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Efforts on Capturing Prototyping and Design Activity in Engineering Design Research

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Abstract

Prototyping is one of the core activities of product development, and understanding prototyping should therefore be of great interest to both researchers and professionals. Yet, when considering the many definitions of prototype in engineering design literature, prototyping is not fully understood. Aimed at engineering design researchers, this article compares various efforts that attempt to understand prototyping by capturing design activity. This comparison is used as a basis for discussing various methods, tools and resources available to the engineering design researcher, as well as the contexts of the studies (i.e. laboratory, intermediate and in-situ studies).
From this comparison of studies on capturing prototyping in engineering design research, the authors identify that many of the studies have relatively low robustness—i.e. the ability to generalize and apply the findings to a wider engineering design context. The authors argue that the factors that contribute to the relatively low robustness of these studies are a combination of the methods, tools and resources (including participants) available to the researchers for both capturing and analyzing the data. Therefore, the authors conclude that to increase the robustness of research on prototyping in engineering design—i.e. ensure that relevant, realistic and representative data is captured—more suitable tools and methods are needed.

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Keywords: capturing; prototyping; design activity; engineering design; robustness

1. Introduction and Background

Prototyping is one of the core activities of Product Development (PD) [1], and has been a relevant topic in industry and academia for decades [2]. Wall et al. [3] state that "prototyping is one of the most critical activities of new product development". Consequently, understanding prototyping is of key interest to the engineering design researcher—yet Camburn et al. [4] state that "prototyping may be simultaneously one of the most important and least formally explored areas of design".

1.1. Motivation and Aim

Though prototyping is a core activity in PD, it is not fully understood by the engineering design research community—as shown by Jensen et al. [1]. Hence, there is motivation and need for further investigating the use of prototypes and prototyping in PD. There are many efforts on capturing prototyping in engineering design research, with the underlying assumption that there are insights to be gained from observing and (retrospectively) analyzing the activity. This article aims to compare various efforts on capturing prototyping and design activity in engineering design research, and to discuss what steps can be taken in order to increase the robustness of studies capturing prototyping.

1.2. Defining Prototypes and Prototyping

Underlining the statement from Camburn et al. [4], Wall et al. [3] highlight the importance of prototyping without actually defining the activity, but rather by describing what defines a prototype. Similarly, Eppinger and Ulrich [5] define prototyping simply as the activity of producing prototypes.

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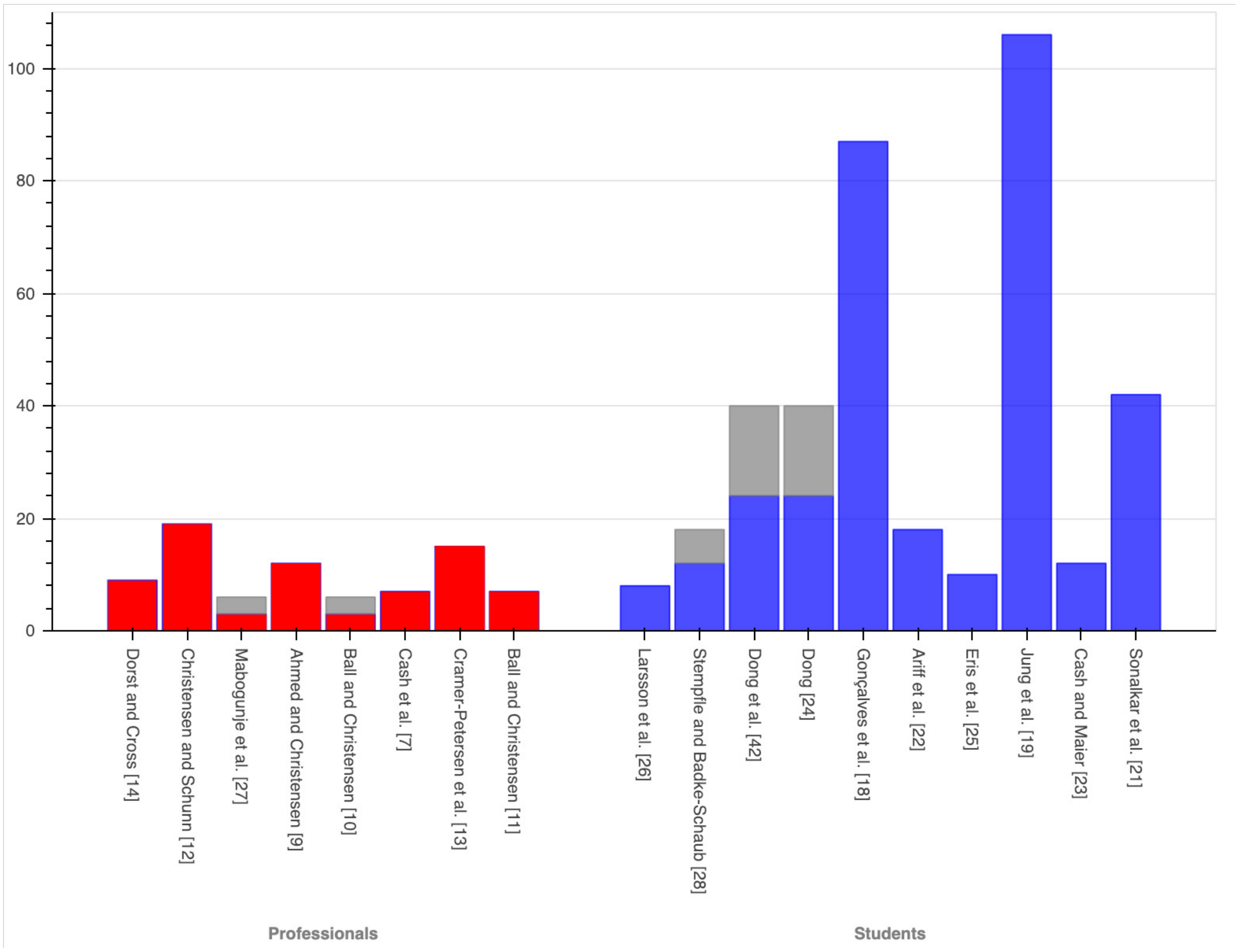

Fig. 1. Number of participants used in literature studying design activity in a professional (left, shown in red) and educational setting (right, shown in blue).

However, the authors argue that prototyping is more than the activity of producing prototypes—it is a learning activity that contributes in generating information, skills and knowledge for the designers involved [6]. Therefore, in this article, the term *prototyping* is used to describe the activity of exploring various concepts and ideas during the PD process. This includes designing, building and testing various aspects of concepts and ideas, which often creates output in the form of prototypes. While there are many definitions of prototypes in engineering design literature—e.g. the 19 definitions listed by Jensen et al. [1]—this article uses the term *prototype* as tangible output from the activity of prototyping. Following this definition, prototypes can be physical artefacts, but can also be virtual—e.g. Computer Aided Design (CAD) models or drawings.

1.3. Scope and Structure

Ideally, to understand all aspects of prototyping, it would be very helpful to the engineering design researcher to be able to fully capture the prototyping activity in all possible formats, including what the designer is thinking and conceptualizing, as well as the artefacts that are created during the activity. There are many contributions in engineering design literature that reference 'design activity' without explicitly using the word prototyping—yet, the authors still consider some of these activities prototyping.

This article presents a brief overview of contexts for capturing prototyping, before discussing the types and number of participants, as well as the methods, tools and resources available for capture and analysis. This article identifies that robustness—the ability to generalize and apply the findings to a wider engineering design context—is relatively low for some of the studies, and argues that this a result of the methods, tools and resources available to the engineering design researchers. Based on these findings, the article presents a discussion on possible steps and approaches for increasing the robustness of future studies.

2. Contexts for Capturing Prototyping

Cash et al. [7] identify different contexts of empirical engineering design research, ranging from studying activity in design practice to studying activity in laboratories, with intermediary studies as somewhat of a middle ground between the two former—e.g. "Experimental studies using practitioners, varying little from normal practice" [7]. These three contexts vary in realism and controllability. Experiments in the laboratory are controllable (and constrainable), allowing for detailed examination of a single, less complex phenomenon, while observing practitioners in-situ allows for higher degrees of realism. Intermediate experiments allow for a compromise between controllability and realism, as these experiments often use practitioners as participants. Cash and Culley [8] emphasize the importance of conducting both practice and laboratory studies, aiming to draw from strengths of both the detailed examinations in a laboratory and the realism of studying practice. They state that "The role of experimentation serves to support both theory building and theory testing – both of which must be considered in order to develop meaningful understanding."

While in-situ observations of design activity offer greater realism regarding both participants and nature of the task, these studies often have few—less than 20, sometimes even less than 10—participants [7,9–15]. The number of participants in laboratory studies also vary from larger—i.e. more than 20 participants—controlled and semi-controlled experiments [16–21] to smaller design sessions considering a handful of students [22–28].

In the laboratory, the availability of and proximity to students make it possible for researchers to capture larger data sets. The use of students as substitutes for professional participants leads to questioning if the studies capture realistic data. Findings from Salman et al. [29] include that there is no significant difference in code quality when using software engineering students as substitutes for software engineering professionals when doing relatively small programming tasks, and correspond with findings from Höst et al. [30]. However, Smith and Leong [31] capture significant differences between students and professionals doing simulated design tasks in engineering design, stating that "real differences exist between the processes used by the student groups and the processes used by the professional groups". Consequently, there is not enough evidence to state that students are a fully realistic substitute for practitioners—especially in the context of PD.

Fig. 1 is included to show the number of participants used in the studies considered in this section, and differentiates the studies using professional participants (shown in red) from the studies using student participants (shown in blue). The grey columns represent where the studies report ambiguous or indefinite numbers, e.g. "3 groups of 4-6 students", which implies that there were minimum 12 and maximum 18 student participants [28].

3. On Robustness of Studies Capturing Prototyping

There are two trends that are apparent in Fig. 1; many of the studies have low sample sizes—e.g. when using practitioners in their 'natural' context—and the many of the studies are using student participants. The use of low sample sizes makes it difficult to generalize findings because of low statistical power and potential inflated effect size. While the observations found in the studies may be valid for the context they were observed in; the use of low samples sizes implies that the observations may not be reproducible or generalizable to a wider PD context.

Many of the studies in Fig. 1 arguably capture highly relevant data for engineering design research—yet assessing the applicability of the studies is difficult due to the use of small sample sizes and few investigated prototypes. Moreover, it is also difficult to assess the degree of realism of the studies extensively using student participants. The authors have identified this difficulty in assessing applicability and realism of studies capturing prototyping as a shortcoming of current PD research. To understand how to remedy this shortcoming, and to increase the robustness of research on prototyping in early-stage PD, this article considers the following RQ: "What factors are causing the relatively low level of robustness of research on prototyping in early-stage PD?"

4. Investigating the Methods, Tools and Resources Required for Capturing Prototyping

To attempt to answer the RQ, the task and duration of current studies must be considered—as must the methods, tools and resources required for capturing and analyzing the activity.

4.1. Capturing Methods of In-Situ and Laboratory Experiments

The method chosen in many of the in-situ studies is protocol studies, a method proving high fidelity and detailed transcripts of what the participants (often in teams) say and do [9–12,14,15]. Protocol studies are exhaustive in both data gathering and analysis, and the protocols are often recorded from short meetings or sessions. There are efforts where the listed durations are longer, e.g. efforts by Ball and Christensen [11] and Christensen and Schunn [12], where protocols from nine hours of design meetings are presented. In a more extreme example of high fidelity capture, Cash et al. [7] present 12 weeks of design activity captured on video (using multiple cameras for redundancy) of 7 practitioners doing regular design activity at their desks in a company.

In the laboratory experiments, elaborate infrastructure is often in place, allowing for systematic capture of video and audio [11,16,19,20,23,26,27,32]. For instance, to aid researchers in capturing design activities, the Design Observatory was built at Stanford University [32], based on the work from Tang and Leifer [33,34]. Tang and Leifer [33,34] focused on fast iterations of "observe—analyze—intervene", with the underlying assumption that design activity could be observed and then forcefully changed (by facilitators) to improve performance. The Design Observatory was developed to provide researchers with various tools and technologies for conducting design observations, and the observatory addressed two fundamental questions; "what are designers doing, thinking, and experiencing when they do design and how can we [Red. the design community] improve their performance?" [32]. Though built around the idea of "observe—analyze—intervene", the facility focused more on observation than intervention and although it was built without choosing a specific capturing technology, video was eventually the preferred format for capturing the activity [35].

4.2. Tools for Capturing Activity

Notably, there are various technologies being explored to aid in capturing design activities. [36] suggest various alternatives for capturing activity using other technologies than cameras, e.g. using GPS trackers or wireless signals of connected devices. Similarly, Sjöman and Steinert [37] present a Radio Frequency Identification (RFID) based tool for sensing proximity in the design workspace, attempting to capture interactions through other means than cameras.

Through advances in both video recording and (digital) storage technology over the last decade, video capture has become a benchmark for capturing design activities in design observation [35,38]. In such sessions, multiple cameras and microphones record high fidelity images and audio, and this is often in stored large local storage systems. The sessions are often tuned towards particular activities in order to explore topics such as the prototyping media used by the design team [16,21,39] or to capture team dynamics and emotion [20]. Törlind et al. [35] stress that video and audio quality are important factors to consider, yet emphasize that the main limitation of design observation through video recordings is resources required to analyze the captured data.

4.3. Tools for Analyzing Captured Activity

While doing video recordings require relatively low effort from researchers, the material is often manually coded by multiple coders that go through and interpret the data [11,16,19,20,23,26,27,32]. Manual video coding is a laborious task [35,40,41], and these sessions are therefore relatively short—often less than 60 minutes per team. However, there are exceptions where the studies are more longitudinal, e.g. studies by Cash et al. [7] and Ball and Christensen [11]—both these studies include professionals doing design activity captured on video for many hours, which would have required a monumental effort in (manual) analysis. These studies are notably high in both realism and relevance.

There are indeed efforts that try to tackle the resource problem of analysis in design observations and protocol studies. Dong [24] and Dong et al. [42] present Latent Semantic Analysis (LSA) as a way of analyzing protocols, Wulvik et al. [40,43] present a method for preliminary analysis of longer video recordings captured from observational studies called Temporal Static Visualizations (TSV). This method uses the DTRS11 dataset [11] for pre-screening larger video recordings in order to find interesting events. Moreover, Wulvik et al. [41] have published an article on various tools and technologies for capturing body language in engineering design, aiming to exemplify other technologies that can be used in addition to manual video coding.

5. Discussion

From comparing the various studies on capturing prototyping in engineering design research, the authors argue that the factors that contribute to the relatively low robustness of these studies are a combination of the methods, tools and resources (including participants) available to the researchers for both capturing and analyzing the data. However, it is apparent that this relatively low robustness does not come from a lack of effort from the engineering design researchers, as many of the methods and tools used in the considered literature are labor-, cost- and resource-intensive, e.g. Cash et al. [7].

The comparatively low robustness is further underlined by Lloyd et al. [44], who state that "A major problem with a [sic.] much of what goes under the general rubric of 'Design Research' is a poorly defined relationship to empirical evidence".

However, there are various efforts that attempt to increase the robustness of engineering design research. One such initiative is the datasets created for DTRS, a biennial effort where design researchers can share the same dataset for comparing and improving their methods [44]. One of these datasets is presented by Ball and Christensen [11] for the 11th Design Thinking Research Symposium (often referred to as the 'DTRS11 dataset'). In this dataset, they "[…] recorded 150+ hours of video footage of the activities of a professional design team (with 7 team members) from a Scandinavian User Involvement Department".

Törlind et al. [35] state that a substantial hindrance for observation-based design research is the effort required to do thorough analysis of the data. One solution for overcoming this hindrance is to use computational analysis methods for (automated) audio and visual classification, e.g. TSV as shown by Wulvik et al. [43], to identify points-of-interest in larger datasets, and thus reducing the effort required for analysis. Such analysis tools should be further researched. Beyond purely focusing on improving the analysis methods, there is also the possibility to explore other inputs as supplementary data for analysis, e.g. body language [41].

Beyond the studies that attempt to capture design activity itself, there are various studies that specifically focus on the output of the activities—e.g. designers' logbooks [45] or sketches [18,25,46-50]. Many of the empirical studies specifically targeting prototypes use them as deliverables, either in university courses or in experiments [51-54]. Here, prototypes are either photographed or physically collected through the experiments for later analysis—e.g. "[…] pictures were taken again to capture the designs during these demonstrations. These pictures were the 'after testing' data. The pictures were captured from many different angles to obtain sufficient details of the cars, so that if necessary, the cars could be reconstructed." [55]. Notably, while many of these studies have more than 20 participants—e.g. Youmans [53] with 120 participants—they are all using student participants, and not practitioners.

To supplement such efforts, the authors suggest that researchers should also investigate physical prototypes, as these artefacts provide a tangible and available starting point for further investigation into prototyping, and capturing physical artefacts is more available (and is potentially less labor-intensive) than capturing the prototyping activity itself.

6. Conclusion

This paper has investigated several studies that capture prototyping in an engineering design context, and has identified that the robustness of many of these studies is relatively low—mainly due to the extensive use of small sample sizes and use of student participants. This paper argues that the root cause of the comparatively low robustness can be traced back to the limitations of the tools, methods and resources available to the PD researchers. Therefore, the authors conclude that to increase the robustness of research on prototyping in engineering design—i.e. ensure that relevant, realistic and representative data is captured—more suitable tools and methods are needed. This is further emphasized by Cash [56], who states that "Lack of ability to use these research methods effectively prevents researchers from addressing important research questions and developing subsequent meaningful theory or robust scientific knowledge". This is a bold statement, and one that must be addressed in order to further strengthen and advance engineering design research.

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References

[1] L. S. Jensen, A. G. Özkil, and N. H. Mortensen, "Prototypes in engineering design: Definitions and strategies," in *14th International Design ConferenceInternational Design Conference*, 2016, pp. 821–830.

[2] J. S. Gero and U. Lindemann, *Human Behaviour in Design 05*. Key Centre of Design Comp & Cogntn, 2005.

[3] M. B. Wall, K. T. Ulrich, and W. C. Flowers, "Evaluating prototyping technologies for product design," *Res. Eng. Des.*, vol. 3, no. 3, pp. 163–177, Sep. 1992.

[4] B. A. Camburn *et al.*, "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment," p. V005T06A033, Aug. 2013.

[5] S. D. Eppinger and K. T. Ulrich, "Product design and development," *1995*, 1995.

[6] D. A. Schön, *The Reflective Practitioner: How Professionals Think in Action*. Basic Books, 1983.

[7] P. Cash, B. Hicks, S. Culley, and F. Salustri, "Designer behaviour and activity: An industrial observation method," in *DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011*, 2011, pp. 151–162.

[8] P. Cash and S. Culley, "The Role of Experimental Studies in Design Research," in *The Routledge Companion to Design Research*, RoutledgeFalmer, 2015.

[9] S. Ahmed and B. T. Christensen, "An In Situ Study of Analogical Reasoning in Novice and Experienced Design Engineers," *J. Mech. Des.*, vol. 131, no. 11, p. 111004, 2009.

[10] L. J. Ball and B. T. Christensen, "Analogical reasoning and mental simulation in design: two strategies linked to uncertainty resolution," *Des. Stud.*, vol. 30, no. 2, pp. 169–186, Mar. 2009.

[11] L. J. Ball and B. T. Christensen, "Designing in the wild," *Des. Stud.*, vol. 57, pp. 1–8, Jul. 2018.

[12] B. T. Christensen and C. D. Schunn, "The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design," *Mem. Cognit.*, vol. 35, no. 1, pp. 29–38, 2007.

[13] C. L. Cramer-Petersen, B. T. Christensen, and S. Ahmed-Kristensen, "Empirically analysing design reasoning patterns: Abductive-deductive reasoning patterns dominate design idea generation," *Des. Stud.*, Oct. 2018.

[14] K. Dorst and N. Cross, "Creativity in the design process: co-evolution of problem–solution," *Des. Stud.*, vol. 22, no. 5, pp. 425–437, Sep. 2001.

[15] J. W. Kan and J. S. Gero, "Acquiring information from linkography in protocol studies of designing," *Des. Stud.*, vol. 29, no. 4, pp. 315–337, 2008.

[16] J. A. Edelman, "Understanding radical breaks: media and behavior in small teams engaged in redesign scenarios," Doctoral Thesis, Stanford University, 2011.

[17] G. Goldschmidt and P. A. Rodgers, "The design thinking approaches of three different groups of designers based on self-reports," *Des. Stud.*, vol. 34, no. 4, pp. 454–471, Jul. 2013.

[18] M. Gonçalves, C. Cardoso, and P. Badke-Schaub, "How far is too far? Using different abstraction levels in textual and visual stimuli," in *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia*, 2012.

[19] M. F. Jung, N. Martelaro, and P. J. Hinds, "Using robots to moderate team conflict: the case of repairing violations," in *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*, 2015, pp. 229–236.

[20] M. F. Jung, "Engineering team performance and emotion: Affective interaction dynamics as indicators of design team performance," Doctoral Thesis, Stanford University, 2011.

[21] N. Sonalkar, K. Jablokow, J. Edelman, A. Mabogunje, and L. Leifer, "Design whodunit: The relationship between individual characteristics and interaction behaviors in design concept generation," in *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2017, p. V007T06A009–V007T06A009.

[22] N. N. A. Ariff, P. Badke-Schaub, Ö. Eris, and S. S. S. Suib, "A framework for reaching common understanding during sketching in design teams," 2012.

[23] P. Cash and A. Maier, "Prototyping with your hands: the many roles of gesture in the communication of design concepts," *J. Eng. Des.*, vol. 27, no. 1–3, pp. 118–145, 2016.

[24] A. Dong, "The latent semantic approach to studying design team communication," *Des. Stud.*, vol. 26, no. 5, pp. 445–461, Sep. 2005.

[25] Ö. Eris, N. Martelaro, and P. Badke-Schaub, "A comparative analysis of multimodal communication during design sketching in co-located and distributed environments," *Des. Stud.*, vol. 35, no. 6, pp. 559–592, Nov. 2014.

[26] A. Larsson, P. Törlind, A. Mabogunje, and A. Milne, "Distributed design teams : embedded one-on-one conversations in one-to-many," presented at the Common Ground International Conference 2002 : 05/09/2002 - 07/09/2002, 2002, pp. 604–614.

[27] A. Mabogunje, O. Eris, N. Sonalkar, M. Jung, and L. J. Leifer, "Spider Webbing: A Paradigm for Engineering Design Conversations During Concept Generation," in *About Designing: Analysing Design Meetings, J. McDonnell, and P. Llyod, eds., Taylor & Francis, London, UK*, 2009, pp. 49–65.

[28] J. Stempfle and P. Badke-Schaub, “Thinking in design teams - an analysis of team communication,” *Des. Stud.*, vol. 23, no. 5, pp. 473–496, Sep. 2002.

[29] I. Salman, A. T. Misirli, and N. Juristo, “Are Students Representatives of Professionals in Software Engineering Experiments?,” in *2015 IEEE/ACM 37th IEEE International Conference on Software Engineering*, 2015, vol. 1, pp. 666–676.

[30] M. Höst, B. Regnell, and C. Wohlin, “Using Students as Subjects—A Comparative Study of Students and Professionals in Lead-Time Impact Assessment,” *Empir. Softw. Eng.*, vol. 5, no. 3, pp. 201–214, Nov. 2000.

[31] R. P. Smith and A. Leong, “An Observational Study of Design Team Process: A Comparison of Student and Professional Engineers,” *J. Mech. Des.*, vol. 120, no. 4, pp. 636–642, Dec. 1998.

[32] K. Carrizosa, Ö. Eris, A. Milne, and A. Mabogunje, “Building the design observatory: a core instrument for design research,” in *DS 30: Proceedings of DESIGN 2002, the 7th International Design Conference, Dubrovnik*, 2002, pp. 37–42.

[33] J. C. Tang and L. J. Leifer, “An observational methodology for studying group design activity,” *Res. Eng. Des.*, vol. 2, no. 4, pp. 209–219, 1991.

[34] J. Tang and L. Leifer, “Observations from an Empirical Study of the Workspace Activity of Design Teams,” in *Proceedings of the First International ASME Conference on Design Theory and Methodology*, 1989.

[35] P. Törlind, N. Sonalkar, M. Bergström, E. Blanco, B. Hicks, and H. McAlpine, “Lessons learned and future challenges for design observatory research,” in *DS 58-2: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 2, Design Theory and Research Methodology, Palo Alto, CA, USA, 24.-27.08. 2009*, 2009.

[36] K. Thoring, R. M. Mueller, and P. Badke-Schaub, “Technology-supported design research,” *80*, vol. 11, 2015.

[37] H. Sjöman and M. Steinert, “Applying Sequential Pattern Mining to Portable RFID System Data,” 2016.

[38] P. Törlind, “A Framework for Data Collection of Collaborative Design Research,” in *Guidelines for a Decision Support Method Adapted to NPD Processes*, Paris, France, 2007, pp. 453–454.

[39] J. Edelman, A. Agarwal, C. Paterson, S. Mark, and L. Leifer, “Understanding radical breaks,” in *Design Thinking Research*, Springer, 2012, pp. 31–51.

[40] A. Wulvik, M. B. Jensen, and M. Steinert, “Temporal Static Visualisation of Transcripts for Pre-Analysis of Video Material: Identifying Modes of Information Sharing,” *Anal. Des. Think. Stud. Cross-Cult. Co-Creat. Leiden CRC Press. Francis*, 2017.

[41] A. Wulvik, J. Erichsen, and M. Steinert, “Capturing Body Language in Engineering Design–Tools and Technologies,” in *DS 85-1: Proceedings of NordDesign 2016, Volume 1, Trondheim, Norway, 10th-12th August 2016*, 2016.

[42] A. Dong, A. W. Hill, and A. M. Agogino, “A Document Analysis Method for Characterizing Design Team Performance,” *J. Mech. Des.*, vol. 126, no. 3, p. 378, 2004.

[43] A. Wulvik, A. Menning, and M. Steinert, “A computational approach to expose conversation dynamics in engineering design activities,” in *DS 87-2 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 2: Design Processes, Design Organisation and Management, Vancouver, Canada, 21-25.08. 2017*, 2017, pp. 101–110.

[44] P. Lloyd, J. McDonnell, and N. Cross, “ANALYSING DESIGN BEHAVIOUR: THE DESIGN THINKING RESEARCH SYMPOSIA SERIES,” *Proc Int Assoc. Soc. Des. Res. IASDR07*, p. 11, 2007.

[45] H. McAlpine, P. Cash, and B. Hicks, “The role of logbooks as mediators of engineering design work,” *Des. Stud.*, vol. 48, pp. 1–29, Jan. 2017.

[46] A. Acuna and R. Sosa, “The Complementary Role of Representations in Design Creativity: Sketches and Models,” in *Design Creativity 2010*, Springer, 2011, pp. 265–270.

[47] O. Atilola, M. Tomko, and J. S. Linsey, “The effects of representation on idea generation and design fixation: A study comparing sketches and function trees,” *Des. Stud.*, vol. 42, pp. 110–136, Jan. 2016.

[48] J. J. Shah, N. Vargas-Hernandez, J. D. Summers, and S. Kulkarni, “Collaborative Sketching (C-Sketch) — An Idea Generation Technique for Engineering Design,” *J. Creat. Behav.*, vol. 35, no. 3, pp. 168–198, Sep. 2001.

[49] M. C. Yang, “Observations on concept generation and sketching in engineering design,” *Res. Eng. Des.*, vol. 20, no. 1, pp. 1–11, Mar. 2009.

[50] V. Viswanathan and J. Linsey, “A study on the role of expertise in design fixation and its mitigation,” in *ASME 2012 international design engineering technical conferences and computers and information in engineering conference*, 2012, pp. 901–911.

[51] S. P. Dow, K. Heddleston, and S. R. Klemmer, “The efficacy of prototyping under time constraints,” in *Proceedings of the seventh ACM conference on Creativity and cognition*, 2009, pp. 165–174.

[52] C. Kriesi *et al.*, “Distributed Experiments in Design Sciences, a Next Step in Design Observation Studies?,” in *DS 80-2 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 2: Design Theory and Research Methodology Design Processes, Milan, Italy, 27-30.07. 15*, 2015.

[53] R. J. Youmans, “The effects of physical prototyping and group work on the reduction of design fixation,” *Des. Stud.*, vol. 32, no. 2, pp. 115–138, Mar. 2011.

[54] D. Mathias, D. Boa, B. Hicks, C. Snider, P. Bennett, and C. Taylor, “Design variation through richness of rules embedded in LEGO bricks,” in *DS 87-8 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 8: Human Behaviour in Design, Vancouver, Canada, 21-25.08. 2017*, 2017, pp. 099–108.

[55] V. Viswanathan, O. Atilola, N. Esposito, and J. Linsey, “A study on the role of physical models in the mitigation of design fixation,” *J. Eng. Des.*, vol. 25, no. 1–3, pp. 25–43, Mar. 2014.

[56] P. Cash, “Developing theory-driven design research,” *Des. Stud.*, vol. 56, pp. 84–119, May 2018.