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Temporal Network Analysis of Collaborative Prototyping from a Knowledge Creation Perspective

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Abstract

This study analyzed data from prototyping sessions to support learners' engagement in collaborative problem-solving through design-mode thinking. Knowledge creation (KC) is essential for addressing 21st-century complex problems, yet learners struggle to share incomplete ideas due to unfamiliarity with design-mode thinking. Although prototyping is known to be effective for sharing and improving incomplete ideas in the business sector, few studies analyze design activities during prototyping from a KC perspective across different design disciplines. This study examined three teams (engineering, product design, service design) during 30-minute prototyping sessions. Using a novel combination of techniques—temporal socio-semantic network analysis (tSSNA) and ordered network analysis (ONA)—we analyzed teams' shared epistemic agency, segmenting activities into three phases based on idea improvement patterns. Engineers focused on generative collaborative actions, product designers emphasized creating shared understanding, and service designers concentrated on alleviating lack of knowledge. Statistical tests revealed significant differences between teams and phases. The findings suggest three design principles for KC practice: attending to disciplinary differences in interdisciplinary teams, providing timely educator support for concept creation, and using short task durations to encourage sharing incomplete ideas. Furthermore, this work demonstrates the potential of combining tSSNA and ONA for analyzing collaborative KC processes.

Notes for Practice

- Knowledge creation (KC), an emerging educational approach for innovation, necessitates a safe and positive environment for students to share and refine their ideas.
- This study proposes using prototyping, an approach employed in knowledge-creating organizations, to support students unfamiliar with design thinking in expressing incomplete and unfinished ideas. We propose an analytical method for capturing the practices of KC in prototyping and demonstrate its usefulness by analyzing data from design teams.
- Our method combined temporal socio-semantic network analysis (tSSNA) and ordered network analysis (ONA), tracing the differences among design disciplines by visualizing the transitions of idea changing and shared epistemic agency.
- Our results suggest three recommendations for designing learning environments for KC: (1) analyzing students' activities through a specific disciplinary framework, (2) supporting concept creation, and (3) setting short time frames for activities to encourage sharing of incomplete ideas.

Keywords
Knowledge creation, prototyping, temporal socio-semantic network analysis, ordered network analysis, collaborative problem-solving.

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1. Introduction

The ability to create new knowledge, as opposed to solely applying existing knowledge, is increasingly important for addressing the complex problems of the 21st century (Razzouk & Shute, 2012; Koh et al., 2015; Aviña et al., 2018). In turn, the OECD's Learning Framework for 2030 has identified the development of knowledge, skills, and attitudes for innovation as a critical goal (OECD, 2019). The framework emphasizes the development of transformative capacities to tackle future uncertainties, wherein knowledge creation (KC) plays a central role. However, traditional education systems are ill prepared to teach KC skills because they primarily focus on the transfer and acquisition of existing knowledge (Chen & Zhang, 2016; Chan & van Aalst, 2018).

The process of creating knowledge transcends domains but is often described with different terminology. For example, in the learning sciences, *knowledge building* has been discussed as a way to engage learners in the KC process (Scardamalia & Bereiter, 2021). This approach aims to make learners active participants in generating, improving, and integrating ideas, rather than just recipients of knowledge. The concept of a *knowledge-creating organization* (Nonaka & Takeuchi, 1995), which has focused on KC in the field of organizational science, is synonymous with knowledge building (Scardamalia & Bereiter, 2021). As we argue in more detail below, *design thinking*, discussed in the context of design research, and *design-mode thinking* in knowledge building, share commonalities. According to Koh and colleagues (2015), while design thinking targets a wide range of artifacts, including cultural practices, design-mode thinking focuses on knowledge artifacts such as theories and explanations.

Despite the links between design and KC, there have been few analyses of design activities during prototyping from the perspective of KC. Such studies could be important for several reasons. First, looking at designers' activities could reveal aspects of KC that may not be apparent from simply comparing high-achieving and low-achieving learners. This is because KC is characterized as a social learning process based on design principles rather than solely an evaluative outcome (Scardamalia, 2002). Such an understanding could help researchers and educators find effective ways to engage learners in more authentic KC activities, including team-based ideation sessions, iterative prototyping with user feedback, or collaborative reflection sessions. Second, a comparative analysis of groups of designers from different disciplines can show how disciplinary differences impact KC, providing insights for facilitating interdisciplinary KC. In the context of design education, a decade-long empirical study about interdisciplinary collaboration was based on the premise that designers in the different fields act differently (Goldberg & Malassigné, 2017). This study identified participants' perceptions about designers from different fields, such as each discipline having its own "vocabulary" and approach to solving the problem. Furthermore, Yu and colleagues (2018) analyzed the prototyping of nine designers from three different design contexts and reported that prototyping approaches differ depending on their backgrounds. In other words, by identifying the differences between fields from the KC perspective, educators may grasp the characteristics of different disciplines, determine the timing of interventions, and design scaffolding to collaborate in a manner that considers these characteristics. Finally, the emphasis of KC on the improvement of ideas, rather than the pursuit of fixed answers and results from previous research (Gerber & Carroll, 2012), suggests that prototyping promotes the perception of failure as an opportunity for learning. Thus, analyzing prototyping from a KC perspective may provide insights into how to engage learners not accustomed to collaborative, creative activities.

In this study, we used the KC perspective to analyze the prototyping sessions of designers from different disciplinary backgrounds using a novel combination of temporal socio-semantic network analysis (tSSNA) (Ohsaki & Oshima, 2021) and ordered network analysis (ONA) (Tan et al., 2022). This study is novel in that it analyzes the authentic activities of designers from the perspective of KC using an analytic approach that addresses the limitations of previous work and clarifies different disciplinary characteristics described qualitatively in previous studies (Goldberg & Malassigné, 2017; Yu et al., 2018).

2. Background

Although KC is an approach to education for innovation, it may be difficult for learners to engage in authentic KC practices because design-mode thinking differs from what is often taught in school. Traditional schooling tends to focus on *belief-mode thinking*, which emphasizes "correct" knowledge (Bereiter & Scardamalia, 2003; Chen & Zhang, 2016). Researchers have argued for the need to provide students with the opportunities to engage with KC practices (Chen & Zhang, 2016), but learners not used to design-mode thinking may avoid representing incomplete ideas or products due to feelings of uncertainty (Gerber & Carroll, 2012; Frambach et al., 2014). Thus, environments designed to teach KC practices need to provide a safe and positive space to share and improve ideas. This study proposes to use prototyping—an approach used in real knowledge-creating organizations—to assist students unfamiliar with design-mode thinking with representing incomplete and imperfect ideas.

Prototyping is the process of creating a design that expresses the characteristics of a service or product before its concepts and design specifications are determined or before production, to make improvements and decisions and contribute to fostering a culture of learning from failure through experimentation (Lim et al., 2008; Camburn et al., 2017). Historically, prototyping approaches have differed between the engineering and business sectors. In the engineering sector, prototyping typically involves physical prototyping after specifications have been determined to improve the quality of the final product and assess the likelihood of defects on the mass production line. As digital fabrication tools such as 3D printers have increased the speed of physical prototyping, *rapid prototyping* has become possible (Viswanathan & Linsey, 2011; Christie et al., 2012). In the software engineering sector, rapid prototyping takes place in the early stage of software development to clarify specifications and detect key design considerations (Gordon & Bieman, 1995).

In the business sector, it is increasingly recognized that prototyping promotes innovation and that multiple rounds of quick prototyping improve quality, and the timing of prototyping is pre-determined in the product development schedule to lead to idea improvement (Schrage, 1996). In addition, prototyping has been reported to be useful as an opportunity to develop the ability of participants to see failure as a learning opportunity and to improve their designs through the process. Gerber and Carroll (2012) confirmed the effectiveness of low-fidelity prototyping for evaluating ideas in the very early stages of the design process as a solution to the issue that people are anxious about uncertainty when creating knowledge.

In knowledge-creating organizations, it is well known that simple prototyping that allows for imperfection and awkwardness can be effective. For example, Adam Skaates and Coe Leta Stafford used a prototype video created in just one hour to allow skeptical stakeholders to simulate the user experience and demonstrate the value of the new game to them (IDEO-U, 2016). These key elements of prototyping—that is, creating imperfect and improvable ideas which take the form of designs or physical products—overlap significantly with KC. In general, the process of KC is characterized by a cyclical turn of divergent and convergent thinking (Treffinger, 1995; Goldschmidt, 2016). This process of generating a wide range of ideas and evaluating and integrating them to derive new knowledge is the foundation of KC. The design principles for KC activities (Scardamalia, 2002) state that "idea diversity" and "improvable ideas" lay the foundation for the improvement of divergent ideas—inspiring the question of whether the community is continuously changing ideas to improve the quality, consistency, and usefulness of ideas. Furthermore, Scardamalia and Bereiter (2014) presented the iterative process of problem solving and further development undertaken by engineers and designers as an example of idea improvement in KC. Therefore, analyzing the activities of designers and engineers during prototyping from the KC perspective and clarifying how ideas change and are changed provides a new bridge between design process research and KC research.

KC's focus on sequential idea improvement suggests that understanding KC practices requires methods sensitive to the interrelated and evolving nature of discourse. Previous studies on KC practice have employed a combination of socio-semantic network analysis (SSNA) (Oshima et al., 2012) and epistemic network analysis (ENA) (Shaffer, 2017) to examine changes in ideas and their relationships over time within KC practice. SSNA is a method for analyzing idea improvement in KC practices. It visualizes the network of key phrases in discourse, illustrating how ideas change and evolve. SSNA uses total degree centrality (TDC) to quantitatively evaluate the degree of idea improvement. ENA is a method for understanding how concepts or actions in discourse connect to or are related to one another. The method quantifies qualitative data and visualizes the differences between various sociocultural practices. In prior work, Oshima and colleagues (2020) proposed a combination of SSNA and ENA to analyze KC practices. By using the proposed method, Ohsaki and Oshima (2023) found that the idea improvement activities of engineers and product designers are continuous and have similar characteristics to the high-performance groups discussed in previous studies. Moreover, it was revealed that engineers engage in idea improvement using various epistemic actions, whereas product designers do not. This difference was thought to reflect the characteristics of engineers who prototype functions based on user requirements and the characteristics of product designers who design the interface between users and products.

Although the above work provided insight into the KC practices involved in prototyping, it had two important limitations. First, it was limited in its consideration of the relationship between KC and the different kinds of design teams. While engineers and product designers are both designers who design solutions as a new knowledge, their specific design activities might differ because they constitute different communities of practice with different training programs and cultural norms. For example, in the Japanese educational and professional system in which our study is situated, design education is divided into "Design," which means exterior design, and "Sekkei," which means function and mechanism design (Ohtomi, 2009; Matsuoka, 2005). Due largely to historical differences (Matsuoka, 2005; Weber, 2019), "Design" is typically an arts subject and is also called "product design" or "industrial design." On the other hand, "Sekkei" is typically an engineering subject. In addition to engineering and product design, service design has also emerged from the business sector as a distinct field with its own view on design (Mager et al., 2020). Service design is an area that is process oriented in its activities, and its process typically follows steps of planning and preparation, research, ideation, prototyping, and implementation (Scardamalia, 2002). Moreover, this process should be human-centred, collaborative, iterative, sequential, real, and holistic (Stickdorn et al., 2018). Hence, even designers engaged in the same design activities but with different historical and cultural backgrounds may use different knowledge and skills in the KC process. The present study extends prior work by comparing the prototyping processes of teams from these three diverse backgrounds.

Second, the analysis conducted by Ohsaki and Oshima (2023) was limited in its methodological approach. The prior analysis followed existing recommendations from the computer-supported collaborative learning (CSCL) and quantitative ethnography communities that highlight the importance of co-occurrences between discourse moves (Csanadi et al., 2018) and the importance of data segmentation based on recent temporal context (Siebert-Evenstone et al., 2017). However, it is possible for improvements to be made on each of these fronts.

Tan and colleagues (2022) distinguish between unordered temporal and ordered temporal approaches to modelling collaborative problem-solving using the concepts of *common ground*—the collection of prior actions observed by the group—and *response*—the subsequent action. Unordered temporal approaches identify the co-occurrence of discourse moves in the common ground with those in the response but do not explicitly represent the order of the co-occurrence. Ordered temporal approaches are similar except that they explicitly represent the order of co-occurrence. The study by Ohsaki and Oshima (2023) applied ENA—an unordered temporal approach—to examine the prototyping processes of design teams. However, it is plausible that the specific order in which discourse moves occur in this context is important. For example, a transition from focusing on the end user to focusing on the designer's vision of the prototype would indicate a user-first approach. The opposite transition would indicate a designer-first approach. In this study, we apply the ordered temporal approach, ONA, to study KC during prototyping.

Regarding data segmentation, the prior analysis analyzed the data based on SSNA, which operationalizes changes in topics using changes in the degree centrality of key terms in the discourse. In this prior study, SSNA measured changes in degree centrality on a turn-by-turn basis in the discourse. Such an approach assumes that the relationship between the current turn and the previous turns—i.e., the common ground of the discussion—is limited to immediate exchanges. However, work by Seibert-Evenstone and colleagues (2017) and Ruis and colleagues (2019) has shown that the current turn of discourse can be influenced by turns beyond the most recent one. To address this issue, this study applies the tSSNA approach, which identifies changes in topics via finite fluctuations in the degree centrality of key terms within moving windows that include several turns of talk.

Furthermore, although data in the prior study was segmented for analysis to avoid the identification of spurious co-occurrences, the final analysis was conducted at the aggregated level. Here, in addition to analyzing the data on aggregate, we compare the prototyping behaviours of the teams in different segments over time to better understand changes in their behaviour. Overall, this work should provide a more nuanced and valid understanding of the KC practices involved in prototyping that can be used to inform the design of future KC-based learning environments. Specifically, our study seeks to address the following research questions:

1. How do the KC practices of engineers, product designers, and service designers differ during prototyping?

2. Do these differences change over time? If so, how?

3. Methods

3.1 Dataset

Our data comes from the prototyping sessions of three teams. The data providers were from teams assisting in the development of a human-centred design course. Each team was tasked with creating exemplary records and prototypes of design practices to be used in the course. Teams were asked to design a new wallet based on a set of user needs in a single 30-minute session. The 30-minute duration was a work period that could be embedded into typical 45- to 90-minute lessons in Japanese schools. This task was not a focused challenge, such as the "egg-dropping challenge" or "new use of old phone" used in previous studies (Yu et al., 2018), which investigated differences in activities between fields during the prototyping process. In contrast, it was a complex challenge that incorporated all of the important activities in the design process, including research, analysis, producing a design solution, and evaluation. Participants were given the flexibility to schedule the entire session at their convenience. The facilitator did not prescribe specific activities and time, such as interviewing, ideation, prototype creation, or evaluation within the session. This allowed us to observe the characteristics of designers' epistemic agency in collaborative problem-solving based on how they performed or did not perform these activities. During the session, teams could communicate with the "user," whose role was played by the session facilitator. The user was a woman in her thirties aspiring to adopt a minimalist and healthy lifestyle. She did not have any particular preferences regarding a wallet. Thus, she served as a suitable user for this case study, as it necessitated the extraction of insights through the interview process that she may not have been consciously aware of.

Each session was audio-/video-recorded, and we transcribed the audio and segmented the transcription by turn of talk. During the activities, teams conversed in Japanese. The analysis was conducted by bilingual analysts (Japanese and English) who analyzed the original data, and English speakers analyzed the data translated into English. To avoid issues arising from translation from Japanese to English, English speakers could consult the bilingual analysts at any time, who could explain complex interactions and cultural backgrounds.

The first team consisted of three students at a professional graduate school in software engineering. The second team consisted of three undergraduate students in their final year as product design majors. The final team included three professional service designers. We refer to these teams as the Engineering, Product Design, and Service Design Teams, respectively. Demographic data for each team is shown in Table 1. Each team participant has experience participating in design projects, either individually or as part of a team. The table lists the median design experience of team participants for each team. The transcribed prototyping sessions included 325 turns of talk for the Engineering Team, 435 turns for the Product Design Team, and 585 turns for the Service Design Team, for a total of 1,345 turns.

Table 1. Participant demographics.

Team	Sex	Age Range	Median design experience (individual project)	Median design experience (team project)
Engineering	Male	20s	3 projects	5 projects
	Male	40s		
	Male	60s		
Product Design	Female	20s	10 projects	4 projects
	Female	20s		
	Male	20s		
Service Design	Female	40s	3 projects	12 projects
	Male	40s		
	Male	40s		

3.2 Coding

Based on previous research by Ohsaki and Oshima (2023), we analyzed the team discourse using a coding framework grounded in *shared epistemic agency*. This analytical approach was chosen because shared epistemic agency is a well-established framework for analyzing KC (Damşa et al., 2010; Oshima et al., 2020). Previous research examined design processes from two perspectives—design activities and shared epistemic agency—aiming to achieve a comprehensive understanding (Ohsaki & Oshima, 2023). However, with regard to shared epistemic agency, there remains room for more detailed analysis to explore the relationship between different design cultures and KC. We coded the data using a social moderation process where two raters discussed and resolved differences in coding after both of them coded the same data independently (Herrenkohl & Cornelius, 2013).

As Chen and Zhang (2016) argue, in a KC environment where students need to use design-mode thinking, epistemic agency—or having control over their own epistemic actions—is a critical element because educators may not be as involved in the process. Shared epistemic agency goes beyond individual epistemic agency and describes how members engage in a community for the purpose of creating shared knowledge objects as productive participants. In order to explain this specific form of shared epistemic agency, which Scardamalia (2002) identified as one of the KC design principles, Damşa and colleagues (2010) analyzed the group activities of university students in terms of the seven behaviours described in Table 2. This framework has two dimensions: the epistemic dimension is related to knowledge, and the regulative dimension is related to process. Moreover, this framework has been used in previous KC studies to qualitatively evaluate KC practices (Oshima et al., 2020; Ohsaki & Oshima, 2023). These categories include (1) creating awareness (CA) by identifying what is missing, (2) alleviating lack of knowledge (ALoK) by attempting to acquire missing information and critiquing the source, (3) creating shared understanding (CSU) by comparing and checking knowledge and understanding, (4) generative collaborative actions (GCA) by improving the created knowledge object—i.e., the final stage of epistemic dimension of shared epistemic agency, (5) planning activities toward a goal (projective), (6) monitoring the object created by the participants (regulative), and (7) providing space for other members to contribute (relational). The categories CA, AloK, CSU, and GCA are in the epistemic dimension, and projective, regulative, and relational are in the regulative dimension. Furthermore, based on the design principles of KC activities (Scardamalia, 2002), it is important to consider whether the community is continuously changing ideas and improving their quality, consistency, and usefulness. From this perspective, GCA could be placed as the most advanced level of the four stages of activities in the epistemic dimension.

3.3 Analysis

To address our research questions, we combined tSSNA—a novel method for exploring the temporal dynamics of discourse—and ONA—a method for exploring the ordered relationships between concepts or actions in discourse. To segment the data for further analysis, we identified separate phases of idea improvement using tSSNA. Next, we compared the three teams in terms of their shared epistemic agency using ONA aggregated across phases (RQ1) and by each separate phase (RQ2).

3.3.1 Analytics for Idea Improvement

SSNA is a method for understanding idea improvement in knowledge-building research via networks constructed using unique terms in the discourse as nodes (Oshima et al., 2012; Scardamalia & Bereiter, 2014; Chen et al., 2015; Scardamalia & Bereiter,

Table 2. Shared epistemic agency codes.

Category	Definition	Example
Creating awareness (CA)	Pointing out what is missing	Is there a difference between wallets used in Japan and those used overseas?
Alleviating lack of knowledge (ALoK)	Trying to acquire missing knowledge and criticizing the information source	By the way, why did you choose the current wallet?
Creating shared understanding (CSU)	Bringing up their knowledge and checking another person's understanding to create a knowledge object	Thin is also good, right? Minimalist-like...
Generative collaborative actions (GCA)	Improving the created knowledge object	Additionally, we can extend the functionality of this wallet by...
Projective	Planning activities for a goal	We have about 10 minutes left
Regulative	Monitoring the object created by the participants	This [prototype] is fine [for us].
Relational	Giving other members space for contribution	Oh, that's nice. Let me see your wallet.

2021). Figure 1 shows SSNA networks visualizing participants' ideas. In this figure, there is an extensive network of various terms (in Japanese) interconnected at the centre, demonstrating how this team focused on a core idea expressed with diverse terms. Unconnected terms are located in the corners of the space, contrasting terms associated with the core idea and those that are not. The figure is a snapshot of a specific point in time, but to quantitatively represent the activity process, the structure and evolution of the SSNA network are expressed using the total degree centralities (TDCs). TDC is a sum of the degree centrality (DC) scores for each node within a given interval between turns of talk x and y (see (1)). DC is calculated based on the adjacency matrix for each pair of nodes i and j in the network a_{ij} (Oshima et al., 2012) (see (2)):

$$TDC = \sum_{i=x}^{y} DC_i \tag{1}$$

$$DC_i = \frac{1}{m-1} \sum_{j=1}^{m} a_{ij} \tag{2}$$

tSSNA extends SSNA in three ways (Holme & Saramäki, 2012; Siebert-Evenstone et al., 2017; Ohsaki & Oshima, 2019, 2021). First, because tSSNA tracks conversational changes via timestamps rather than just turns of talk, it can show the similarities and differences in idea changes between teams on the same time scale (Ohsaki & Oshima, 2021). Second, by using moving windows over the data—rather than accumulating degree changes on a turn-by-turn basis—tSSNA is sensitive to relationships between terms that occur within the recent temporal context of the conversation (Siebert-Evenstone et al., 2017). Finally, by using the concept of network lifetime, which resets the network to zero edges after a specified number of windows, tSSNA is sensitive to the local fluctuations that occur in conversations over time, rather than the aggregative nature of conversations.

Figure 2 compares SSNA (top) and tSSNA (bottom) using an example of two teams' data from this study. Y-axes in the graphs show TDC. The rise and fall of the values on the Y-axis show when and how ideas changed during the activity process. The X-axis in Figure 2a illustrates the turn identifier for the discourse, and the X-axis in Figure 2b shows the timestamp of the discourse. Comparing the X-axes highlights the difference between the two methods. Specifically, the effect of network lifetime and moving windows is shown at Arrow 1. In SSNA, increasing TDC indicates a new term connected to existing networks, but the difference is small. This is because SSNA sums up the DC of key terms beginning with the first turn of talk. tSSNA emphasizes the difference of TDC because it calculates TDC based on windows of turns of talk that reset. Consequently, tSSNA more effectively indicates when the idea change was actually activated or deactivated. Moreover, the timestamp information clarifies that the end of conversations indicated by the roots of Arrows 2 and 3 occurred at similar times. In summary, the use of tSSNA with timestamp information visualization offers significant benefits, allowing for the representation of real-time learning

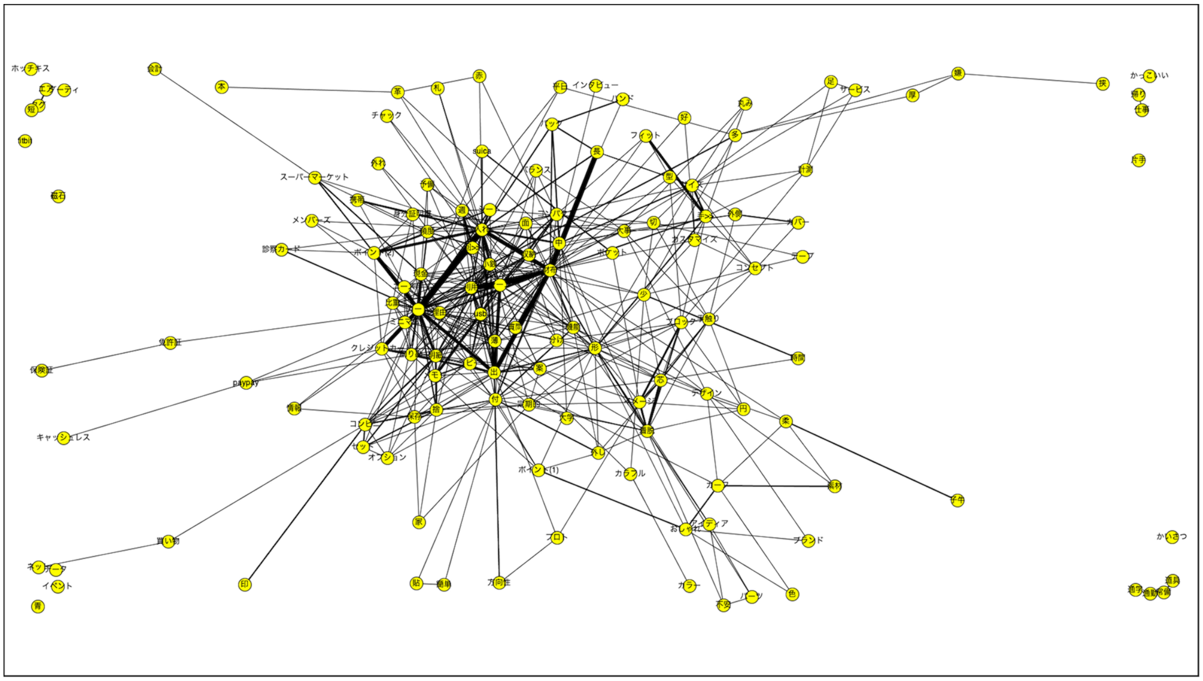


Figure 1. The density of key phrases in SSNA.

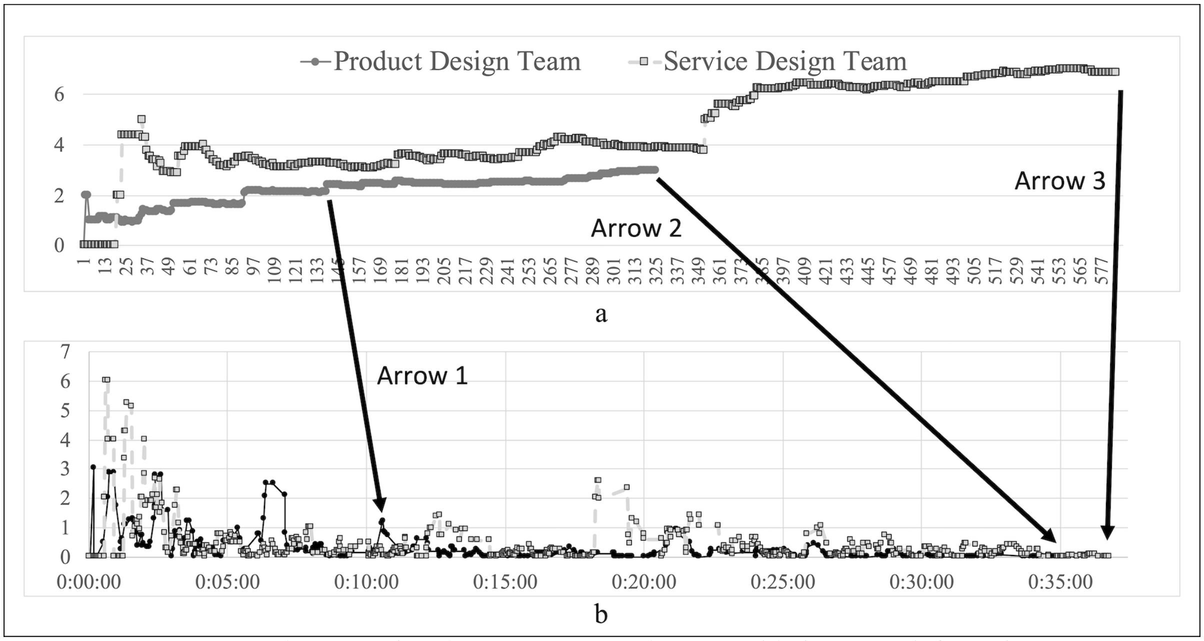


Figure 2. The comparison between SSNA and tSSNA with timestamp information.

events and enabling comparisons across different contexts on the same time scale. For this tSSNA analysis, we used a moving window size of four turns of talk, a network lifetime of two windows, and connections between 287 unique key terms.

Following Barany and colleagues (2022) and Ohsaki and Oshima (2023), we used tSSNA to segment each team discussion into phases of sustained idea improvement. More specifically, we segmented the data of three teams using the tSSNA visualization. We marked the division points for each phase and each team by identifying repeated decays in the TDC score—that is, a new phase began when TDC decreased in two consecutive windows. This process produced three phases of distinct idea improvement for each team.

3.3.2 Analytics for Shared Epistemic Agency

To analyze the patterns of shared epistemic agency while prototyping, we used ONA (Tan et al., 2022). Building on ENA (Shaffer, 2017), ONA constructs directed network models that account for the interactive, interdependent, and temporal nature of collaboration, but also the order of events in collaborative processes. ONA can model the order of events in collaboration by concurrently measuring the actions people respond with and what actions they respond to.

In ONA, network nodes correspond to codes; edges correspond to the frequency with which codes co-occur within the same window of discourse, where each window is defined by a set number of turns of talk. To represent the sequence in which codes appeared, ONA uses a "broadcast" model, where the code someone responds to (ground) is placed at the apex of a triangle, and the code someone responds with (response) is placed at its base. To facilitate interpretation, the dark chevrons inside the triangles indicate the direction of the connection from ground to response.

For example, in Figure 3, between codes A and C, the thicker and more saturated triangle with a chevron represents how often this unit of analysis responded to code C with code A. In other words, code C is in the common ground, and code A is the response. Similarly, the thinner and less saturated triangle between A and C represents how often this unit of analysis responded to code A with code C. The dark chevron pointing toward A from C helps viewers identify that A is more often a response to C than the other way around. Between any pair of codes, if there is a bidirectional connection, the chevron only appears on the side with stronger connections. This helps viewers differentiate heavier edges in cases such as between codes A and C, where the connection strengths from both directions are similar. If the connection strengths are identical between two codes, the chevron will appear on both edges.

Node size is proportional to the number of occurrences of that code as a response to other codes in the data, with larger nodes indicating more responses. The colour and saturation of the circle within each node are proportional to the number of self-connections for that code, that is, when a code appears in both the response and ground of a given window. Coloured circles that are larger and more saturated reflect codes with more frequent self-connections. For example, Figure 3 indicates that approximately 50% of responses made with code C were responding to code C. The location of the directed network in the low-dimensional space is indicated by the point. This point closely corresponds with the centre of mass of the network. The directed edge weights of individual ONA networks can be averaged, and this average network can be summarized by a mean point in the space. The networks that follow are averaged networks for different groups, and the square points indicate the average position of their networks in the space. Brackets on the squares represent 95% confidence intervals.

ONA networks are created following the same algorithm as ENA save that ordered co-occurrences are measured (Bowman et al., 2021). That is, the algorithm passes a moving window of fixed size over the data, counts the co-occurrences between codes within the window for each unit of analysis, and represents networks of co-occurrences as high-dimensional vectors. A dimensional reduction via singular value decomposition (SVD) is performed on the collection of vectors to produce low-dimensional representations of each network known as ONA scores—each unit of analysis has a corresponding network and ONA score. Units of analysis can be compared in the low-dimensional space visually via network graphs and statistically in terms of their scores. In this study, each combination of unique speaker and phase was considered a unit of analysis for ENA and subsequent regressions for a total *N* of 27; the data was grouped by team and phase to count co-occurrences between the codes in Table 2, and the window size was four turns of talk.

3.4 Regression Analysis

To statistically test for differences between teams in terms of the patterns of codes in their discourse, we conducted regression analyses on the ONA networks. These models regressed the ONA scores on the first two dimensions of the reduced space, which account for the largest amount of variance in the data, on categorical variables for team and phase. The team variable indicated whether a given ONA score was from a participant in the Engineer, Product Designer, or Service Designer Team; the phase variable indicated whether the ONA score was from the first, second, or third phase of the design session as indicated by the tSSNA analysis.

In this study, ONA scores were nested within participants—that is, each participant had three ONA scores, one corresponding to each phase. Accounting for this kind of nesting typically requires mixed-effects regression analysis (Snijders & Bosker, 2011); however, tests of the intraclass correlation coefficient (ICC) for the nesting of observations within participants suggested that the nested structure of this data was not significant (Janssen et al., 2011). Therefore, we proceeded with a fixed-effects

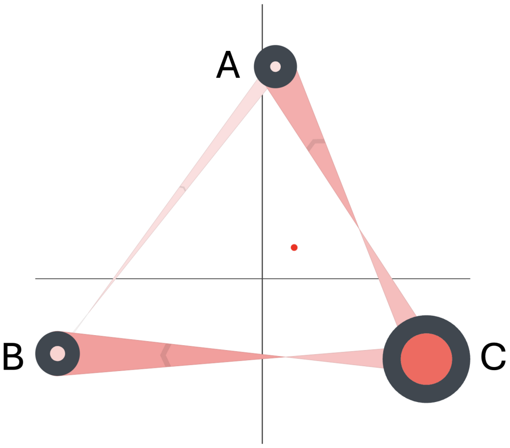


Figure 3. Example ONA network.

Table 3. Summary of regression analysis comparisons. Main effects in orange; contrasts in blue.

Team	Phase 1	Phase 2	Phase 3	
Engineering	RQ2	RQ2	RQ2	RQ1
Product Design	RQ2	RQ2	RQ2	RQ1
Service Design	RQ2	RQ2	RQ2	RQ1

regression analysis (McNeish & Kelley, 2019). For each model, we also tested for interactions between the team and phase variable.

For RQ1, the outputs of interest were the model estimated means for each team—that is, whether there were significant differences among the ONA scores for each team; for RQ2, the outputs of interest were the model estimated means for different combinations of team and phase (contrasts). Here, we compared the means of the same team across time-phases and different teams within each phase. See Table 3 for a visual explanation. Due to the presence of interactions between categorical variables within these models, we estimated the means for each comparison using the estimated marginal means (`emmeans`) package in R, rather than comparing the corresponding regression coefficients (Lenth et al., 2023). The `emmeans` package automatically adjusts p-values using the Tukey method to account for the family-wise error of multiple tests—e.g., testing for differences between each phase within a given role. To estimate the strength of any significant differences, we calculated effect size for differences between means using Cohen's d (Cohen, 1988), where the mean differences were taken from the model estimates.

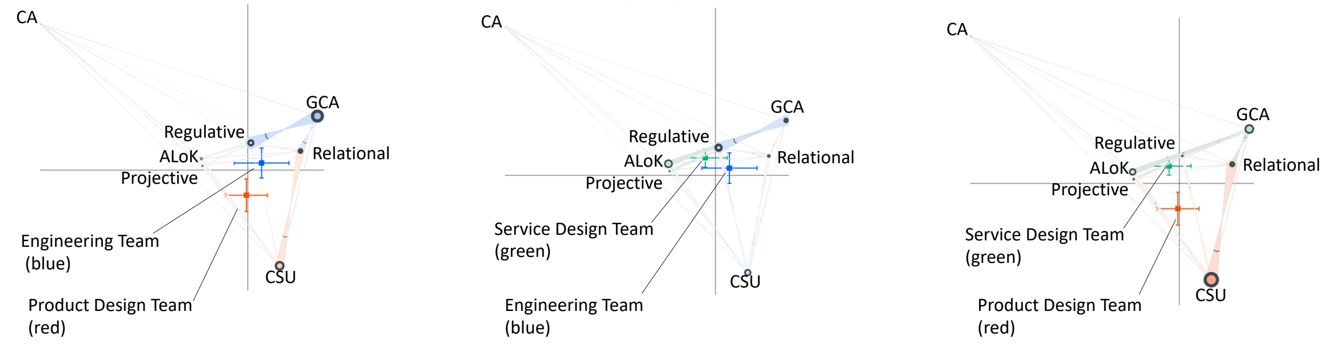
4. Results

4.1 RQ1

4.1.1 ONA for Shared Epistemic Agency

Figure 4 shows the ONA network comparisons between each pair of teams in terms of the shared epistemic agency. The X-axis distinguishes between connections among CA, ALoK, and Projective on the left versus GCA, Relational, and CSU on the right. The Y-axis distinguishes between connections to CSU at the bottom and between GCA and CA at the top. However, notice that while connections to CA are more extreme on both dimensions, those connections are weak in all group comparisons, suggesting that they did not play a significant role in distinguishing between the groups. Thus, we consider connections among GCA, Regulative, and Relational to be the most distinguishing connections on the positive side of the Y-axis.

Table 4 shows the main effects for team on each dimension of the ONA space. These effects were calculated from regression models that included the position on the relevant dimension as the outcome and categorical variables for team, phase, and their interaction. For each team-wise comparison, there is at least one significant difference. Members of the Engineering Team were significantly lower on both dimensions than members of the Product Design Team: $t(24) = 2.52$, $p < 0.05$, $d = 0.496$ along the X-axis and $t(24) = 5.46$, $p < 0.05$, $d = 1.49$ along the Y-axis. The Engineering Team members were also significantly higher along the X-axis than the Service Design Team members: $t(24) = 4.26$, $p < 0.05$, $d = 0.79$. Finally, the Product Design Team members were significantly higher on the Y-axis than the Service Design Team: $t(24) = -7.10$, $p < 0.05$, $d = -2.1$. Figure 4a shows the mean network comparison between the Engineering Team (blue) and the Product Design Team (red). The Engineering Team shows stronger connections between CGA and Relational, GCA and Regulative, and self-connections



(a) Engineering and Product Design Teams.

(b) Engineering and Service Design Teams.

(c) Product Design and Service Design Teams.

Figure 4. Subtracted graphs for shared epistemic agency.

Table 4. Main effects for team (shared epistemic agency).

Contrast	Dimension	Estimate (Mean Difference)	Std Error	df	t	$p^{\dagger}$	$d^{\dagger\dagger}$
Engineering – Product Design	X	0.270	0.107	24	2.520	**0.048***	0.496
	Y	0.530	0.097	24	5.470	$<$ **.001****	1.493
Engineering – Service Design	X	0.448	0.105	24	4.265	**0.001****	0.792
	Y	−0.127	0.095	24	−1.341	0.387	
Product Design – Service Design	X	0.178	0.102	24	1.737	0.212	
	Y	−0.657	0.092	24	−7.104	$<$ **.001****	−2.122

† Reported p-values have been adjusted for family-wise error using Tukey's method.
†† d-values are only reported for statistically significant differences.

to GCA. The GCA code has a leading role with stronger connections to Relational and Regulative. In contrast, the Product Design Team made stronger connections from Relational to and stronger self-connections to CSU. These differences reflect how engineers and product designers bring their different problem-solving approaches to KC's practice. The research of Goldberg and colleagues (2017) indicates that engineers prioritize functionality and testing, whereas product designers emphasize aesthetics and prefer sketches as tools for design and communication. Furthermore, it has been reported that engineers tend to engage in linear problem-solving, while product designers tend to engage in non-linear problem-solving. Additionally, Yu and colleagues (2018) reported that "Interaction Designers" who studied product design were characterized by their activities to create ideas individually and engage in long discussions to examine all of those ideas, regardless of whether the task was technical or open-ended. Based on this prior research, we can infer that engineering teams that quickly developed activities to refine their ideas were able to make rapid decisions on functionality and improve their ideas through verification. Product design teams are presumed to have thoroughly focused on creating shared concepts of the wallet's exterior within the team, despite engaging in rapid prototyping. This characteristic is supported by a statistically significant difference ($p < 0.001$, $d = 1.49$) along the Y-axis, where CSU, which shows creating shared understanding, is contrasted with other codes.

Figure 4b shows the mean network comparison between the Engineering Team (blue) and the Service Design Team (green). The Engineering Team made stronger connections between GCA and Regulative and stronger connections overall to Relational and CSU. GCA plays a distinctive role, with stronger connections from GCA to Regulative. The Service Design Team made stronger connections from GCA to ALoK and Projective. In addition, they made stronger self-connections to ALoK. From a statistical perspective, although significant differences were observed on the X-axis, the magnitude of these differences was smaller than other comparisons between engineers and product designers or service designers and product designers. Additionally, on the Y-axis, which contrasts CSU with other codes for building shared understanding, no significant differences were observed. In other words, the difference between engineers and service designers lies in the fact that engineers are connected to nodes related to the restructuring of ideas and other shared epistemic agencies. In contrast, service designers are connected to nodes related to information acquisition and other shared epistemic agencies. This aligns with prior research on engineers and the definition of service design, which highlights that engineers prioritize functional verification (Goldberg & Malassigné, 2017), and service designers, who focus on human-centred and comprehensive design (Stickdorn et al., 2018).

Figure 4c shows the mean network comparison between the Product Design Team (red) and the Service Design Team (green). The Product Design Team made stronger connections from Relational to CSU and stronger self-connections to CSU. The Service Design Team made stronger connections among GCA, ALoK, and Projective and self-connections to GCA. GCA tended to precede ALoK more, and Projective tended to precede GCA more. Along the Y-axis, which contrasts CSU for building shared understanding with other codes, the Product Design and Service Design Teams were significantly different, with a relatively large effect size of $d = -2.12$. This difference suggests that the product designers thoroughly engaged in creating shared concepts of the wallet's appearance among themselves. The difference between the two groups was also evident in the information-gathering process. Service designers are characterized by their process of connecting idea improvement from information gathering. In contrast, product designers are characterized by their approach to information gathering, which is based on creating a shared concept. The research of Goldberg and colleagues (2017) also notes that product designers have a user-centric characteristic, which aligns with the user-centric and holistic design approach of service design (Stickdorn et al., 2018). In other words, despite both teams prioritizing users, their problem-solving methods differed.

4.2 RQ2

4.2.1 tSSNA for Idea Improvement

Figure 5 shows the similarities and differences of participants' activities in terms of their tSSNA results. In Figure 5, the X-axis shows time; the Y-axis shows TDC. The results illustrate the continuous fluctuations in the TDC values of all teams, meaning each team consistently evolved their ideas for the entire duration of the study. All teams initially exhibited high scores and frequent oscillations in TDC. Variability decreased overall between minutes 7 and 12 and began to increase again afterwards. Beginning around minute 20, TDC values decreased, while the variability of TDC remained relatively stable.

We used repeated decays in the TDC score of each team to distinguish phases and proceed with the ONA analysis. For each team, the first phase extends from the starting point to approximately 10 minutes; the second phase extends from approximately 10 minutes to approximately 27 minutes; the third phase extends from approximately 27 minutes to the end of the sessions.

These three phases illustrated how the discussions of each team shifted. All teams fluctuate from low to high TDC in Phase 1. Here, team members were engaged in user interviews. Interviewers needed various words to seek the user's needs, as reflected in the relatively high TDC scores. In Phase 2, the fluctuations of these teams are still drastic. However, it was the trend that the TDCs were lower than the fluctuations in Phase 1. The Engineering Team scored the highest point at around 17 min in Phase 2. In the last phase, the lines of all teams fluctuated with low values until the end of their sessions. These graphs show that all teams continued to change their ideas with limited words toward the end of the session.

The Engineering Team concluded prototyping two minutes early, indicating earlier convergence and a shorter exploration phase. This result may be attributed to the characteristic of engineers to solve problems efficiently (Yu et al., 2018). In contrast, other teams worked with prototyping beyond the time limit. However, the TDC of these two teams did not change in the last few minutes. This is because they concentrated on creating prototypes instead of having discussions. This situation indicates a characteristic of project-based activities, in which participants focus on the creation of outcomes just before the time limit.

4.2.2 ONA for Shared Epistemic Agency over Time

The differences between the three teams in each phase are shown in the ONA graph of shared epistemic agency and statistical tests. Figure 6 shows these mean scores of the teams by phase in terms of shared epistemic agency. The statistical tests (Table 5) indicate that the teams tended to behave differently in Phases 2 and 3. In Phase 1 (red hues), there were no significant differences among the three teams. The graph suggests that all groups focused on activities based on ALoK and Projective. This shows that each team began their activities by gathering information while keeping their project goals in mind, regardless of their field, revealing similarities in the collaborative problem-solving approaches of designers. In Phase 2 (blue hues), statistically significant differences were found among all teams. The Engineering Team differed from the Product Design and Service Design Teams on both dimensions, tending to focus more on GCA, Relational, and CSU. These results are consistent with previous studies (Goldberg & Malassigné, 2017), indicating that engineers prioritize functionality and focus on testing it. They demonstrate that engineers quickly decided on wallet functionality and concentrated on improving their ideas through testing. These results confirm that the findings suggested in Figure 4 and Table 4 were already evident in Phase 2, providing more empirical evidence. The Product Design Team differed from the Service Design Team along the Y-axis, focusing more on GCA, Relational, and CSU. These differences in Phase 2 are also influenced by the fact that the Service Design Team is continuing to gather information. It also suggests that the product designers have decided that they have gathered sufficient information and moved on to creating a common concept for the team. Finally, in Phase 3, the Service Design Team differed from the Engineering Team and the Product Design Team along the Y-axis, tending to focus more on GCA in the final phase of their process. The product designers still created their common concept even in the last phase. This suggests that they were not satisfied with their concept until the last phase, as Scardamalia and Bereiter (2014) described the characteristics of designers' idea improvement. However, based on Goldberg and Malassigné (2017), we can interpret that product designers and engineers adopted different approaches: product designers spent time integrating individual ideas into a cohesive group

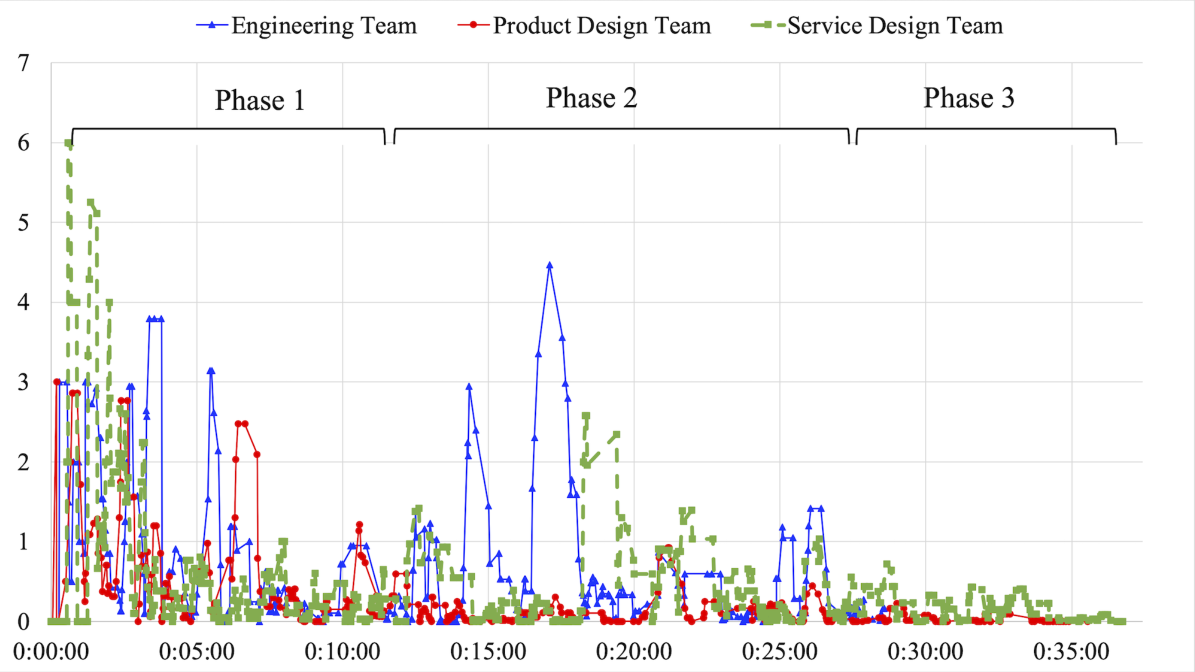


Figure 5. tSSNA graph of TDC versus time for each team.

concept regarding what their wallet should be like, whereas engineers quickly decided on what functions the product should have and then focused on improving those functions. It is noteworthy that the mean point of the engineers moved from Phase 2 toward the CSU direction, and there is a significant difference along the Y-axis between the mean points of the engineers and the service designers. Previous research (Yu et al., 2018) suggested that engineers tend to solve problems linearly. However, our results confirmed that engineers engage in non-linear problem-solving, returning from improving the constructed common understanding to building shared understanding. This may be influenced by societal changes or shifts in educational curricula that are beginning to incorporate non-linear problem-solving approaches such as human-centred design, design thinking, and prototyping into engineering.

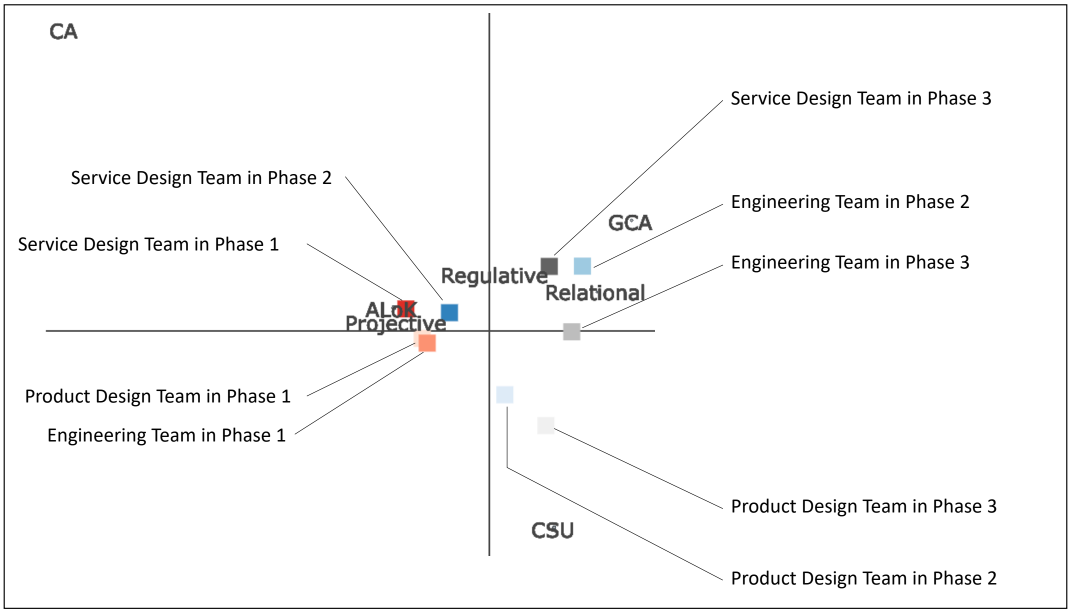


Figure 6. Mean ONA scores of each team by phase in terms of shared epistemic agency.

Table 5. Contrasting teams by phase: shared epistemic agency (statistically significant differences only).

Contrast	Phase	Dimension	Estimate	Std Error	df	t.ratio	p.value
Engineering – Product Design	2	X	0.591	0.187	24	3.16	**0.011***
		Y	0.979	0.169	24	5.803	$<$ **.001****
	3	Y	0.714	0.18	24	3.958	**0.002****
Engineering – Service Design	2	X	1.012	0.187	24	5.415	$<$ **.001****
	3	Y	−0.498	0.169	24	−2.95	**0.018***
Product Design – Service Design	2	Y	−0.624	0.156	24	−3.998	**0.001****
	3	Y	−1.212	0.169	24	−7.181	$<$ **.001****

Table 6. Contrasting phases within teams: shared epistemic agency (statistically significant differences only).

Team	Contrast	Dimension	Estimate	Std Error	df	t.ratio	p.value
Engineering	Phase1 – Phase2	X	−1.181	0.187	24	−6.321	$<$ **.001****
		Y	−0.586	0.169	24	−3.475	**0.005****
	Phase1 – Phase3	X	−1.1	0.187	24	−5.885	$<$ **.001****
	Phase2 – Phase3	Y	0.5	0.18	24	2.772	**0.028***
Product Design	Phase1 – Phase2	X	−0.629	0.173	24	−3.635	**0.004****
		Y	0.429	0.156	24	2.745	**0.029***
	Phase1 – Phase3	X	−0.942	0.187	24	−5.038	$<$ **.001****
		Y	0.664	0.169	24	3.933	**0.002****
Service Design	Phase1 – Phase3	X	−1.091	0.173	24	−6.306	$<$ **.001****
	Phase2 – Phase3	X	−0.759	0.173	24	−4.389	**0.001****

To confirm that the differences between teams in each phase statistically indicate changes in each team's process, we performed statistical tests on the differences between phases within the same team and found that each team showed variety in their processes over time (Table 6). The Engineering Team began by focusing on ALoK, then transitioned to GCA, and ended by focusing more on GCA and CSU. Differences were statistically significant between Phases 1 and 2 on both dimensions, Phases 1 and 3 along the X-axis, and Phases 2 and 3 along the Y-axis. The Product Design Team focused on ALoK in Phase 1 and moved to CSU in Phases 2 and 3. Differences were statistically significant between Phases 1 and 2 on both dimensions, and Phases 1 and 3 on both dimensions. However, there are no statistical differences between Phases 2 and 3. The Service Design Team followed a similar trajectory to the Engineering Team, maintaining a focus on ALoK in Phases 1 and 2 and shifting to GCA in Phase 3. The differences were statistically significant between Phases 1 and 3 along the X-axis and Phases 2 and 3 along the X-axis. These statistical results support the phase-specific characteristics between teams interpreted in the previous paragraph.

5. Discussion

This study proposed introducing prototyping as a way to help students engage in KC practices, even if they are unfamiliar with design-mode thinking, and a novel combination of techniques to understand how KC practices occur during prototyping. Moreover, we examined the prototyping process in disciplinary contexts from the KC perspective, focusing on design-mode thinking and idea improvement. The study builds upon previous research by Ohsaki and Oshima (2023), addressing two limitations: (1) not considering the different epistemological backgrounds of design teams and (2) not examining how KC practices change over time. To address these limitations, this study applied a combination of learning analytics techniques: tSSNA and ONA with the coding scheme—shared epistemic agency for design-mode thinking. The research questions focused on how the KC practices of engineers, product designers, and service designers differ during prototyping and whether these differences change over time.

Regarding our first research question—How do the KC practices of engineers, product designers, and service designers differ during prototyping?—we examined similarities and differences in shared epistemic agency. In terms of shared epistemic agency, Figure 4 and Table 5 show that the Engineering Team tended to focus more on GCA, the Service Design Team tended to focus more on ALoK, and the Product Design Team tended to focus on CSU. GCA is the final stage of epistemic actions for

KC. Hence, the results indicate differences in the level of KC they were able to attain. However, we cannot evaluate the quality of the teams in terms of KC based only on these results because these graphs aggregated entire activities. It could be that some teams did not focus on GCA overall, but still integrated it as part of their process at different times.

Regarding our second research question—Do these differences change over time? If so, how?—we divided team activities into three phases based on the patterns of discourse. In terms of idea improvement, our tSSNA analysis found fluctuations in the TDC values of all teams and higher TDC values at the starting points of their activities than at the end (Figure 5). Specifically, the first phase was the most active. In the second phase, we can see high TDC scores at various points. In the last phase, all teams showed low TDC scores that fluctuated until the end of the prototyping sessions. This result suggests that teams used a variety of phrases early in the session, and then the diversity of language used decreased, although they continued to change their ideas until the end of their activity. These observed activities align with the principles of ideal KC practices (Scardamalia, 2002) and previous studies of KC practice in classrooms (Ohsaki & Oshima, 2019, 2021). Furthermore, the transitions in the diversity of key phrases show that participants discussed their ideas divergently at first—as indicated by highly fluctuating TDC scores in the first phase—and then discussion converged—as indicated by lower and less variable TDC scores—toward the end of the sessions. Divergent thinking and convergent thinking are critical characteristics of design thinking (Goldschmidt, 2016).

The ONA analysis for the shared epistemic agency (Figure 6 and Table 6) shows that the activities of the Engineering Team and the Service Design Team moved from ALoK to GCA, while the Product Design Team moved from ALoK to CSU. In other words, the Service Design Team was not characterized with GCA in the aggregative network, but we confirmed they reached GCA in the analysis over time. In Phase 1, all teams worked on user interviews and began their activities by gathering information, which was equivalent to alleviating the lack of knowledge as an initial step in collaborative problem-solving. During Phase 2, the Service Design Team continued to work on eliminating the lack of knowledge by conducting user interviews, similar to Phase 1. The Engineering Team made the most progress, discussing advanced functions and exteriors beyond shared understanding. In contrast, the Product Design Team focused on building a common understanding among team members, such as deciding whether to build a prototype individually or as a team. In Phase 3, the Product Design Team continued confirming a shared understanding of their product, while the Engineering Team remained in the GCA stage, with a slight shift toward CSU as they evaluated their product. Although the Service Design Team was also in the GCA stage, they considered additional features, such as incorporating magnets into their design. The biggest difference in the whole activity between the Product Design Team and the Engineering and Service Design Teams was that the Product Design Team discussed the details, such as their image of the fashion brand and colours, before deciding on the concept. This contrast was not found in prior work (Ohsaki & Oshima, 2023), which compared only engineering and product design teams. These results suggest that supporting the creation of concepts is important, especially for students who get lost in too-detailed discussions before deciding on a concept. In our data, the Engineering Team created their concept the quickest and reached GCA the fastest. The Service Design Team spent much time conducting user interviews, but they decided on their concept quickly and reached GCA. On the other hand, the Product Design Team continued creating their concept and did not reach GCA.

These results suggest two scaffolding approaches for KC practices. The first approach is to show learners the nonlinear problem-solving process, which includes gathering information, creating shared concepts, and evaluating and improving ideas. In KC, since it is important for learners to demonstrate epistemic agency, activities are not regulated in detail, such as the information-gathering stage or the concept creation stage, allowing trial and error. In KC, even in learning, participants need to engage in authentic KC. Approaching authentic KC without understanding the problem-solving process is like setting sail without a map, which unnecessarily raises the barrier to participation for beginners in KC practice. The three teams analyzed in this study all began their activities by gathering information while keeping the project in mind. Even for beginner participants in KC practice, where learners need to choose when to engage in an activity, which activity to engage in, and how to engage in it, presenting them with a range of possible activities that may arise throughout the project serves as a road map to guide their journey in the practice. Repeating KC practices through rapid prototyping activities, which involve a series of steps in a short period, is effective in helping participants become familiar with KC. This study showed that even when group outcomes are completed, participants may spend a significant amount of time on a single activity they prioritize during the session, resulting in a reduced proportion of KC activities focused on improving shared ideas. Educators should take this insight into account and check during the session whether a shared concept is being created or whether activities are being conducted to revise the concepts. If concept convergence is not occurring, educators should provide prompts to help participants become aware of this.

The second approach involves introducing initiatives to help educators and learners recognize the characteristics of each field, thereby facilitating smooth activities among interdisciplinary teams. Our results showed that the changes in ideas followed similar trends among teams, and all teams continued to revise their ideas throughout the process. However, from the epistemic agency perspective, the characteristics of each field were clearly reflected in the actions. Understanding these differences in characteristics and their content reduces the risk of conflict during interdisciplinary collaboration. The previous study analyzing interdisciplinary teams of engineers and designers reported that participants were surprised by the differences in each other's activities and the terms they used (Goldberg & Malassigné, 2017). Furthermore, our study also pointed out the importance of ensuring sufficient time for mutual understanding within. Incorporating interdisciplinary team activities into general classrooms with fixed class times may be an effective way to facilitate authentic collaboration. To make these activities more effective, educators need to identify pivotal points for focused support by conducting short-term activities, such as rapid prototyping within each disciplinary team, and clarifying their characteristics from the KC perspective, as in this study.

6. Conclusion

This study analyzed the KC practices of Engineering, Product Design, and Service Design Teams during prototyping activities to support learner engagement in complex collaborative problem solving using design-mode thinking. In summary, the advanced learning analytics techniques proposed in this study, including tSSNA and ONA, were effective for evaluating KC as a process, not as an outcome. Our analysis approach revealed distinct patterns in shared epistemic agency across the three teams. Identifying such differences helps clarify target areas for promoting interdisciplinary KC and improving teacher support. Furthermore, understanding participants' tendencies in KC practices makes it possible to determine specific strategies for drawing learners unfamiliar with collaborative creative activities into KC processes.

Through an analysis of the whole process and a phase-based analysis based on differences in the changing of ideas, we conclude that the differences between the Engineering, Product Design, and Service Design Teams in KC practice during prototyping are as follows: (1) the engineers tended to focus more on generative actions, and they demonstrated efficient problem-solving, progressing most rapidly to the stage of improving their own shared ideas; (2) the product designers tended to respect individual ideas and spend time building shared understanding; (3) the service designers, guided by their user-centred principles, tended to alleviate their lack of knowledge through user interviews, but they also quickly reached the stage of improving their own shared ideas. While all designers aimed to build better solutions to problems, the characteristics of their collaborative problem-solving differed. If they work together without awareness of these differences, their collaboration could carry the risk of conflict. However, through the analysis in this study, we were able to identify their specific priorities and tendencies. Hence, we could design scaffolding in advance if they engage in interdisciplinary work.

From these findings, our study has three specific implications for designing KC practice.

Attending to disciplinary differences. Our study highlights the design processes of the three disciplines from the KC perspective, making it possible to identify the characteristics of each discipline, such as which viewpoints take the most time and which viewpoints lead to other actions. Identifying these differences suggests that educators might be able to use these results to target discipline-specific interventions in the design process.

Timely teacher intervention to guide concept creation. It is important to support shared concept creation, especially for students who become overly focused on activities before establishing a clear concept. Based on our study, educators may be able to support students in reaching the stage of generative action by confirming their progress in concept design at the middle phase. It would also be helpful to show students examples of possible activities, including creating shared concepts, improving their ideas, and employing non-linear problem-solving processes, to plan their activities.

Setting a short activity duration to encourage the sharing of incomplete ideas. Given that all teams in our study completed their prototypes, our results suggest that a short activity duration can help students present their uncompleted ideas and may assuage their worries about imperfect products. Our results suggest that prototyping, which enhances the iterative process and allows incomplete and messy outcomes, supports learning KC. These results align with prior research showing that people who feel anxious in an environment of uncertainty are able to learn from their mistakes through simple prototyping (Gerber & Carroll, 2012).

Our study has several limitations. First, we examined only one design context that designs and prototypes "a wallet for the user." Thus, the results are limited by the sample of data we had. In future work, we will expand our study to include more teams and improve the generalizability of our findings. Second, this study focuses on engineering design, product design, and service design in Japan. The difference between engineers and designers has attracted international attention. Although this study confirmed similarities with studies conducted in Denmark and the United States (Goldberg & Malassigné, 2017; Yu et al., 2018), we have not directly compared the groups in Japan with groups from other countries using our methods. Future studies will work on international comparisons. Third, our study used a novel combination of tSSNA and ONA to examine design processes. However, it did not directly compare these techniques to other potentially useful combinations of techniques, such as SSNA and ENA. While our methodological choices are theoretically justified, it remains possible that combining these other, simpler techniques may do just as well at describing salient differences between teams and between teams over time. In our future work, we plan to systematically compare different combinations of SSNA, ENA, tSSNA, and ONA to find the most effective and parsimonious method for data of this kind.

Despite these limitations, this study develops a new bridge between design studies and learning as KC. Recently, there has been increasing discussion of KC practice and the need for educators and researchers to support learners in complex and ill-formed problem-solving. To involve and support learners who may avoid failing and representing incomplete ideas, this study analyzed the prototyping practices of three teams from a KC perspective. Through this investigation, this research reveals promising design principles for optimizing the learning environment to foster KC. Moreover, by combining network analyses, we found that these sessions can support idea improvement and highlight differences in the processes of different communities of practice. The proposed analysis approach may help educators to design more effective pedagogical experiences tailored to learners from different educational and professional backgrounds.

Declaration of Conflicting Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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