to mitigate these, but there is a need for additional synergy and cross-fertilization.

There is potential in exploring the combination of diagrams and visual frameworks from design and systems thinking to shape how we might understand complex design problems. We, as a research design research team, propose two alternative diagrams at this overlap: causal loop journey maps and causal loop storyboards. Using examples from our work studying postpartum healthcare, we describe the core ideas behind the diagrams and their possible variations. In light of the literature, we describe the expected benefits and limitations of using the diagrams. We believe that the diagrams can make complex causality easier to understand for stakeholders with various backgrounds and levels of understanding of causal diagramming conventions. The

diagrams also communicate additional narrative and temporal characteristics of complex problems.

Introduction

Representing complex causality: the potential for synergy

Wicked problems are by their nature ill-defined, and messy, and the way wicked problems are described determines its possible solutions (3). Many important global challenges of present times are by their nature wicked – climate change, social and racial disparities, and public health, among many others. How wicked problems are addressed, hence is an important methodological focus of various disciplines. Each discipline with its own expertise and perspective is limited in its ability to tackle wicked problems, making it more important than ever to find interdisciplinary synergies (105).

Wicked problems include complex dynamics and causal interactions (4). How complex causal problems are analyzed and communicated is important by extension. To begin to address the wicked problems of today, one must be able to grasp and understand their various layers, facets, and emergent dynamics. For interdisciplinary action, one must also have tools to communicate this complexity, build a shared understanding, and to align and generate momentum towards action. Systems thinking and human-centered design are two domain-agnostic disciplines that offer complementary capabilities and tools to represent complexity.

Systems thinking (used inter-changeably here with related terms system dynamics, systems view and systems theory) at its core, is about holistic and integrative thinking – with the tenet that the sum is greater than its parts and cannot be understood through reductionism and isolation (1). It focuses on understanding a system's behavior and structure (5). Originating as a response to reductionist science in the early 20th century, a systems view was born in the field of

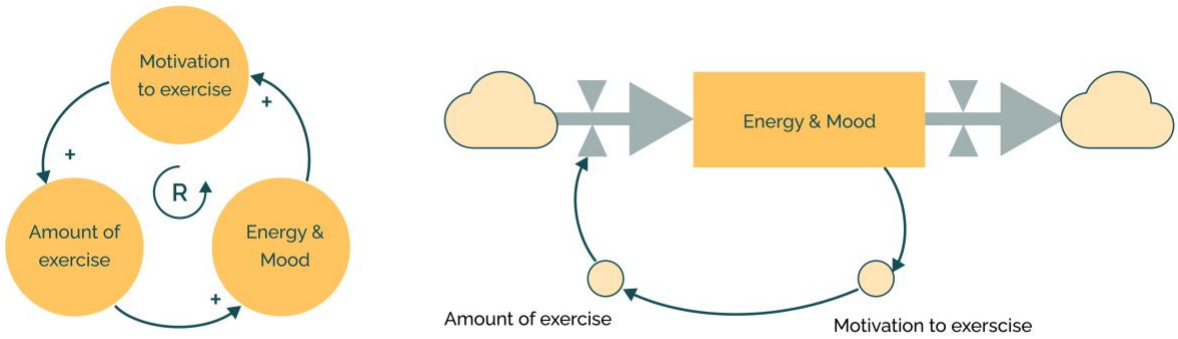
biology as General Systems Theory (1). Since then, systems theory has taken multiple forms and been applied in various fields across the physical and social sciences. A systems view is simultaneously a paradigm, a language, and technology - it can be a way to think about the world and relationships, a way to diagram systemic understanding, and as technology for modeling and simulation of systems (6). Hence, by taking a holistic and integrative view that considers relational aspects, systems thinking has the potential to impact wicked challenges.

The language of systems thinking is key to communicating complexity through its various visual analytical tools and diagrams. Causal loop diagrams and stock-and-flow diagrams are two such diagrams that are often used to represent causality (1,7). Figure 4.1 shows simple examples of causal loop diagrams and stock-and-flow diagrams. A causal loop diagram consists of a network of causal relationships between variables, represented by variables and arrows/linkages between them. Arrows indicate causal linkages wherein a change in the first variable will trigger a change in the connected variable, all else equal. A '+' or 's' sign corresponding to a link is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding increase (decrease) in the connected variable, or that they move in the same direction. A '-' or 'o' sign is used to represent a causal relationship where an increase (decrease) in the first variable leads to a corresponding decrease (increase) in the connected variable, or that they move in opposite directions. This sign is also referred to as the polarity of the relationship. Chains of arrows that close a circle (and thus repeat) are important structures and can be of two types. A reinforcing feedback loop is like a 'vicious cycle' or 'virtuous cycle' (depending on whether results are desired or not), where an increase in one of its variables leads to its own continued increase over time, or a decrease in the variable leads to its continued decrease over time. Reinforcing loops are powerful and drive exponential change. A

balancing feedback loop on the other hand ‘keeps the system in check’, where an increase in a variable is balanced by a decrease in it over time, and vice versa. Balancing loops are also important in that they resist change.

A stock-and-flow diagram (8) takes a similar form of a combination of variables and linkages. Stocks are focal variables that represent quantities that can accumulate over time, such as the amount of a resource like water or money, or even non-physical quantities such as love or anger (1). Flows change a stock over time, hence in-flows and out-flows represent system elements that can increase or decrease the stock’s quantity over time (1). The valves on the in-flow and out-flow indicate the flow rate. The cloud symbols represent sources and sinks for the stock that are assumed to have an infinite capacity. Links connect dependencies between different stock & flow diagram elements. Hence, the language of systems thinking makes it effective at understanding and representing complex system structures.

Figure 4.1. Examples of simple causal loop diagram and stock-and-flow diagram.



(a) Causal loop diagram

(b) Stock-and-flow diagram

Design methods too have the potential to impact wicked problems (13). The design disciplines have evolved from a product and artifact centric focus to one that is increasingly broader, and about issues such as experience, sustainability and transformation (14). Empathy is

considered central to design practice and can be valuable when seeking to understand social problems. Rapid prototyping and a bias towards action can be complementary and useful assets when designers collaborate with disciplines which are traditionally focused on understanding and analyzing problems. Designers are also considered skilled at communication and visualization. Indeed, the design toolkit includes various frameworks and types of diagrams to represent complex journeys and flows, and make these digestible to various stakeholders, although arguably none of these directly represent causal complexity. Design problems can be represented in different ways including journey maps, storyboards, stakeholder maps, and concept maps (106). Journey maps (Figure 4.2(a)) describe people's story when interacting with a product, service or experience, including actions, emotions, perceptions, frame of mind, scenarios, expectations, and design opportunity areas (106,107). They are event and scenario based representations along a linear timeline (107). It is recommended for journey maps to be from the standpoint of one persona (107), but multiple users can also be represented (e.g., over multiple swim lanes). Such maps can be used to pin-point opportunities for design innovation and to build a shared vision (106). Storyboards (Figure 4.2(b)) are a visualization frequently used in design and other disciplines such as films, animation, and comics. A storyboard uses images displayed in a sequence of panels to communicate a particular experience or journey's events (108). They are a more visual form of description of a problem to represent context and generate empathy (106). By illustrating in a style similar to comics with supplementary text or dialogue, they can capture social, environmental and technical factors (106). Storyboards too are an event or scenario-based representation and typically adopt a linear timeline. In design, these can be used both for depicting a problem area or describing a potential proposal or solution (108).

Figure 4.2. Schematic description/example of journey maps and storyboards.

A synergy between design and other disciplines must be taken seriously, but for complex problems solutions may not lie within the design domain alone (109). Truly transdisciplinary ways of working may require transgression or transcendence of design's disciplinary norms, and adapting ways of working from other disciplines (110). A synergy between systems thinking and design is not a new concept and has been explored by different communities of research and practice, journals, and conferences at the intersection of the two fields, such as the Relating Systems Thinking and Design conference, and the Context systemic design journal. This also includes communities focused on the practice of visually mapping complex systems (111). Yet even though design disciplines are increasingly interested in complex problems, a large part of the discourse on research methods of design lacks a discussion on complex causality and causal diagrams. Based on surveying popular design research method reference texts, we found little to no discussion of such methods or the usage of causal diagrams (109,112–115). Muratovski describes how designers may need to encounter challenges of navigating the divide between descriptive and causal research approaches (109). Gibson and Owens (116) describe the utility of concept maps in representing relationships between conditional factors, circumstantial issues, actors and networks - which would include aspects of cause-and-effect – in supporting

collaboration between those inside and outside the field of design. Hence, design's strengths for addressing wicked problems are having an empathy-based and human-centric approach, a bias towards action and prototyping, visual and communication skills, and diagrams to engage stakeholders and evoke empathy. Yet, the methods for studying, representing, and addressing complex causality in design seem limited.

In addition to design and systems thinking, various other disciplines are interested in the visual representation of complex causality including distributed systems, system analysis & design, process engineering, visual analytics, and data analysis. Some examples of visual representations of causality from other disciplines include:

- Hasse diagrams: Diagram with parallel lines describing different processes and connecting lines between them describing relationships along the timeline (9)
- X-Y plots: Two dimensional plot describing the relationship between any two variables or factors from a system (10)
- X-Y-Z plots: Visualization of relationship between three variables, with one considered as dependent and other two as independent (10)

Social and cognitive roles of visual representations and causal diagrams

Black and Andersen (117) use a sociological lens to reflect on the attributes of visual representations as *boundary objects* that are helpful for conflict resolution in groups. The tangible representation of ideas plays multiple roles in their view – to show dependencies and conflicts among the different participants' objectives and resources, to transform ideas and to represent shared agreement of ideas to take forward. They also find that by working collaboratively using such boundary objects, an implicit stock of shared trust and respect can be built between participants.

On a more individual and cognitive level, causal diagrams can be useful for improved causal reasoning and comprehension, as demonstrated by multiple experimental studies. McCrudden et al. (118) in their study of the effects of causal diagrams on science text

comprehension found that causal diagrams improved the participants' understanding of causal sequences when the diagrams were studied while reading text. When either only diagram or only text were provided, they found no difference in participants' memory of main ideas or causal sequences, suggesting that causal diagram can successfully impact understanding even as standalone objects. Easterday et al. (119) similarly found that providing causal diagrams to students as a supplement to text increases their accuracy of inferences. Causal diagrams can positively impact the ability to identify indirect pathways between variables as compared with text or list descriptions of the same (120), which seems an important requirement when seeking to understand complex systems and unexpected or unintended consequences. Interestingly, the very act of constructing causal diagrams for a particular scenario can positively impact learning in future unrelated scenarios (119), suggesting benefits to active interaction with causal diagrams.

Methods

In Aim 1 of this dissertation, we conducted a systematic literature review of qualitative coding practices for constructing causal diagrams. As part of this process, we recorded the types of challenges described by the studies, including challenges related to visualization and communication of causal complexity. We also recorded the ways in which causal diagrams have been visualized beyond typical conventions, to identify unique practices and innovations. We leverage these components of Aim 1 and supplement this with additional relevant literature the frame the problem and to identify potential opportunities and effective practices.

We then propose two novel visual diagrams or visual frameworks that we believe have the potential to address some of the challenges we describe. Leveraging examples from research we conducted at the Postnatal Patient Safety Learning Lab, we present examples of the diagrams.

We discuss the key characteristics of the diagrams and their possible variations, and comparing with key literature, discuss their potential benefits and limitations.

Limitations and challenges of causal diagrams

The inherent psychological limitations and biases of humans impact how the processing and interpretation of causal diagrams. Meitner et al.'s (26) exploration of visualization of forest complexity points to examples of such limitations - difficulties at estimating absolute values as opposed to relative proportions, at performing spontaneous calculations, at accurately assessing duration, and change blindness all impact how humans interpret complexity. The limited number of variables that can be mentally manipulated also plays a role (26), and understandably this is challenging when causal diagrams often contain large sets of variables and other diagram elements.

The visual choices and treatments of a diagram can impact how effectively their information is processed. Stoyko (30) proposes multiple ways in which system diagrams can be ineffective from an information design standpoint, such as through false equivalence (equal treatment of unequally important items), and the all too common "spaghetti problem" (a jumble of connections being difficult to parse). Having inappropriate levels of abstraction and conflation of different levels of the system (e.g. of what happens at individual vs. environmental scale) can also be challenging (30). In an inter-disciplinary context, using specialist notation styles particular to one discipline can make it difficult for those from other disciplines to engage (30). Indeed, system notations of different types have their own implicit theories, which is challenging if different premises are adopted (30).

Considering these psychological limitations and the ways in which diagrams can potentially fail, it is no wonder that multiple studies report on the difficulties of using causal

diagrams as communication tools with stakeholders and users of the diagrams (46,59,121). Users of hasse diagrams often have difficulty answering even basic questions using them or require a lot of time to do so (121). Causal diagrams can often involve visual clutter (9), and particularly as system scale and complexity increase, these can get overwhelming (27). The challenges of interpreting these diagrams reduce wider acceptance and there is a need to make them more accessible (28,59).

Another overarching challenge of visually representing causal complexity is to represent its varied temporal characteristics. At a basic level, many traditional types of causal diagrams do not illustrate the dynamics such as initial conditions of the system, legacy effects, sequences of events, non-linearity of relationships, and time delays (10,30,34,39,44). Since static representations often use spatial metaphors for time (e.g. time moving from left to right), they can send mixed signals and conflict with other spatial metaphors used (30). What is more, emergent properties and effects of causal structures can mean that the structures themselves can vary over time (34,44) - for example, the direction of a relationship may change over time (10). Systems can have tipping points that are difficult to investigate (67).

Causality can be highly nuanced and context specific, and these nuances are difficult to illustrate in a causal diagram. For example, causal semantics such as multiple or combinations of factors leading to effects, meditation of causality, bidirectional causality are challenging to represent (9,10). Variability such as path-dependency is also difficult to illustrate (10). At times, the level of a variable is what determines a particular path e.g. low level and high level of variable leading to different paths (67). Relationships can vary in different contexts, at different levels of scale and granularity, and this is concealed in the diagrams (34,44).

Levels of uncertainty in diagrams are difficult to communicate. For example, the data used to create the diagram of a system may contain conflicting views in regards to elements of diagrams (38). There may be varied strengths associated with causal relationships, and some causal relationships may only be valid infrequently i.e. the stochasticity of a relationships may be under-described (10). The typical notation styles of diagrams such as causal loop diagrams and stock-and-flow diagrams do not represent such uncertainty (10).

In summary, due to the complex and context specific nature of causality, causal diagrams often fall short to be effectively communicating causal complexity. Because of the inherent benefits and drawbacks of different visualization choices, there is a trade-off to decide which aspects of complexity to communicate and which to exclude (10).

Theories and tactics to impact effectiveness of causal diagrams

We now review the literature for a range of theoretical and visual approaches to innovate and improve the effectiveness of causal diagrams.

Malinova Mandelburger and Mendling (122) conducted a systematic review that consolidates theory on cognitive processing of diagrams in various fields. They propose a consolidated framework of task performance and understanding with diagrams. Their corresponding criteria for effective visual processing through diagrams include visual consistency, visual simplicity, aesthetics, appropriate emphasis to elements, grouping of elements, symbolic distinctiveness, and clarity. They include additional criteria relating to processing of text, and semantic and task processing. Noteworthy here are the suggestions to reuse concepts from existing languages and support users for this, and to reduce cognitive effort for information processing.

Stoyko's (123) multiple information design projects around system visualization offer a rich array of visualization considerations, theoretical sensitizing concepts, and visual vocabulary of tools. With a goal to promote interdisciplinary system visualization and cross-fertilization of siloed practices, these include a few inter-related sub-projects. The Anatomy of System Notations (29) includes a list of various graphical devices that are used in system notation such as variations in nodes, links, modifiers, ways to show branching or merging, etc. that can be considered as a dictionary of multiple options that can be used when creating causal diagrams or system visualization more generally. At a more conceptual level, the Visual Vocabulary of Systems is a visual codex that includes illustrative icons and descriptions for various system characteristics related to drivers, signals, states, boundaries, relations, and domains. The Pattern Atlas of System Vulnerabilities (124) uses visual metaphors to represent weaknesses inherent in various systems, such as quirkiness and precariousness. Finally, the Escalade Framework (30) offers broad design criteria for system mapping – this is described as a 'dashboard' of qualities one can dial up or dial down as appropriate. These include criteria for the treatment of visual space, scale of analysis, temporal rhythms, level of visual abstraction, layering of system information, aggregation or grouping, level of visual detail, and sound and interactivity. This framework incorporates system characteristics that are particularly challenging to describe, and the cognitive challenges of how humans absorb information.

In our systematic review in Aim 1, we found that researchers used various small but potentially impactful visual tactics to enhance effectiveness of the causal diagrams. Many of these utilize the above-mentioned visual criteria as, well. We observed usage of the following practices in the studies:

- Using sub-diagrams for different aspects or sub-systems of a problem to make interacting with the diagram more manageable for stakeholders

- Creating additional supplementary diagrams such as systemigrams, bar charts, tables, line charts and influence maps to represent particular related aspects of causal complexity
- Variations in shapes, colors, line thickness, font and other visual encodings to categorize or emphasize theoretically different elements e.g. to communicate varying strengths of relationships or different sub-systems, or using curvy arrows only if a causal relationships is part of a feedback loop (47)
- Using additional graphic codes and objects as a layer over causal diagrams for additional context
- Intentionally placing, clustering and grouping diagram elements in theoretically useful ways e.g. radial placement of factors for communicating different socio-ecological levels or different levels of importance (59,125).
- Including metrics corresponding and relevant to diagram elements over or near the diagram elements
- Progressively increasing scale and complexity of diagrams as they are revealed though the narrative of a study i.e. starting with a core diagram and progressively expanding (65,69)

Innovations and experiments in enhancing causal visualizations

Multiple studies have proposed, prototyped and/or evaluated innovations specifically targeted at enhancing visualization of complex causality, including the following approaches.

Diagram simplification

Van Zijl (28) developed tools to improve causality maps for process engineering fault analysis by incorporating process knowledge – or what might be called deductive or a-priori understanding – to constrain which connection sand potential root causes are visualized, and to enable a hierarchical simplification of variables. They discuss other potential simplification techniques such as pruning of diagram elements, layout styles, assigning importance to particular nodes and identifying most likely traversed causal paths. In a similar study, Dang et al. (126) developed a visual analytics application for analysis of biochemical pathways that enables filtering, clustering and selection capabilities, along with presenting animated flows through different pathways, hence enabling users to see causality associated with different goals e.g. visualizing downstream consequences or finding shortest path between two nodes. Both these studies were favorably evaluated through usability and expert evaluations.

Creating multiple adjacent diagrams of the same type

Banitz et al. (10) propose that multiple diagrams visualizing causality can be presented next to one another for additional analytical value. For example, they suggest that including multiple X-Y plots or X-Y-Z plots can show relationships between the two or three variables while highlighting precise quantitative relationships, also showing other relational characteristics such as the effect of one variable on multiple other variables to show its trade-offs.

Combining or presenting multiple diagram types or information

Studies described various ways to supplement causal visualizations with other types of information. Combining visuals can be a way to benefit from each type of visuals respective strength (10). Augmenting visualizations with textual narratives can lead to increased correctness (27). Banitz et al. (10) propose other examples of combination such as plotting X-Y plots to show the temporal development of causal relationships overlayed with thumbnails of the causal structure's state at multiple different time points, or combining Venn diagrams with causal diagrams to describe the necessary and sufficient conditions for an outcome. Hu (127) developed an interactive diagram that combines an abstract causality visualization juxtaposed with a domain-specific human figure drawing to highlight relevant segments and describe correspondence across the two figures. Aimed at addressing intuitiveness, efficiency, and sufficiency of diagram to understanding neuropathic pain, their tool was favorably evaluated by experts. Finally, Gigamaps (128) is a mapping approaches that often combines various types of maps and diagrams at different system scales to conduct "super extensive mapping across multiple layers and time scales" and investigate relationships between seemingly unrelated system parts. While gigamaps are focused on the designerly generation of new knowledge to

understand a problem and critique its boundaries, the similar Synthesis Maps (129) illuminate design understanding and make evidence based proposals.

Digital interaction & motion-based approaches

Some studies used digital interaction - where the user of the diagram can in some way digitally manipulate or modify a visualization - and/or motion-based approaches where elements of the visualization are animated. The purpose varied for the different approaches, ranging from increased efficiency and accuracy when using visualizations, communicating specific nuances of causal relationships, representing time, understanding relationships when large numbers of variables are involved, and detection of bugs. Growing Squares and Growing Polygons (121) are two approaches for representing causality in distributed systems that use color, animation and visual texture. Using a visual metaphor of pools of color spreading on pieces of paper, the animation works by 'contaminating' the color nodes corresponding to a particular process with the color of the process influencing it. They represent the passage of time through increase in size of the geometric primitive shapes that are used for the nodes as the 'occur'. Depending on the density of the visualization, they found an improvement in efficiency and correctness compared to a traditional Hasse diagram. Neufeld et al. (130) developed a tool where each node in a causal diagram is represented by a bar chart with slider to increase, decrease or set a particular value. They propose that the user of the diagram can witness movement of variables and have the impression of causal influence, in a way that would help understand relationships when many variables are involved and detect bugs if the causal model is created using data mining. Kadaba et al. (9) and Ware (131) in separate studies developed interactive and/or animated tools that present nuances of causality and causal semantics with two or more variables involved such as causal effect blocking, amplification, dampening, multiplicity, etc. Their tools

were evaluated to be successful in enabling causal effects to be reliably judged, increased accuracy and speed. It is worth noting that some of the approaches that have been successful at a small levels of system scale and complexity anticipate challenges when scaling up to larger and more complex systems (9,131). In a more domain specific example, Meitner et al. (26) propose using 3D geographic visualizations along with additional information overlays to represent causal complexity in forestry.

Approaches centering narrative and temporal dynamics

The Laboratory for Analytical Sciences use Causal Storyboards to create tools for intelligence analysts to test the fit of particular causal narratives with the evidence (132,133). The causal storyboards take the visual form not unlike other types of node-and-link diagrams to represent causation but with the text in them focused on specific narratives e.g. Jack and Jill went up the hill > (causes or enables) > Jack fell down. They propose that such storyboards can help analysts compare different narratives for their fit with the evidence through a *narrative abduction* mental process. Talgorn and Hendricks (134) use Systemic Stories: parallel storylines of different stakeholders intersecting with each other to show different actors' perspectives, non-linearity and cyclical nature of stories, and to enable zooming in and out between levels of comprehension. They suggest that such an approach can be useful to engage stakeholders, communicate "intangible aspects" of systems, memorization, simplification, ideation on future systems and behavior change. They also suggest that complex system diagrams can be simplified by using text "storyblocks" to represent deleted elements of diagram. Similarly, Göksoy's (135) sustainability focused course and its exploration of using visual storyboards to represent systems suggests that narrative elements can be used to make sense of systems, especially in relation to key features of narratives such as temporality, sequentiality, intentional state entailment

(subjectivity and points of view) and particularity (situated content of narratives). Behnam Asl et al. (136) use a visual storytelling approach through digital animations to represent stories of patients' experiences in the postpartum care setting. These animations are proposed as tools to engage healthcare professionals to identify potential root causes of issues driving care experiences.

To represent emergent properties of social-ecological systems, Herzog et al. (34) develop a Social-Ecological Action Situation Framework. In this type of diagram, nodes describe pairs of actors in an action situation (where each pair may be either fully social, fully ecological, or social-ecological). Interactions between action situations are visualized as directional arrows between them. The same study also proposes that limitations of static frameworks to represent time can be potentially overcome by having different diagrams for different time spans.

Problem statement

As described above, representing complex causality in systems is – true to its name – complex. Two specific goals we aim to address in this paper are:

- Enabling stakeholders from various backgrounds to be able to understand and interpret complex causal systems regardless of their levels of knowledge of traditional causal diagrams and notation styles
- Enabling communication of the additional information that is interwoven with causality – specifically narrative aspects such as temporality, the sequence of events, intentional state entailment and particularity

We propose two types of diagrams or visual frameworks that enhance causal diagrams by addressing the above goals.

Research context: postpartum healthcare experiences

The background of the authors of this article is a combination of design, postpartum and maternal healthcare research, systems thinking and decisions science. Multiple of the authors have been part of the Postnatal Patient Safety Learning Lab (137), focused on re-designing

systems of postpartum healthcare to enable all families to thrive. As part of the lab's efforts, we have conducted various types of qualitative and quantitative data collection and analysis, developed, and tested interventions, and engaged with community partners. The examples of diagrams in the following sections are based on analysis of one of the data collection methods: naturalistic video footage of the postpartum unit. Specifically, the video recordings were of 15 postpartum birthing persons and their companions in their rooms on the postpartum unit at a large Southeastern hospital in the United States. A total of 461 hours of footage was recorded. With our research team members, we analyzed twelve hours of recording for each participant prior to discharge. This initial analysis included activities to code the vast amounts of data in 5-minute increments with a behavioral and content coding taxonomy, establishing inter-coder reliability, many discussions for building consensus, and the development of detailed vignettes. For the current study, approval was obtained from NC State University's Institutional Review Board (protocol #2672). The vignettes developed through the initial analysis were rich with timestamped and chronological descriptions of events, participants, situations, interactions between people and behaviors, and included quotes, field notes and de-identified screenshots from the recordings for visual context. Informed by Aim 1 of this dissertation, a qualitative coding process to analyze the vignettes and identify causal connections was developed, using a spreadsheet to record information including variables, relationship direction, polarity, supporting quotes and additional field notes. Based on a portion of the analysis for one participant's data, we produced the following diagrams to illustrate their usage. Note that this illustration includes a subset of the data and includes simplification of insights for illustrative purposes.

Proposed combination of diagrams

We propose two types of diagrams or visual frameworks that juxtapose attributes of diagrams traditionally found in systems thinking and design. We consider three core typologies of diagrams for this combination: causal loop diagrams, journey maps and storyboards. We draw inspiration from the rich examples, graphic devices and notations from the cross-disciplinary literature on system visualization (138), and from other systems thinking tools such as reference modes and stocks. In the following sub-sections, we first describe the core concept of each proposed diagram and its potential variations. Then, considering the key precedents and literature, we describe the potential benefits and limitations of the diagrams.

Causal loop journey maps

This diagram is a combination of causal loop diagrams and journey maps. At its most basic level, the causal loop journey map overlays segments of causal loop diagram structures in a swim lane of a journey map. These segments are at places corresponding to a particular phase or scene in a journey on a timeline. The causal loop journey map also includes a form of narrative description of the phase or scenes in parallel with the structure. Figure 4.3 presents an example of the causal loop journey map of three ‘scenes’ on one morning of a patient’s experience in the postpartum unit, including remote and in-person interactions with their healthcare team. This example includes an additional optional element: a stock. In this example, the narrative is in the form of a descriptive note that includes quotes, de-identified screenshots, and a summarizing phrase to name the scene. Each scene is color coded as being an overall positive or negative experience based on the sentiment observed through the vignettes. Corresponding to the narrative in each scene, the causal chain swim lane describes the corresponding causal connections. The upward or downward arrows in the badge at the top right of each variable

describes its direction in the current scene i.e. if it is generally increasing or decreasing. The notation on the connecting arrows, like causal loop diagrams, describes the direction and polarity of the relationship between the two variables it connects. In this example, we add an additional optional layer of a soft 'stock' to illustrate an additional use for the diagram. Here, in relation to patient experience, frustration with care received is seen as a stock that accumulates over time and impacts the family's decision making. It is visualized as a line chart along the timeline. Similar to the badges for variables, the up or down arrows describes when there is inflow or outflow to the stock, and the arrows feeding into the badge describe the variables that influence it. A causal connection running from the stock to a variable shows one of the ways the stock influences other variables in the system: here, frustration in care increases the family's desire to go home.

The causal loop journey map is a flexible type of diagram that can be adapted to include or emphasize different types of information. Figure 4.4 represents a schematic causal loop journey map to show some additional variations in diagram. In this schematic, the causal journey map includes the following:

- Highlighting causal loops: This is done in one of two ways. Loops that occur within one scene are highlighted in a particular color along with a signifier to indicate an identified number type of loop (here, R1 means Reinforcing Loop 1). Causal relationships that correspond to loops that occur over multiple scenes are represented with a particular color and dashed arrows along with a similar signifier denoting identifier number and type of loop (here, B1 means Balancing Loop 1). A separate key of loops at the bottom of the diagram describes them in further detail.
- Delays: A causal relationship extending across multiple scenes is highlighted as a delay by using the standard notation of double dashed arrow to communicate this.
- Reference modes: Key variables (other than stocks) that increase or decrease over time can be presented in separate swim lanes as line charts. This aligns with the systems thinking notion of behavior over time graphs that are used in quantitative system or simulation models. In this diagram, the reference mode can be used to represent the central trends of the central variable(s) of the problem.
- Additional swim lanes be added for various types of information: Here, we include a swim lane to record challenges and opportunities as yellow and green sticky notes.

Figure 4.3. Example of a causal loop journey map along with a stock.

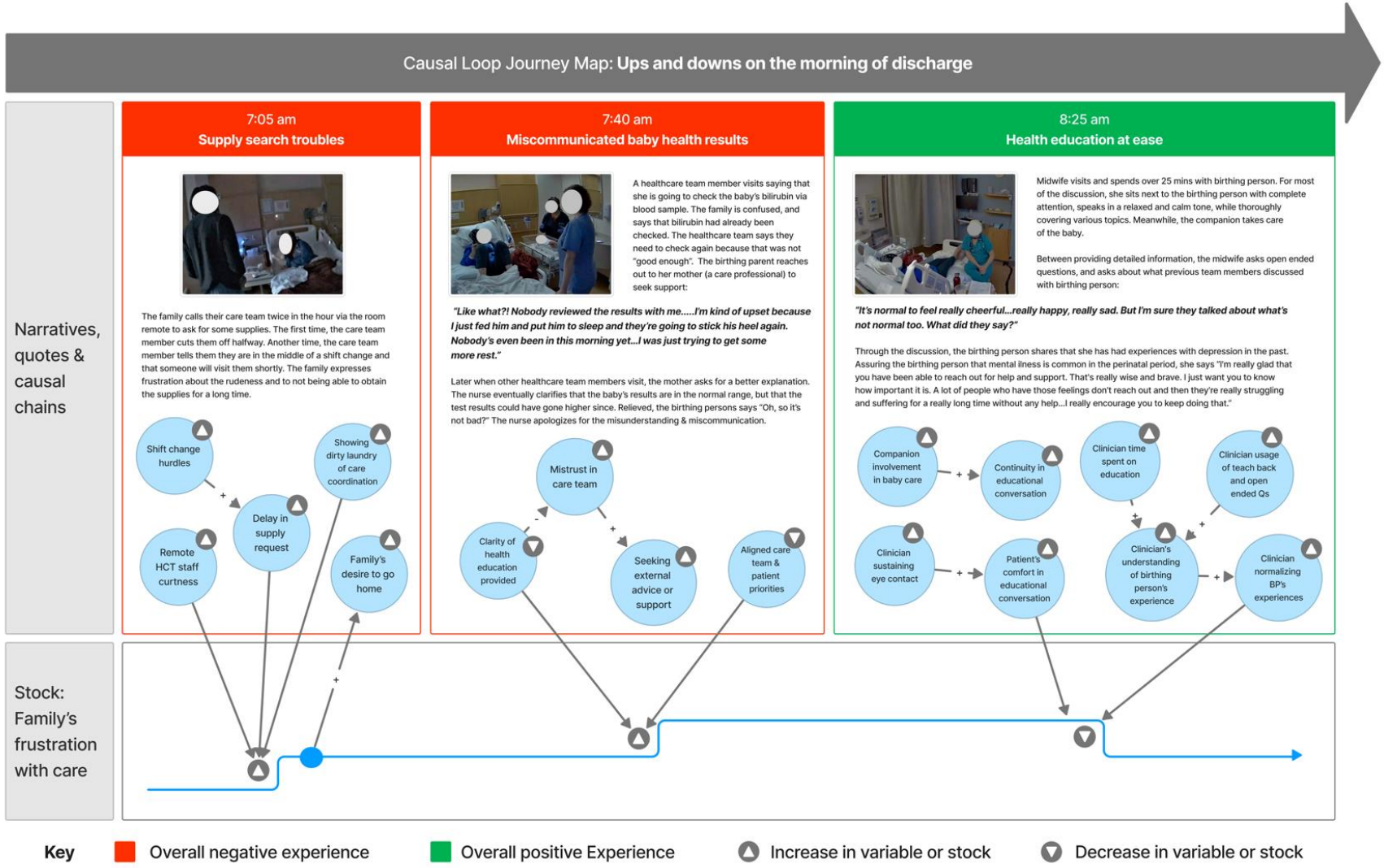
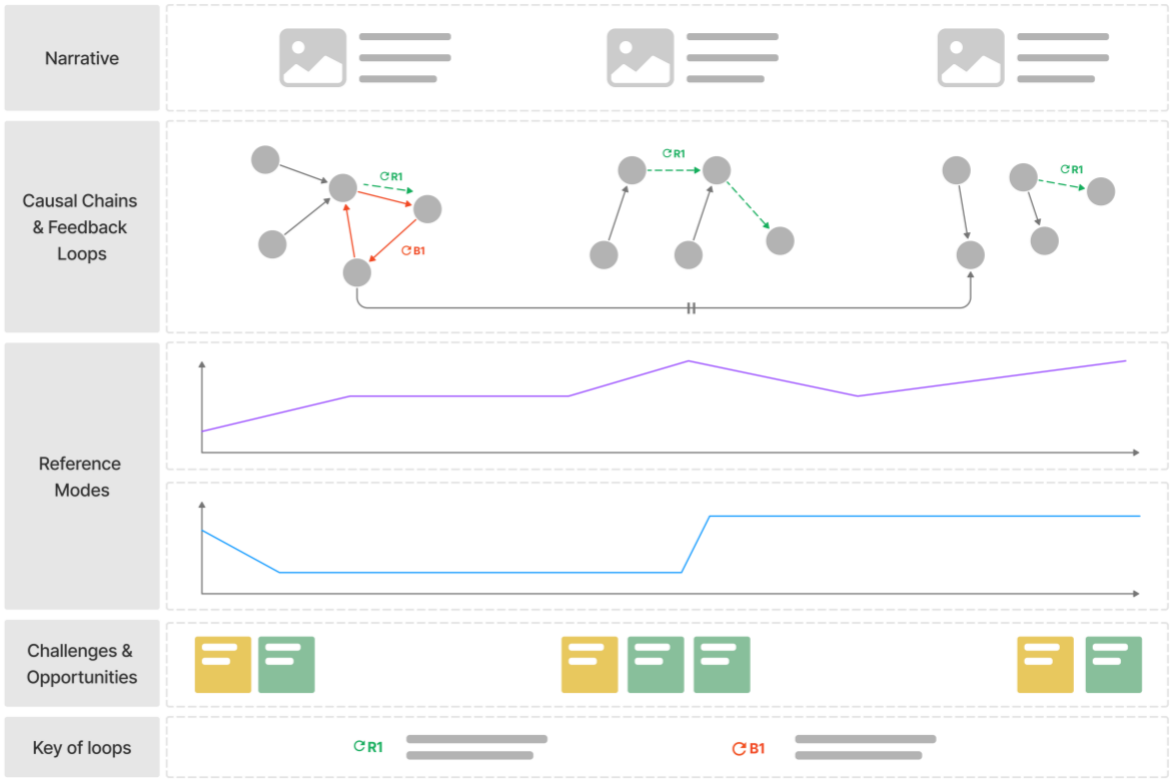


Figure 4.4. Potential variations of a causal loop journey map.



It is worth noting that this diagram does not perfectly observe a spatial metaphor for time. What this means is that the passage of time is *generally* communicated to move from left to right, but at a more local level within a scene, a variable's horizontal position does not precisely describe its occurrence in time. At a local level, even the relative horizontal position of two variables does not precisely describe if they occur before or after each other. The variables placement along the horizontal axis only needs to be roughly aligned with the primary scene or event it is part of.

Development of the concept

In seeking to analyze the naturalistic video footage dataset described earlier, we sought a way to represent complex causal information in intermediate artifacts different from traditional causal loop diagrams. We drew inspiration from a figure in Nassauer and Legewie's (139)

chapter on analysis methods for video data, that described turning points in a chain of cause and effect over time, visualized in node-and-linkage convention over a timeline. We considered juxtaposing causal structures over a linear timeline to be a natural approach to experiment with and developed an initial version of the causal loop journey map that included only causal structures along a timeline, segmented by different scenes, and including supporting images and quotes. Anecdotally noticing the potential in this, we considered additional ways to improve the framework and include additional types of information such as stocks, and long-term causal loops across scenes. We sketched and ideated variations of ways to represent the loops, linkages, stocks, and variable behavior. Overall, three iterations of the diagram were developed as we refined its format.

The causal loop journey map is a process to visually organize information that is flexible and can be used to include different information. Its outputs can range from being low fidelity versions such as whiteboard drawings with sticky notes pinned up, to being high fidelity graphically designed versions for presentation purposes. Each form may be useful for different purposes. While the example illustrated in Figure 4.4 is only an iteration and has not undergone a full process of graphic refinement, we made certain design choices that we now describe. We included a horizontal arrow across the diagram with a thick line weight to emphasize the linear timeline, as well as included containers that vertically frame the narratives and causal chains. This was done so that a viewer has clarity on both the time component, and on the essential correspondence between narratives and causal structures. The header for the frame corresponding to each scene includes a phase and timestamp describing the scene. The containers for such headers are either in red or green to indicate the overall negative and positive experiences respectively. Depending on the width of the containers for the scenes, we placed the

images as either center or left aligned to have the narrative text wrap around the images where possible. This was done so that a larger amount of information can be communicated within the diagram as it was intended to be visualized on one page, for this paper. We broke the text segments in each scene down to smaller segments, while shortening and simplifying the content of the text itself. We used different font characteristics for descriptions and for quotes. We expect these measures to make cognitive processing of the text easier. To communicate variable behavior, we chose to use badges (29) with arrows describing variable direction corresponding to each variable. Other options we considered included having no badges, but having the variable behavior described within its text (e.g., naming a variable '*lack of* clarity of health education provided' as opposed to 'clarity of health education provided' with a downward pointing badged arrow). While the option of using names to describe variable behavior has the advantage of describing more nuanced variable behaviors (e.g., increase, exponential increase, resistance to decrease, etc.), the badged arrow option we chose allows for the variables to be named in the exact same way as those in a causal loop diagram, making transitioning between or comparing the causal loop journey map and a traditional causal loop diagram for the same system to require less cognitive effort. To represent stocks, we opted for a line chart like visualization, to leverage existing data visualization standards in visualizing a quantitative behavior over time.

The graphic design choices we make have their potential limitations. For example, if the causal structures have too many variables close to one another or if a scene has too large a block of text, the diagram may still be overwhelming to look at. The container width for a scene – determined here by the scale of the narrative and causal structures within it - may not accurately indicate the duration of the time it corresponds to. These graphic design choices, of course, can

be further refined, and are one among many ways to use the general process and diagram type we propose.

Causal loop storyboards

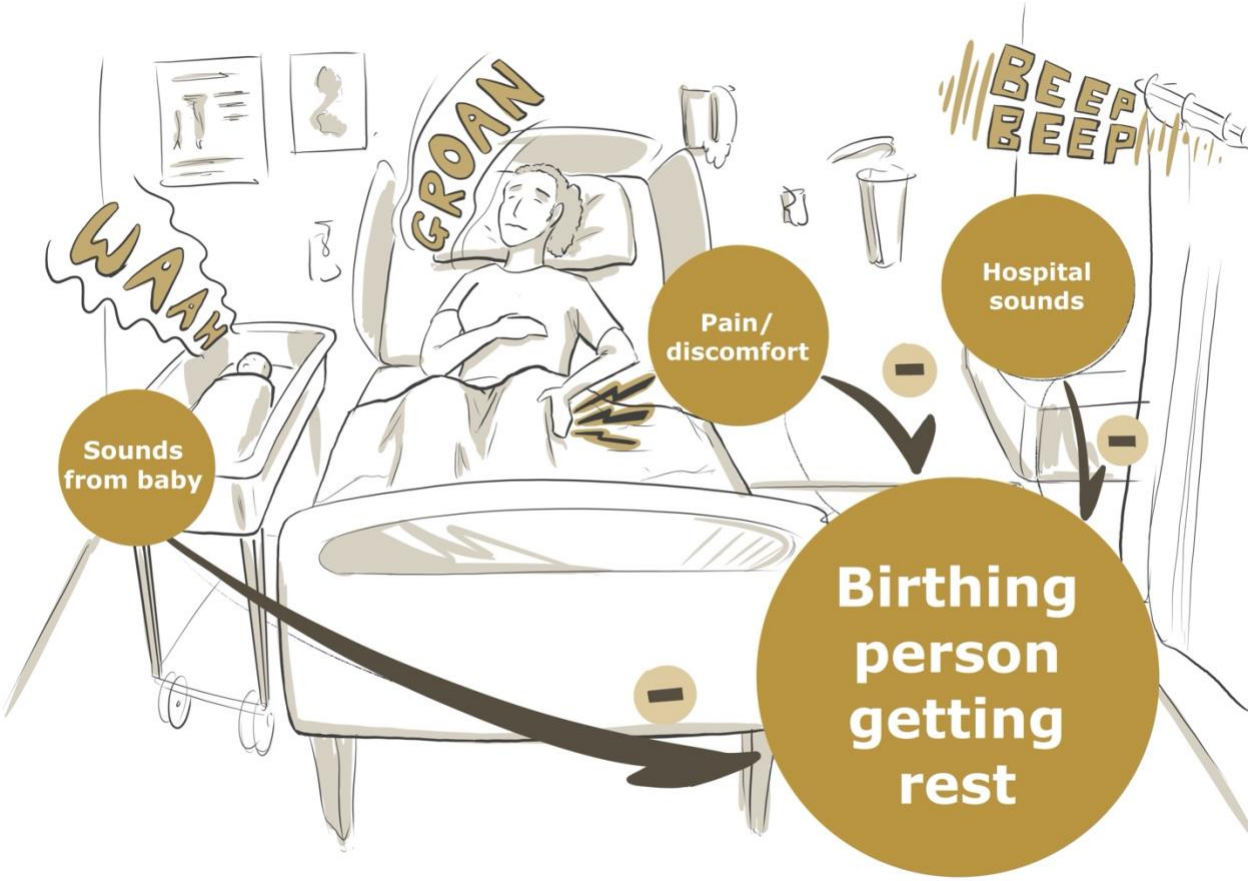
This diagram is a combination of causal loop diagrams and storyboards. At its most basic level, the causal loop storyboard overlays one or more segments of sub-structures from causal loop diagrams with one or more frames of a storyboard depicting the narrative corresponding to the structures.

Figure 4.5 illustrates an example of a causal loop storyboard from the postpartum healthcare experience example. In this example, one frame of the storyboard corresponds with a causal structure that has three variables feeding into one variable. Arrows representing the causal relationships between the variables are visualized along with polarity. In this case, the three variables – 'Sounds from baby', 'Pain/discomfort', and 'Hospital sounds' all have qualities that can be depicted in a spatially meaningful way adjacent to elements in the frame that visually describe these qualities i.e. the location in the diagram where the sounds are coming from. Like a typical causal structure, arrows depict relationship direction and polarity. The dependent variable in this substructure, being a central focus of the frame, is dominant in the hierarchy of the storyboard.

Similar to the causal loop journey map, the causal loop storyboards also are flexible and can be adapted based on the context of the research. What we might call the *relative abstraction or granularity* of the information in the causal structures corresponding to the abstraction or granularity of details in the frames can help decide what type of correspondence between causal structure and storyboard frame is appropriate. Figure 4.6 shows some potential variations of causal loop storyboards. One storyboard frame can correspond to isolated substructures that are

with loops in them (sub-figure (c)) without loops in them (sub-figure (a)), or to single variables in a sequence (sub-figure (b)). By having frames woven through a larger causal structure, details of path dependencies can also potentially be described (sub-figure (d)).

Figure 4.5. Example of a causal loop storyboard.



Development of the concept

As we started to envision ways of enhancing causal visualization, and the possibility of combining systems thinking and design approaches, we considered the storyboard. Prior to this, part of our team had also participated in the Map the System global systems thinking competition in 2022. Many of the teams in their presentations - ours included - developed visualizations that combined causal loop structures with other visuals in interesting and useful ways. For example,

our team presented substructures from a causal loop diagram with visual iconography corresponding to each variable. Witnessing this rich variety of experimentation in diagramming was indeed an inspiration when we started to explore combinations of frameworks. As a result, the first versions of the causal loop storyboard were envisioned as rough sketches. Realizing that there may need to be different types of correspondence between frames and causal structures for different projects, we sketched alternative versions.

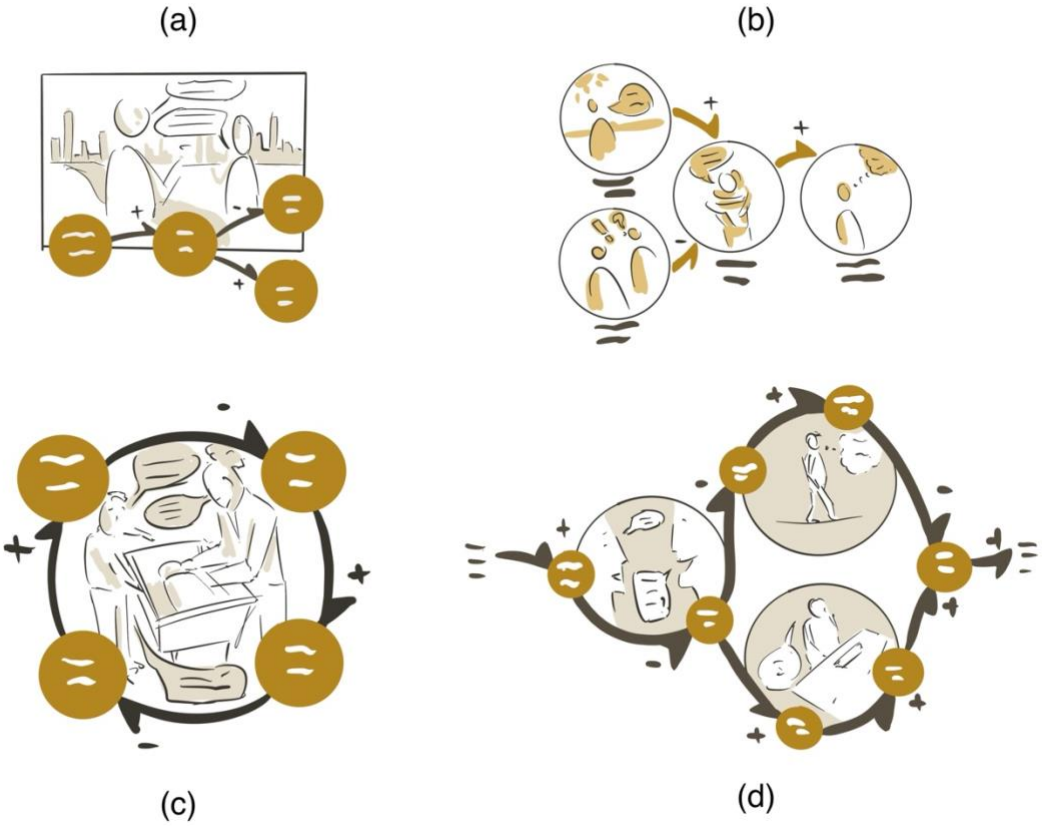
Like the causal loop journey map, the fidelity of the causal loop storyboard can also have a wide range depending on the purposes it is used for. In the example in Figure 4.6, we made particular design choices that we now describe. For sketching of the frame (i.e., the visual part of the causal loop storyboard), we used simple ink styles with a low resolution of visual detail. The fidelity was the minimum we considered as necessary for representing the environmental context in enough detail and communicating the challenge, while being aesthetically pleasing. Additionally, the colors used for the frame were muted tones of the primary color we selected. The colors of the causal chain variables, in contrast, were more saturated. This was to emphasize the causal chains over the diagrams, since the diagrams were more likely to naturally demand a viewer's attention compared to the more abstract and schematic causal structures. Like we described above, the variables were overlayed on the frame at spatially meaningful locations for the story represented. This again, was only an iteration for the specific presentation purpose for this paper. The design choices for the causal loop storyboard too, can be varied for different project needs.

Benefits and limitations of the diagrams

Fundamentally, both the diagrams incorporate narrative and temporal aspects of the system described alongside causal structures. Both also enable communicating additional

contextual information and simplify or chunk the process of learning from a causal diagram. This brings corresponding benefits and drawbacks considering the literature reviewed in earlier sections. Overall, we think both diagrams can make complex causality more accessible and understandable to a broader range of stakeholders and communicate additional insights, especially narrative aspects of causality.

Figure 4.6. Potential variations of a causal loop storyboard with (a) one frame corresponding to a non-looping substructure (b) one frame corresponding to a variable (c) one frame corresponding to a looping substructure and (d) multiple frames as corresponding to a few variables each from a larger causal structure depicting path dependency.



Both diagrams communicate additional information such as text, visual images, illustrations, and graphs. Benefits of combining causal visualizations of different types to

communicate complex causality has been proposed and is an approach used by various studies (10). For example, Choudhry et al. (27) found that augmenting visuals with text led to increased correctness. Similar benefits to accuracy of interpretations can be expected for both proposed diagrams.

Narrative is central to both the causal loop journey map and causal loop storyboard. We believe that this narrative thread will increase the engagement of stakeholders with different backgrounds with the diagrams, since narratives are central to how we think and perceive as human beings. By virtue of the types of information that can be included in the narrative components of a diagram (e.g., dialogues, environmental context, events, and emotions being represented in a storyboard frame) we believe that various additional types of information interwoven with causality can be communicated by the diagrams. Similar to Talgorn and Hendricks (134) and Göksoy (135), we propose that the diagrams are enhanced by juxtaposing narratives and causal structures, and would more effectively communicate narrative aspects such as sequentiality, temporality, state entailment, and particularity. The causal sub-structures that are part of causal journey maps share similarity with the concept of 'Causal Storyboards' (132), a sequential causal narrative described using a node and link based diagram. In our case, we propose a specific way to use the node and link-based notation: using variables names in line with standard notation for causal diagrams (i.e. a variable being a quantity that can increase or decrease, and being described in neutral terms) supplemented with badged arrows (29) indicating the variable's state in the particular scene it is part of. Göksoy's (135) work includes examples of student-produced storyboards as part of their studio course. These examples show what may be traces of causal structures being depicted along with storyboard frames e.g. directional arrows between frames, but this is not described in any detail. While diagrams such as journey maps can

often imply or indirectly suggest causal information (e.g., a challenge *leading to* a particular response by a persona, where the challenge and response may be in different swim lanes), examples of directly incorporating causal information in journey maps are difficult to find. An example experience map developed by Gene Smith and Trevor von Gorp in Kalbach (140) comes close to doing this by directly describing influences that lead to certain behavior. In comparison, we propose a more complete framework to combine various types of causal structures with storyboard elements and propose multiple variations of this combination. Due to the narrative qualities, depending on how they are produced, the diagrams we propose may also help communicate initial conditions of a system and communicate variations in relationships at different scales and contexts.

As discussed above, humans have limits to the number of variables that can be mentally manipulated (26). Causal diagrams can be visually cluttered and overwhelming. Some of the works mentioned above address this by presenting sub-diagrams or by gradually presenting increased scale and complexity. By breaking down the experience of understanding complex causality in a system by virtue an event-based system or linear timeline, we believe our proposed diagrams would achieve a similar effect.

It is a general limitation of the diagrams that they use some specialized notations that are not common across disciplines i.e. causal loop diagramming conventions and additional symbols. This limitation could be approached in a couple of ways. On the one hand, the diagrams can be further simplified to use lesser causal loop diagramming convention, for example, by including in the verbal description of the variable if it is increasing or decreasing in a particular situation rather than using upwards or downward badged arrows for this. On the other hand, this

juxtaposition of diagrams that include specialized notations may be an effective way to introduce the diagramming conventions to stakeholders, prior to usage in other types of diagrams.

Another limitation is in relation to compatibility with different types of data and problems. Since the data source for the study was chronological and event-based, the proposed diagrams may not as compatible with other types of data that are less event based or where the temporal qualities are very complex. This should be tested and investigated further. On a related note, these diagrams might give the false impression of a complex causal problem being more linear than it truly is, hence oversimplifying a research team's or stakeholders' understanding of the problem. To mitigate this, we suggest not using the diagrams as exclusive tools, but in combination with other tools with complementary strengths. For example, either diagram can be used in combination with a traditional causal diagram or stock-and-flow diagram to ensure that the cohesive, non-linear picture of the problem is not lost.

Now, let us consider some of the unique qualities and uses of the two diagrams. We propose that causal loop journey maps can be effective both as an analytical tool, and as a presentation/communication tool. Considering these diagrams are relatively quick to produce and can flexibly include various types of analytical information useful for research teams such as challenge areas and opportunities, these could be produced as a preliminary analytical artefact for individual cases or groups of cases when data source is coded, prior to producing complementary visuals such as traditional causal diagrams. Used this way, the diagram would help researchers stay closely grounded to the data in process of developing theory. The diagram could be used post-hoc to present findings to stakeholders for the benefits of understandability and narrative communication described above. At the overlap of the two uses, this diagram can also be used during contemporaneous methods of systems-focused research such as during

participatory research or group model building. Building a picture of causality over a linear diagram may be a more accessible way for research participants to describe causal insights. The diagram can communicate both the understanding of a particular problem, and multi-pronged design or intervention proposals to address a problem.

A potential limitation of causal loop journey maps is that it does not perfectly observe a spatial metaphor for time. As described above, the placement of variables and connections on the diagram follows only a rough or general alignment to the timeline. This notion might be confusing for some viewers, considering the potential of the metaphor to send mixed signals in presence of other time related metaphors used in the diagram (30). For example, a viewer may think that the width of the frames corresponding to scenes in journey maps may suggest the duration of the scene, but this is not necessarily true if it is dictated instead by the size of the narrative text and causal structures within it. We believe that embracing this inconsistency is worth the benefits it brings and for the efficiency of diagramming this way, as long as the adopted diagramming conventions are clearly defined.

Causal loop storyboards on the other hand are intended primarily as a communication and presentation tool, though arguably, developing these during the analysis process can also help the researchers maintain and stay grounded in the visual context of the problem. This diagram may be most useful as a presentation tool when the causal theory being developed is at a high level of abstraction – i.e. causal variables and connections are very abstract and distant from the data. This is similar to the role played by ‘storyblocks’ (134) to simplify a diagram and use narratives to represent deleted sections of a diagram. Similarly, the visual qualities of the storyboards could very quickly sensitize a viewer to layers of contextual information about actors, emotions,

interactions, and environment. As described earlier, based on how the causal loop storyboards are developed, they could describe other nuances of causality such as path dependency.

A key limitation of causal loop storyboards are the inefficiency of producing them. Storyboards are traditionally more time consuming to produce and it is often assumed that they need to be produced through skilled artistry. Here, we offer two suggestions. First, the most important goal of a storyboard is to communicate and describe the context and problem. Hence, research teams considering using such a tool can choose to prioritize having the visuals be at the minimum fidelity needed for this, which would make producing the visuals a lot more accessible and efficient. Second, many tools for easily storyboarding using templates and existing graphic elements are available. With the increasing capabilities of generative AI tools and text-to-image models, it will be increasingly easy to create effective visual artefacts for such storyboards.

Another potential limitation of the causal loop storyboard is the persuasive power of visuals. One could argue that such visuals are not the most objective way for research findings to be communicated. While this is a reasonable concern, this can be mitigated through practices that are described in the literature on evidence based storytelling (141) and visual storytelling (136). For instance, researchers can be mindful of the ways in which interpretations of data are visually translated and member check even the visual artefacts to ensure they effectively communicate experiences.

How the diagrams can be used by designers

Both the diagrams can be used by designers in various ways and are compatible with different steps in the design process. In early stages, when conducting discovery research for a project, the diagrams can be used for data collection. For example, in participatory activities or when used as cultural probes (142), participants can be asked to sketch out journey maps or

storyboards, followed by co-analyzing and representing the underlying causal structures. When designers analyze a qualitative data source, the diagrams can be used as analytical artifacts that represent journeys of the stakeholder along with underlying causal influences. As an analytical artifact, these diagrams can lead up to developing a full causal loop diagram. When generating ideas for concepts, causal substructures representing an intervention's causal logic model can act as inspiration or a micro design brief for designers to ideate towards, and the concepts can themselves be represented by either diagram type combining a narrative description of the solution with corresponding causal structures. Presenting design concepts using such visuals along with causal structures may promote clearer articulation of a designer's or team's assumptions, and potentially even anticipating unintended consequences, while maintaining descriptive detail of a concepts working in its physical, digital, or environmental context. Overall, we believe that infusing the visual vocabulary of designers with causal information connects the work of design to that of various other disciplines, elevates the scope of impact design has to more strategic levels, and extends the *material* through which a designer can have impact on complex problems beyond the constraints of traditional skillsets such as graphic, industrial, architectural or user experience design.

Future research scope

While grounded in insights from various areas of literature, this article does not empirically evaluate either of the proposed diagrams. Future studies could explore, for example, what the impact of using the diagrams is on accuracy of interpretations, efficiency of interpretation, the quantities and qualities of intervention ideas developed as a result of using different diagrams and frameworks to understand problems, etc. Future research is also needed to evaluate the compatibility of the diagrams with different types of source data, different research

methods and paradigms. Both diagrams are highly flexible, and other sources that offer comprehensive visual vocabularies such as Stoyko's (138) body of work on system visualization can be used to enhance and extend the utility of the diagrams. Such adaptations are another area of possible future research.

Conclusion

We have synthesized literature from various disciplines to illustrate the roles, limitations, and challenges of causal diagrams. In the light of theories of information processing and innovations in causal diagramming, we have proposed two novel diagrams: causal loop journey maps and causal loop storyboards. The diagrams can be effective ways to increase understandability, communicate additional information and temporal qualities, and hence support inter-disciplinary collaboration and innovation to contribute to addressing the wicked problems of today.

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APPENDICES

Appendix A - Literature search strings

Web of Science / 2012-01-01 to 2022-09-02 / English language only / Abstract search
213 results
(“causal loop diagram” OR “causal loop diagrams” OR “causal map” OR “causal maps” OR “directed acyclic graph” OR “directed acyclic graphs” OR “health impact pathway diagram” OR “health impact pathway diagrams” OR “causal process” OR “causal processes” OR “causal diagram” OR “causal diagrams” OR “system map” OR “system maps” OR (“stock” AND “flow” AND (“diagram” OR “diagrams”)))
AND
(“qualitative” OR "interpretive" OR "inductive")
AND
(“coding” OR “codes” OR “coded” OR “code” OR “modeling” OR “modelling” OR “model” OR “modeled” OR “modelled” OR “develop” OR “developing” OR “developed” OR “development” OR “generate” OR “generating” OR “generated” OR “generation” OR “diagrammed” OR “diagramming” OR “mapped” OR “mapping” OR “visualize” OR “visualization” OR “visualized” OR “visualizing”)

Scopus / Title, abstract, keyword search / 2012-present (search conducted on 2022-09-02) / English language only
352 results
(TITLE-ABS-KEY (("causal loop diagram" OR "causal loop diagrams" OR "causal map" OR "causal maps" OR "directed acyclic graph" OR "directed acyclic graphs" OR "health impact pathway diagram" OR "health impact pathway diagrams" OR "causal process" OR "causal processes" OR "causal diagram" OR "causal diagrams" OR "system map" OR "system maps" OR ("stock" AND "flow" AND ("diagram" OR "diagrams"))))) AND TITLE-ABS-KEY (("qualitative" OR "interpretive" OR "inductive")) AND TITLE-ABS-KEY (("coding" OR "codes" OR "coded" OR "code" OR "modeling" OR "modelling" OR "model" OR "modeled" OR "modelled" OR "develop" OR "developing" OR "developed" OR "development" OR "generate" OR "generating" OR "generated" OR "generation" OR "diagrammed" OR "diagramming" OR "mapped" OR "mapping" OR "visualize" OR "visualization" OR "visualized" OR "visualizing"))) AND PUBYEAR > 2011 AND (LIMIT-TO (LANGUAGE , "English"))

APPENDIX B – Screening process

Abstract Screening

- Initial abstract level screening was conducted by one researcher independently (RM), in consultation with senior researcher (KHL).
    - Here, we erred on the side of inclusion, considering the abstracts did not always clearly describe issues of interest even if they may have occurred.

Full text screening

- This occurred in phases starting with greater overlap between screened studies and more discussion to reach consensus and ended with a greater percentage of independently screening. Spreadsheets were used to manage screening at this stage.
- Independent copies of spreadsheets were created for each researcher that participated to cast their votes along with one common spreadsheet to merge and compare votes.
- Inter-rater reliability was gauged by the percentage of votes screened similarly. If one researcher cast their vote for a study as 'Maybe', this was not considered as an inconsistent vote and was discussed with the team to resolve and build consensus. Researchers brought up any confusing cases to the team for discussion.
- While screening, we noted reasons for exclusion. Any conflict in reasons for exclusion was resolved through consensus.
- The following were the phases in which full text screening was conducted:
    - Initially, three researchers made votes (triple screening; HF, DK & RM) - discussion with senior researcher (KHL) for conflicting votes - 20 studies screened this way.
    - In the next three rounds, double screening was conducted between combinations of researchers with a similar process to check reliability and build consensus - 70 studies screened this way. 80% reliability was successfully reached by this point.
    - In the next round, independent screening was conducted with 10% overlap for double screening - 76 studies screened this way.
    - In the last round for remaining studies, independent screening was conducted with 10% overlap for double screening with senior researcher (KHL).

APPENDIX C – Data extraction instructions

Article Type

Choose one based on primary focus: Methods/Recommendation/Empirical

Types of causal diagram created

Name each separated by ';' e.g. Causal Loop Diagram; Stock & Flow Diagram

Do not include diagrams that exclude causal information e.g. Iceberg Model

Types of data sources or data collected

Name each separated by ';' e.g. Meeting transcripts; interviews; focus groups
Core types of data can be described by the same term e.g. all types of interviews can simply be described as 'Interviews.'

Activities and steps to build causal diagram

Describe each step in the sequence separated by '>'
For each step use the following format for description [activity] ([output1]; [output2], .. | [tool1]; [tool2], ..)
e.g. open coding (table of identified variables; topic of each reference) > diagramming (intermediate causal diagram | Vensim PLE)

As far as possible, use author's own language to describe all the elements - activities, output, and tools - with minimal editing for grammar and comprehension. If authors describe steps as being iterative or cyclical, exclude this information and note the steps in the general sequence they describe.

Below the coded steps, include quoted the part of text that describe their steps to build causal diagram. Optionally break down the quotes by particular steps and include any additional comments.

If any framework is used that influences the format of their coding, include this here. e.g. 4-chain causal links rather than just 2.

Include activities relevant to going from data to causal diagram. Use square brackets for steps/activities that you think may not need to be included in core activities e.g. [step(output | tool].

What is coded & their definitions, if included

Name and (if information available) paste definitions of each in the following format.

[Name1]: [Paste definition, if included]
[Name2]: [Paste definition, if included]
e.g.
Variables: "A variable is a condition, situation, action or decision that can influence.."

Include what is explicitly described as being coded and also what is implied e.g. through charts or visuals. As far as possible, use language as used by authors.

Details of documents/artefacts supporting method including any documents/artefacts not described in steps to build causal diagram

Name and describe and define each in following format.
[Name1]: [description]/"[pasted description]"
[Name2]: [description]/"[pasted description]"

Include documents and artefacts supporting process even if they have been described in steps to build causal diagram.

Tools or software used (if any)

Name approach(es) separated by ';' and include any additional relevant notes below. Also include software that may already be described in steps to build causal diagram.

Strategy to connect causal map to underlying data (if any)

Describe strategy in own words, including any relevant artefacts or tools. If helpful, include any quotes to provide context. If multiple strategies are included , separate these by line breaks.

Strategy or method to identify leverage or requirements for design or action

Describe strategy in own words, including any relevant artefacts or tools. If helpful, include any quotes to provide context. If multiple strategies are included , separate these by line breaks.

Strategy or tactics for visualizing system beyond typical causal diagram

Describe strategy in own words, including any relevant artefacts or tools.

Methodological concerns or challenges unaddressed - as described (if any)

Include a statement to paraphrase followed by a line break and paste a quote supporting challenge described within double quotes. i.e. [paraphrased description] "[statement or quote supporting this]"
This field can include redundant/overlapping information compared with other fields where applicable.

APPENDIX D – Analytic process

Coding of methodological activities

General coding criteria

- If a core method was described along with one or more case studies as examples, only activities from the main method were coded.
- If an activity was described as possible variation of the study and not an activity that the authors either did or fully recommend doing as part of their method, it was not coded.
- The sequence of activities and any inference of two activities being done simultaneously was based on the researchers' description.
- If activities from the codebook were done for other purposes beyond building the causal diagram (e.g. if factors were coded after a CLD was generated, but not used to inform an iteration of the CLD), this was not coded.
- If a studies description did not directly suggest the sequence of two activities that were described in the same segment of text, these were coded as activities parallelly done in the same steps e.g. if a study described coding for both codes and relationships within a particular step.
- If two versions of the same activity were conducted during the same step as described by authors, these were only coded one time for that step e.g. if a study described coding for variables and factors in the same step.
- If additional activities were done during a parent study or overarching study but were not within the scope of a particular component of it described in the study, then those additional activities were not coded.
- If some output was clearly implied. E.g. if in one step, they mentioned output of an activity from previous step such as 'While keeping the codebook updated', corresponding activity was coded for the previous step,

Activity specific coding criteria

Defining system boundaries

- This included steps during analysis that decide what is inside or outside scope.
- If system boundary consideration was discussed but not in relation to any particular activity, this was not coded here. For example, if a study discussed the importance of system boundary considerations but did not describe conducting it or how they conducted it.

Coding of concepts

- If coding variables was not described explicitly in text of study, but implied through a figure, this was coded.
- This included structural codes or broad codes applied to data.

Consolidation of concepts

- This included grouping, merging, filtering or simplification of concepts, themes, variables, or factors.
- This also included labeling or grouping elements not for simplification or condensing of structure in any way e.g. categorization of variables
- This did not include when a study cumulative weights for any concepts.

Coding of relationships

- This included coding two variable relationships, but also multi variable chains or substructures.
- If coding relationships was not described explicitly in text of study, but implied through a figure, this was coded.

Consolidation of relationships

- This included grouping, merging, filtering or simplification of causal relationships, chains or structures e.g. shortening causal chains by removing auxiliary variables
- Even if groups were decided in a previous coding activity, and causal links from a previous activity were combined based on higher order group, this was coded here and not in 'Coding of relationships.'
- This included labeling or grouping elements not for simplification or condensing of structure e.g. if feedback loops were labeled as facilitating or inhibiting for topic, or if step explicitly involved identification of feedback loops or substructures within a version of a diagram.
- This did not include calculating cumulative weights for relationships.

Building confidence in analytical insights

- This included building confidence in analytical insights with any new information e.g. member checking, validation with stakeholders or comparison to external information or framework.
- This did not include having internal research team verifying any insights.
- This did not include validating with existing dataset in another round of process.
- If it was not clearly described when this step was done in sequence of a process this was coded as last step.
- If this was described as an activity that involves refinement of diagram and implied that this would lead to an iteration of diagram, this was coded both here and, in the activity, involving developing the diagram (intermediate or final).
- If the study implied member checking or stakeholder validation only to check if existing insights are accurate and not explicitly describing refining insights, this was only be coded here.
- If an activity involved refinement to codebook, or to coding/grouping of analytical elements prior to diagram, this was only coded here.

Developing intermediate causal diagram(s)

- This included the visual development of any intermediate causal structure described as a step in the process e.g. word-and-arrow diagrams, feedback loops, iteration of final diagram.
- If causal diagrams were built iteratively (e.g. upon aggregating multiple individual causal diagrams one by one) and this step leads up to a final causal diagram, this was coded for both the 'developing intermediate causal diagram(s)' and 'developing final causal diagram(s)'

Developing final causal diagram(s)

- This included the visual development of any final causal structure.
- If creating a causal diagram as an activity was not described explicitly as a step in the study, but implied through a figure, this was still coded as the final step.
- If causal diagrams were built iteratively (e.g. upon aggregating multiple individual causal diagrams one by one) and this step leads up to a final causal diagram, this was coded for both the 'developing intermediate causal diagram(s)' and 'developing final causal diagram(s)'.
- This was coded as either as a separate step if described as such or as a parallel activity to any other activity where it is described or implied that the final diagram would be the resulting output e.g. during member checking or consolidation of concepts or relationships.

Appendix E - Focus group discussion protocol

Activity 1: Homework Review

30 min	5:40-6:10	Activity 1 intro (homework review)	Main room
	5:40-5:45	*Review homework work, join breakout rooms, facilitator explains instructions*	*Breakout room,* *Approx. 4 participants per room*
	5:45-6:10	*Small group UX map sharing and discussion*	*Breakout room*

Pre-Workshop Activity Review

2 min

Share your experience map

Approximately 5 min per person

Repeat instructions, especially focus on feeling PREPARED and INFORMED.

When complete, ask for responses to others experiences if you have extra time.

Notes:

Activity 2: High Blood Pressure and you

25 min	6:10-6:35	Activity 2 intro (HBP + you)	Main room

		Pt 1. What do you know about HBP? Create list.	*Breakout room, facilitator take notes and make list for small group*

Discuss feeling prepared for pregnancy and beyond

Part 1: What do you know about HIGH BLOOD PRESSURE as it relates to your pregnancy?

We want you, as a small group, to make a list of information that you are aware of regarding HBP- both during your pregnancy and beyond.

Facilitators- make a list

Three Prompts-

1. What it is? Why is it important? Why should you care?

How it affects you?

Long term implications?

2. What to pay attention to?

Signs? Symptoms?

How to take BP?

Cuff position?

Body position?

Your 'normal' levels?

Your 'risk' levels?

Frequency? Time of day? When to take?

Consistency of readings?

Confident of your process?

3. What should you do?

Who to call?

When to call?

In hospital? At home?

Prompts for increased participation:

Does anyone have an experience that is the same/ diff

Notes:

		Pt 2. Where when and how did you learn this information? Note in list.	

Part 2: When, where, and how did you learn about this information?

Prompts:

(may be a provider, maybe a friend, maybe online, etc)

When with respect to your pregnancy?

Specific websites? Blogs? Etc?

Learning: Acquiring the information?

Appropriate to your level of understanding?

Information was actionable?

Trust w education process?

Notes:

		Pt 3. Provide examples of feeling prepared and informed. Positive and negative.	*Pick one example to share with the larger group.*

Notes:

Activity 3: Learning about High Blood Pressure

20 min	6:50-7:10	Activity 3 intro (learning about HBP info)	Main room We pick one of the shared examples to take back to breakouts for discussion
		What would a positive learning experience look like for you? Who What Where When How?	*Breakout room*

Part 3: Share examples of feeling prepared and informed? Or not…

Pick an experience to share with the large group.

Prompts:

Provide examples of feeling prepared and informed. You had the right information at the right time.

What went well?

Share examples of NOT feeling prepared and informed. You did not have the right information at the right time.

What did you do?

What went wrong?

What should have happened?

Secret prompts:

Applying: Putting the information into practice?

Taking your blood pressure:

Trust yourself taking?

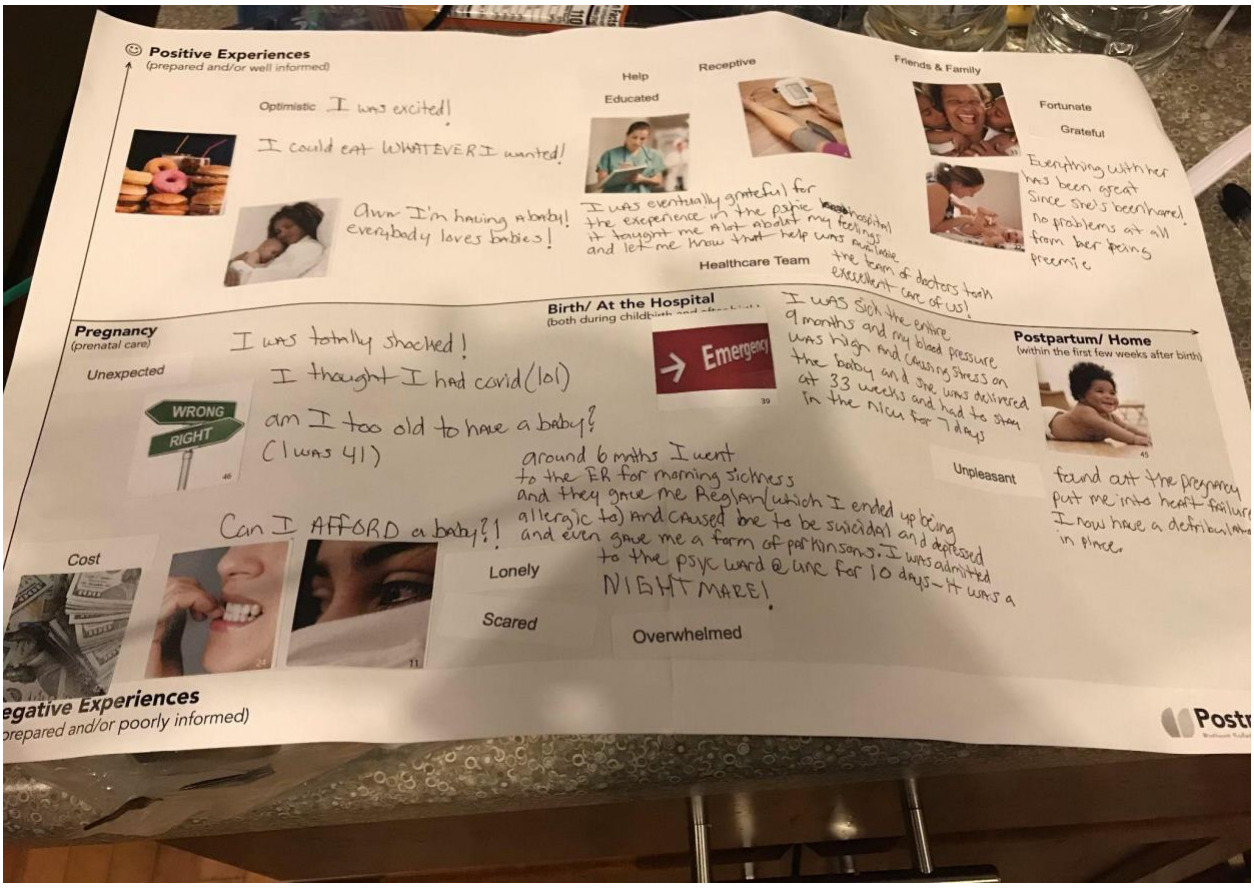
Trust the BP equipment?

Do you trust your readings?

How to remember to take BP?

Notes:

Appendix F - Example of journey map



Appendix G - Codebook of variables

Variable	Description
Patient health	Health status of patient at a particular time point, including physical and mental health. This includes health at different time points such as pre-pregnancy health and prenatal period health.
Continuity of care interactions	Patient having continuity to experience through the same care team or team member for multiple health interactions over time, or repeated discussion of topics or skills
Care team with differing views	Patient's care team or different care teams they interact with having differing views on matters related to care.
Staffing shortages	The lack of capacity of healthcare team available at hospital.
Alternative care team involvement	Involvement of alternative types of care team and providers such as midwives, doulas, and other support organizations.
Care mishaps	Errors, mishaps, or delays in care provision to patient.
Unwelcome traffic in patient's room	Care teams or team members visiting patient's room at an undesirable rate for various reasons including care, and research studies.
Information overwhelm	Large amounts of educational information being packed into a short period of time.
Support person(s) involvement	Presence and involvement of any type of personally related support person to help patient navigate their maternal health experiences.
Patient advocacy	Patient's needs, desires and experiences being advocated for, or the patient being encouraged or empowered to do so.
Continuity of care provision	The continued capacity of care being made available to patient through different time periods of their journey.
Care team understanding of patient health	The care team having a deep understanding of patient's health and what impacts it or would impact it.
Prior pregnancy experience	The patient having experienced pregnancy or delivery in one or more prior instances.
Patient involvement	The healthcare team listening to patient to understand their expectations, needs, perspective and to learn about their understanding of their own bodies and health i.e. leveraging self-knowledge of patient
Patient desire to be in hospital setting	The patient's desire and willingness to stay for a length of time in hospital setting,
Asynchronous learning (e.g. online)	The patient's learning through resources outside of synchronous interactions with care team members.
Synchronous learning (e.g. appointments)	The patient's learning through synchronous interactions with care team members.

Patient knowledge and skills	The patient's knowledge and skills to equip them to navigate their present health and also to know about future risks and conditions they don't presently experience.
Patient self-knowledge	The patient's understanding of their own bodily experience and of their health through it.
Monitoring of patient's health	Monitoring of patient's health, whether through tools or through inquiry/asking patient. This includes patient's monitoring of their own health and care team or support person's monitoring of it.
Firefighting to protect patient health	The care team members taking actions focused heavily on protecting patient's immediate and at-risk health.
Explaining reasoning	Care team members explaining reasoning behind particular care actions they take or recommendations they make.
Having easy to find and reference info	Having informational materials and resources that make it easy to find and reference information.
Patient getting rest	The amount of quality rest that patient is able to get in the hospital or outside of it.
Length of stay	The actual duration of postpartum stay for the patient.
Completeness of education	The comprehensiveness and level of detail of education provided to patients, including for potential conditions.
Ease of using monitoring equipment	The ease of use and adaptability of monitoring equipment for use by patient.
Actionability of education	Provision of education to patient that includes what one can do for managing health in different situations (e.g. keeping blood pressure low) and not just when to call or return back.
Care team time spent with patient	The actual time care team or a care team member spends with patient in their interactions
Racial biases	The racial biases impacting how care team members interact with different patients and the assumptions they have about them.
Patient level of knowledge assumed	The level of knowledge and understanding in relation to various maternal health issues that a care team or team member assumes the patient has.
Care team understanding of SDOH	The care team's knowledge of the social determinants of health and how they can impact patient experiences.
Care team understanding of patient history	The care team knowing of details a patient's past health and outside-of-health experiences
Timeliness of education	The provision of relevant education at appropriate timing - before potential concerns can occur and at appropriate time for patient to process it.
Tailoring of education format	Provision of education in a format that is a good fit for the recipient patient.

Care team following up	Following up with patient by care team after postpartum hospital discharge.
Group education	Provision of education in group format with multiple participants or recipients.
Effectively processing info	The patient effectively using, processing, comprehending, and remembering education they interact with.
Having preferred care team	The patient having the ability to interact and work with a care team member they prefer
General life stressors	Stressful occurring outside of maternal health experiences and concerns
Nursing knowledge level/distribution of knowledge across team	The knowledge level of nurses about health educational topics, relative to knowledge of doctors