Understanding Innovation

Christoph Meinel
Larry Leifer *Editors*

# Design Thinking Research

## Interrogating the Doing

Springer

# Understanding Innovation

**Series Editors**

Christoph Meinel, Potsdam, Germany
Larry Leifer, Stanford, USA

"Everyone loves an innovation, an idea that sells." Few definitions of innovation are more succinct. It cuts to the core. Yet in doing so, it lays bare the reality that selling depends on factors outside the innovation envelope. The "let's get creative" imperative does not control its own destiny. Expressed another way, in how many ways can we define innovation? A corollary lies in asking, in how many ways can the innovative enterprise be organized? For a third iteration, in how many ways can the innovation process be structured? Now we have a question worth addressing. "Understanding Innovation" is a book series designed to expose the reader to the breadth and depth of design thinking modalities in pursuit of innovations that sell. It is not our intent to give the reader a definitive protocol or paradigm. In fact, the very expectation of "one right answer" would be misguided. Instead we offer a journey of discovery, one that is radical, relevant, and rigorous.

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Editors

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## Interrogating the Doing

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# Foreword

Since the founding of the d.school at Stanford University in California and the School of Design Thinking at the Hasso Plattner Institute for Digital Engineering in Potsdam, the aim has been to complement the education of students through a practical, user-centered approach focused on real-life projects. Students from digital engineering and all other fields of study have the opportunity to learn design thinking methods for creating an impact through human-centered design. We are pleased to report that more and more education and research facilities have set about establishing similar programs—to the great benefit of their students. The value of the methodology has not just been apparent in campus settings. Design thinking has been adopted and practiced by individuals and organizations in increasing numbers as a powerful framework to foster innovation in products, services, and operations, and recently in the strategy and the creation of innovation cultures.

In parallel, the Hasso Plattner Design Thinking Research Program, a research initiative conducted jointly by Stanford University in California and the Hasso Plattner Institute for Digital Engineering in Potsdam, Germany, has been working with great effort to learn more about the approach. Researchers in North America and Europe have meanwhile conducted more than 130 research projects investigating, illuminating, and making sense of design thinking. Our understanding of the methodology has increased manifold, and we have a solid body of new knowledge on the characteristics and mechanisms of effective design thinking tools, team dynamics, and its application in various contexts.

In science as in business, radical innovation is often linked to collaboration between previously unconnected disciplines. A very recent example is cooperation with neuroscientists. Design thinking researchers leverage the newly developed research methodologies, approaches, and knowledge to foster new ideas and research in neurodesign emerging in both Stanford and Potsdam. In 2019, the Hasso Plattner Institute in Potsdam was the first to offer a neurodesign curriculum for its IT students. The course was co-designed and delivered in close collaboration with internationally recognized researchers from several countries and continents and illuminates the biological basis of creativity, collaboration, innovation, and human-centered design.

These recent developments demonstrate once again the fruitful research conducted by multidisciplinary teams in the area of design thinking research. One way of bringing the findings to innovators everywhere is through the book series *Design Thinking Research* published by Springer. The series presents a comprehensive collection of research studies carried out by scholars at both the Hasso Plattner Institute in Potsdam and Stanford University. In addition to providing the findings of the most recent projects, the 11th volume of the series, which you are now holding in your hands, again includes a historic perspective investigating the impact of Robert H. McKim's work on design thinking. This deep dive offers an additional way to gain a better understanding of how design thinking has come about.

The Design Thinking Research Program has cultivated a growing community on two continents and has influenced many others around the world. In doing so it has created a setting for the rich exchange between current doctoral candidates, alumni, researchers, and practitioners from diverse disciplines. Through collaboration and partnerships of many kinds, the Design Thinking Research Program brings new perspectives, insights, and lasting value not only to the program and its related researchers but to design thinking itself and the growing community of design thinkers. We invite you to reach out and encourage innovators and researchers to work together, to experiment, and thereby to broaden and deepen our practice and understanding of design thinking and how it can benefit the challenges—both large and small—facing our world today.

Palo Alto, CA Hasso Plattner

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# Introduction

**Larry Leifer and Christoph Meinel**

**Abstract** Extensive research conducted by the Hasso Plattner Design Thinking Research Program (HPDTRP) has yielded valuable insights on why and how design thinking works. Researchers have identified metrics, developed models and conducted studies that are featured in this book as well as in the previous volumes of this series. The HPDTRP research projects each have a problem-orientation strategy. The human-centered mindset is critical to design action, but biases are also inherently present. The solution is to UN-bias our thinking using an UN-design-thinking approach. The first part of the book, "**Effective Design Thinking Training and Practice**", is dedicated to research projects exploring new and improved ways to train and apply design thinking. The second part of the book, "**Understanding Design Thinking Team Dynamics**," compiles research projects that put the Design Team in the petri dish. In the third part of the book "**Design Thinking in Practice—New Approaches and Application Fields**" a variety of application scenarios for application of design thinking are showcased. The fourth part "**Emerging of Neurodesign**" also functions as an approach. Neurodesign is a novel field of research, education and practice that emerges as a cross-disciplinary initiative. Original research seeks to yield deep insights into the nature of human needs and the protocols that design thinking researchers might apply to achieve "insights" versus "data." Researchers study the complex interaction between members of multi-disciplinary teams, with special regard to the necessity of creative collaboration across spatial, temporal, and cultural boundaries. They design, develop, and evaluate innovative tools and methods that support teams in their creative work. The research projects address questions of why structures of successful design thinking teams differ substantially from traditional corporate structures and how design thinking methods mesh with traditional engineering and management approaches.

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# 1 UN-Learning, UN-Biasing, UN-Assuming, UN-Covering, UN-Thinking

We selected the volume title *Interrogating the Doing* because that is the foundation of our work in the field of Design Thinking. Asking simple, direct questions allows us to challenge established frameworks and reimagine both frameworks and processes. The supposition is that the answers to three questions do indeed enable change, this in the form of disruption.

WHAT did you DO?—WHY did you DO THAT?—WHAT did you learn from the DOING?

In the pursuit of breakthrough innovation, we have long realized that one must learn from what one does. Most, if not all, disciplines exhibit tendencies that focus on "learning". After a recent mission in ME310-Global and similarly in the project-based learning within the SUGAR network, we began asking those three questions.

The result was of course disruption. It is a given that all of us have biases, which influence our behavior. As students and faculty alike struggled to answer these questions, we were confronted with the reality that design is linked to our known and unknown biases. We encourage design thinkers therefore to develop a problem-oriented mindset and break free from accepted norms. In order to achieve this, designers must reevaluate five important mindset elements that are inherently subjective.

- UN-learn
- UN-bias
- UN-assume
- UN-cover (discover)
- UN-think

When problems appear, the historical value of designers and managers has been associated with their ability to swiftly recognize the problem, mobilize and solve it. The assurance of such action fulfills the general expectations of the world at large, and this prevailing behavior is further nurtured by urgencies found on the front lines of design practice and increasingly in the demand for applied research.

The Hasso Plattner Design Thinking Research Program (HPDTRP) redirects analytical and generative attention elsewhere, while re-appropriating the prevailing mindset when necessary. We find greater value in the development and nurturing of a problem-oriented mindset to best quell prevailing solution-fixation practices that continue to drive most disciplinary practices today. Our most recent challenge is to face the reality of solution-fixation in design thinking and to now introduce the power of UN-design-thinking and its many corollaries.

Through our engagement with UN-found problems, any tendency to solve is first suspended to better interrogate and reframe problems for the critical-user's gain. This temporary suspension of solution generation better allows for the development of a sustained user-centered mindset and all that we need to UN-do.

This problem-orientation strategy is now evident across 11 years of HPDTRP research-projects and demonstrates a viable tactic for all designers and managers. While both design thinking and design thinking research are of increasing interest to many people, we continue to uncover new features and phenomena that emerge from the human-centered mindset and its application in context-specific design operations. Human-centrism is a prerequisite for our design action, and proper problem-orientation is a requirement for generating meaningful and worthwhile design solutions. It is also biased, and we must now recognize the critical need to UN-bias our thinking and actions. This short overview is by far no comprehensive account, but it illustrates dimensions where the UN-design-thinking approach can be especially impactful.

## *1.1 UN-Learning*

The fruit of one of Larry Leifer's long conversations with John Seely Brown in the late 1980s—which Leifer never let go of—was Seely Brown's assertion that the hardes part of his management job at Xerox PARC was to "help his people UN-LEARN." John Seely Brown's tenure at Xerox PARC (Palo Alto Research Center) included his R&D software team's invention of the "Windows Operating System." One of the Stanford Center for Design Research's earliest PhD's, John Tang,[1] observed that the development team mediated team dynamics via "gestures." To their considerable regret, Xerox PARC never adequately embraced the graphical user operating system while Microsoft and Apple did. We know all too well that Microsoft and Apple are now two of the largest companies on the planet.

## *1.2 UN-Biasing*

Professor George Toye, Stanford's ME310-Global course co-instructor, has long focused on the student/designer's cognitive bias. At long last we are finally guiding design teams to uncover and recognize their biases and those of persons around them in the problem/solution spaces.

[1] John Tang: "Toward an understanding of the use of shared workspaces by design teams," PhD dissertation, 1989.

### 1.3 UN-Assuming

We have long encouraged engineering design teams to identify and challenge their assumptions. This is something that has been curiously lacking among engineering scientists, who tend to assume that theory will hold in their application context.

### 1.4 UN-Covering

Professor Mark Cutkosky, co-instructor for Stanford's ME310-Global course, is particularly fascinated with guiding design teams to "discover" new design requirements. This approach has long proven very effective, with distinctions made between intrinsic machine requirements versus extrinsic user/usage requirement.

### 1.5 UN-Thinking

One of our most frequently needed admonishments to designers of all ages and experiences is to "think less" and "do more". Yet again, we are in the space of UN-doing while what professionals typically do is: talk, talk, think, think. Now we challenge them to think less and do experimentation that is more active. There is a need to measure things and seek evidence to support (or disprove) one's thinking path.

These examples of UN-Design-Thinking clearly show how changes in mindset are possible. Many questions emerge. It is important that we make these distinctions actionable on a day-to-day, session-to-session basis. But how is this possible? Can an exceptional culture of extreme UN-Design-Thinking positively affect the prevailing culture of solution-fixation? And what would this look like?

There are a multitude of questions that we are confronted with in each design challenge. There can be a distinction for example between asking afresh "what are we really doing" versus pushing forward with familiar or pre-conceived solutions to recognizable but ill-identified problems. However, there is no clarity as to whether this is the best lens to tackle the challenge. Many designers introduce rewards to solve an issue. Unfortunately there is no consensus as to whether introducing rewards, for systematized statement-making and systematized design engagement, actually helps. Rewards may in fact generate new problems and exacerbate old ones.

Design research enables our ability to address these questions and others like them, with new metrics and a heightened awareness of the un-intended bias at the core pursuit of breakthrough innovation in business, government, and academia. It promises to also hold great value while navigating new creative possibilities by prioritizing human-centered problem formulation. To find greater resonance, design operations must feature human users at the center of (increasingly digitally supported) endeavors, including the creation of new products, services, processes, and systems.

## 2 Road Map Through This Book

With funding for the HPI-Stanford Design Thinking Research Program renewed, we rededicate ourselves to make the outcomes of our work more broadly known. Now in its eleventh program year, researchers from HPI and Stanford University have conducted a wide range of research projects on design thinking. This annual publication is a compilation of their findings, sharing outcomes, and arranged in four parts, that illustrate a comprehensive approach to design thinking research. At the beginning of this publication, you will again find a historic perspective. Building upon the creative thinking theories of Stanford educator John E. Arnold and Robert McKim's Need-Based Design Theory discussed in previous years, Julia von Thienen and Christoph Meinel investigate the theoretical foundations of design thinking—this time with a focus on Robert McKim's Visual Thinking Theories, "**Theoretical Foundations of Design Thinking. Part III: Robert H. McKim's Visual Thinking Theories**".

The first part of the book, "**Effective Design Thinking Training and Practice**", is dedicated to research projects exploring new and improved ways to train and apply design thinking. Included are examples that encompass both analog and digitally mediated endeavors. Projects that bridge the existing gap between research and practice are described. Chapters in this section develop tools for improving creative practice in terms. Examples include the literal composition of workspaces and tools for student learning.

In an effort towards bridging the gap between research and practice, the first chapter presents new research-based training methods for team-based design. In "**Designing as Performance: Bridging the Gap between Research and Practice in Design Thinking Education**," Jonathan Antonio Edelman, Babajide Owoyele, Joaquin Santuber, and Anne Victoria Talbot introduce training packages in the form of micro-interactions that can be articulated into warm-ups, drills, and exercises for training purposes. Findings from this research demonstrate the effectiveness of the approach for both students of design thinking practice, and coaches.

In the second chapter, "**Developing a Tool to Measure the Transfer of Design Practice from Training Contexts to Applied Contexts**," Adam Royalty, Helen Chen, Bernard Roth, and Sheri Sheppard present a study that investigates the influence academic contexts have on design thinking. Three general influences are revealed, under the headings Supports for Learning Design, Self-differentiation of Design, and Internal Responses.

In "**Using 'Space' in Design Thinking: Concepts, Tools and Insights for Design Thinking Practitioners from Research**," Martin Schwemmle, Claudia Nicolai, and Ulrich Weinberg derive practical implications from theory. Chapter three will thereby allow readers to better understand, reflect, and teach space in a design thinking context and support them in developing their own interventions or variations of the tools presented.

The fourth chapter "**Video Capture Interface Prototype**" by Lawrence Domingo, David Sirkin, and Larry Leifer describes the researchers' own design process in addressing an urgent teaching team's challenge by quickly prototyping a "critical experience prototype" to help students learn, use, and reuse a video-based design archiving system.

How to set up warm-up games in MOOC contexts? in the fifth chapter "**Razors for Arctic VIP Travelers: Using Warm-Up Games in MOOCs**," Karen von Schmieden, Lena Mayer, Mana Taheri, Hanadi Traifeh and Christoph Meinel explore warm-ups in MOOCs, displaying how to set up these visual, interactive games and their purpose.

The second part of the book, "**Understanding Design Thinking Team Dynamics**," compiles research project that put the Design Team in the petri dish. A close examination of the design team necessarily means that communication is a central parameter. Chapters investigate the building blocks of team dynamics.

In "**Design Team Performance: Context, Measurement, and the Prospective Impact of Social Virtual Reality**," Ade Mabogunje, Neeraj Sonalkar, Mark Miller and Jeremy Bailenson explore how virtual reality can be leveraged to construct and simulate different environments, such as to experiment on the effectiveness of teams in different design scenarios and to measure design performance.

In "**The Neuroscience of Team Cooperation versus Team Collaboration**," Stephanie Balters, Naama Mayseless, Grace Hawthorne, and Allan L. Reiss present a scientific approach for applying the methods of fNIRS hyperscanning to decode distinct qualities of team interaction with a specific interest in detecting states of inter-brain synchrony that correlate with the behavioral states of cooperation and collaboration.

In the third chapter "**10 Organizational Learning through a Process of Framing Orientations in Group Discourses**," Andrea Rhinow, Holger Rhinow, Claudia Nicolai, and Ulrich Weinberg investigate how organizational learning unfolds on the level of group discourses.

This section closes with a chapter titled "**Did It Have To End This Way? Understanding the Consistency of Team Fracture**." Mark E. Whiting, Allie Blaising, Chloe Barreau, Laura Fiuza, Nik Marda, Melissa Valentine, and Michael S. Bernstein present insight into the consistency of team fracture: a loss of team viability so severe that the team no longer wants to work together.

In the third part of the book "**Design Thinking in Practice—New Approaches and Application Fields**" a variety of application scenarios for application of design thinking are showcased. Various prototypes are introduced and show potential for advancement and enhanced awareness in a variety of fields.

In "**Design Thinking at Scale—A Multi Team Design Thinking Approach**," **Franziska Dobrigkeit, Ralf Teusner, Danielly de Paula, and Matthias Uflacker** present an approach to scale design thinking to multiple teams and implement the resulting ideas in follow-up projects ultimately converging into one project and product.

In the second chapter, Griffin Dietz, Jenny Han, Hyowon Gweon, and James A. Landay present the results of a grounded-theory analysis of classroom observations and in-depth semi-structured interviews with both students and educators. Their outcomes are condensed into "**Design Guidelines for Early Childhood: Computer Science Education Tools**."

In "**Towards a Theory of Factors That Influence Text Comprehension of Code Documents**," Patrick Rein, Marcel Taeumel and Robert Hirschfeld discuss and illustrate potential factors that influence the text comprehension of code documents.

In the final chapter, Parastoo Abtahi, Neha Sharma, James A. Landay, Sean Follmer investigate the tradeoffs of bodystorming techniques in the context of human-robot interaction design: "**Presenting and Exploring Challenges in Human-Robot Interaction Design through Bodystorming**."

The fourth part "**Emerging of Neurodesign**" also functions as an approach. Neurodesign is a novel field of research, education and practice that emerges as a cross-disciplinary initiative. In cooperation with neuroscientists, researchers of the HPDTRP leverage newly developed research methodologies, approaches and knowledge, which has resulted in an emergence of new ideas and research in neurodesign at both Stanford University and at HPI in Potsdam.

In "**NeuroDesign: From Neuroscience Research to Design Thinking Practice**," Jan Auernhammer, Neeraj Sonalkar, and Manish Saggar explore the gap between neuroscience research and design practice and how the emerging field of neurodesign can bridge this gap. Delving into the epistemology of design practice and the promise of neuroscience, the authors present the understanding and practice of learning as a key bridge between the two fields. Researchers explore the broader implication of learning in the framing of neurodesign and present a research agenda for further studies in the field.

In 2019, the Hasso Plattner Institute (HPI) offered a neurodesign curriculum for the first time. The objective of neurodesign as we pursue it is to explore synergies at the intersection of (1) neuroscience, (2) engineering and (3) design thinking · creativity · collaboration · innovation. In "**Neurodesign Live**" Julia P. A. von Thienen, Caroline Szymanski, Joaquin Santuber, Irene S. Plank, Shama Rahman, Theresa Weinstein, Babajide Owoyele, Matthias Bauer and Christoph Meinel share their insights into the development of a curriculum that quickly became more comprehensive than anticipated for this initial implementation phase. The chapter briefly summarizes input provided by neuroscientists and creative engineers from several countries and different continents, who contributed guest expert talks at HPI to help build a joint knowledge base. The major part of the chapter is a review of neurodesign projects that have emerged, often in collaboration with guest experts of the program. Overall, these projects indicate how intersections of neurodesign (1)–(2)–(3) open up a cornucopia of opportunities.

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# Theoretical Foundations of Design Thinking. Part III: Robert H. McKim's Visual Thinking Theories

**Julia P. A. von Thienen, William J. Clancey, and Christoph Meinel**

**Abstract** With his treatise "Experiences in Visual Thinking" first published in 1972, McKim delivers a milestone in the development of design thinking theory and practice. Building on creative thinking theories advanced by John E. Arnold before, McKim develops a comprehensive framework of creativity as embodied and embedded cognition. He elaborates on the role of the whole body for creative performance. In particular, he describes productive thinking as occurring during interactions with the world, where he specifically emphasizes benefits of prototyping activities. He sets forth a theory of representation systems, based on human sensory modalities (vision, hearing, touch etc.) and cognitive processing systems (such as language or mathematical processing). In each representation system, productive thinking is said to thrive on the triple activity of "perceive-think-act," which McKim elaborates for the case of visual thinking in terms of "seeing-imagining-idea sketching." To foster creative breakthroughs, a sophisticated use of multiple and varying representation systems is recommended. Overall, McKim covers in detail topics such as muscle tonus, emotion, attention, memory, perception, language, sleep and consciousness in relation to creativity. He also translates creativity theories into a creativity curriculum where opportunities for students to gain immersive experiences are considered at least as important as lecture inputs. Furthermore, McKim discusses creativity as embedded in the world and provides comprehensive recommendations for the design of places to facilitate creative work. Moreover, he coins the concept of "ambidextrous thinking," which is the immediate precursor to the concept of "design thinking" in Stanford's innovation education for engineers.

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This essay series on the theoretical foundations of design thinking takes a historical approach to clarify present-day design thinking practices. In particular, the essays explore concepts that played a crucial role in creativity education at Stanford Engineering, where the first official d.school as a university-based training facility for design thinking originated.

Today, design thinking appears as a highly practice-oriented approach to innovation at most training facilities. Notably, it emerged from rich theoretical bases—or certainly so at Stanford Engineering. One might say, when Stanford "exported design thinking culture" to many audiences around the globe, it was primarily an export of practices. The available theories were maintained mostly in-house, as "shared understandings of the locals," barely recognisable as a part of design thinking culture that could be exported as well. Yet, these theories are invaluable in helping design thinking practices become fully understandable and also applicable with greatest mindfulness and intentionality.

Against this background, it is a major purpose of this history series to make theories accessible, which informed design thinking developments at Stanford over multiple decades. The works of two Mechanical Engineering Professors at the institute, John E. Arnold and Robert H. McKim, are helpful starting points in this endeavour, because they introduced topics, theoretical frameworks and university courses with a clear legacy to present-day design thinking classes. In this sense, Bernie Roth—co-founder and Academic Director of Stanford's d.school—also recalls historical developments from his personal perspective.

> In a broad sense it started for me in August of 1962. That was when I first met John Arnold. At the time he was a professor of mechanical engineering and business at Stanford University. [...] In addition to creating and teaching project oriented courses, John consulted on problem solving and [...] organized special courses and workshops [...]. **The written materials from those workshops contain many of the concepts we now label as Design Thinking.** (Roth 2015a, p. 250f., original English manuscript, our emphasis)

One major course manuscript by John Arnold lay at the focus of part I and II in this history series. Under the headline of *Creative Engineering*, Arnold had provided sophisticated theories of creativity and innovation, as based on human needs (von Thienen et al. 2017).

Arnold had also invited world-renowned guest lecturers to his courses, such as the psychologists Joy Paul Guilford and Abraham Maslow, next to the philosopher Robert Hartman. Besides personal teaching in class, they contributed guest essays in the *Creative Engineering* course manuscript.

Robert H. McKim was John Arnold's first hire at Stanford. McKim served as a guest lecturer in the *Creative Engineering* seminar as well. His guest essay, in which he spelled out a design theory based on human needs, was the topic of part II in this history series (von Thienen et al. 2019).

Arnold's full *Creative Engineering* manuscript including all guest essays is made available with an introduction by Clancey (2016).

Beyond written materials, John Arnold and Robert McKim introduced lasting practices at Stanford Engineering. Bernie Roth continues in his personal recollections . . .

> The year I came to Stanford, John Arnold and Bob McKim started a program that they named Product Design. It was concerned with the function of products and also gave weight to its conception [ . . . ]. The Product Design program under Bob McKim's leadership incorporated a large dose [of] what was called need finding, which is essentially the same as what design thinkers call empathy, problem definition and point of view. There was always a big emphasis on prototyping and learning from failure in the program. (Roth 2015a, p. 251, original English manuscript)

In this chapter, part III of the history series, we discuss Robert McKim's book *Experiences in Visual Thinking* (1972), which reveals in a most lucid way how practices emerged from theory.

Experiences in Visual Thinking (EVT) is a surprising book in many regards. Upon first glance, it could be mistaken for the exercise book of a drawing class in art school. It contains many images and drawing exercises. However, upon reading, the book reveals itself as a design thinking fabric mill, in which key ideas from various origins—including especially John Arnold's *Creative Engineering* manuscript—are woven together, so as to form a coherent framework. And then, the framework is put into practice.

The overarching purpose of EVT is to train creative thinking.

> This is not a book about thinking; it is primarily a challenge to learn new thinking skills. An experiential approach is nothing less than mandatory here: no skill, whether it be in basketball, basketweaving, or thinking, can be acquired by passive reading. Skills can be acquired only by active and informed experience. (EVT, p. 4)

Thus, McKim complements his explanations of theory with dedicated practical exercises all throughout the book: the bridge between theory and practice is built right in front of the reader's eyes. Thus, in terms of educational practices, McKim endeavours a thorough shift towards immersive experiences in class. Discussions below will also show why McKim is rather sceptical of long verbal lectures in class, providing even more reasons for a pedagogical approach of immersive experiences in class, combined with only brief lecture or theory input. EVT invokes such a structure throughout—it will be familiar to present-day design thinkers, as design thinking education today follows a similar format.

Moreover, many of the exercises described by McKim will sound familiar to present-day design thinkers, such as the building of a "Spaghetti Tower," often used as an introductory task in design thinking education up to the present. This is McKim's description of the setup: "With 18 sticks of spaghetti and 24 inches of Scotch tape, construct the longest cantilever structure that you can" (EVT, p. 8). But why would it be a good idea to engage with the hands and rapidly create spaghetti tower prototypes?

In terms of special emphasis, EVT carefully explores the role of sensory processing for creative thought and communication, most prominently visual information processing. In terms of practices, this topic is omnipresent at design thinking facilities today. Design thinkers learn to “be visual” (Plattner et al. 2009), i.e. to readily express ideas in visual forms, not only by words. Design thinkers are encouraged to build and iterate prototypes rapidly as a means for rapid learning (Osann et al. 2020), and they “prototype for empathy” (d.school 2010, p. 33). In EVT, McKim spells out the theoretical basis of such practices, why and how they aid creative performance, what to expect and what not to expect of respective skills and interventions.

Given the rich theoretical and practical suggestions of EVT, the preparation of this part III chapter in the history series took a different form than in the cases of chapters before. Along with intensive reading and personal meetings between Robert McKim and William J. Clancey, this time we also tried using the content in practice. At the HPI, Julia von Thienen hosted a one semester university class for digital engineering master students, where EVT was read and exercises were tried live. In class, the content of EVT was also discussed in light of recent research, including social science and neuroscientific perspectives. Here, we found a great alignment and continuity of observations and messages that predominated from the publication of EVT up to present-day research outcomes. Our three lines of preparation—readings, personal exchange with the author of EVT, and the staging of EVT as a university class—equally inform this review of EVT as a milestone in design thinking theory development.

## 1 Robert H. McKim as an Artist of Integration and Practical Experimentation

Robert H. McKim, born September 24 in 1926, is a modest, humble man, with diverse interests in art, engineering, and psychology. Still active in his early 90s, he presents as an artist, surrounded by sculptures and drawings in his backyard studio. His stories of the past combine personal inventions, 1960s experiments in “psychedelic creativity,” and design pedagogy in the classroom and industry.

McKim is highly versed in various lines of theory, which he weaves together skilfully in EVT. Notably, he constructs theory in an artistic fashion, rather than as an act of bureaucratic stocktaking with ethnographic precision of who contributed which idea, when and why. McKim interprets other people’s theories and re-combines them intuitively. He sometimes presents the same theoretical idea repeatedly with slight variations, akin to the way in which painters explore one and the same theme in various paintings, trying out slight variations from one painting to another.

Many impulse streams come from John Arnold, whom McKim also recognizes as a major source of inspiration.

> My greatest debt is to the late Professor John E. Arnold, who not only suggested that I develop a visual-thinking course at Stanford (a course that has been a major testing ground for this book) but also influenced me by his pioneering efforts to educate productive thinking. (EVT, p. vii)

Regular references to John Arnold in subsequent discussions underpin his important influence. At the same time, it also becomes clear how McKim actively assimilates Arnold's theoretical frameworks. They are not treated as sacrosanct final formulations, but as malleable ideas of a colleague, friend and "teammate" to elaborate and build on. A good example in this passage is a research topic attributed to Arnold. McKim says Arnold's pioneering works were aimed at educating "productive thinking." However, Arnold himself rarely ever used this term. The headline Arnold used was "creative thinking." By contrast, the concept of "productive thinking" was prominently discussed by Gestalt theorists (cf. Wertheimer 1945), who provided their own, unique treatments of creativity under this headline. Even on a terminological level, McKim condenses various traditions of thought into a novel whole.

Next to Arnold's personal works and those of Gestalt theorists, the other guest essays in *Creative Engineering* also provide major sources of inspiration for McKim. One example is the essay of Joy Paul Guilford (1959/2016), which appears as a rather disjunctive part in the original *Creative Engineering* seminar manuscript. Guilford had undertaken factor analytic studies to identify independent skills that people would need for high-level creative performance, or intellectual performance in general. He had pioneered intelligence tests to measure people's abilities on various dimensions. McKim follows up on this approach and digs deeper. Have there also been factor analytical studies on visual thinking capacities? Yes, indeed, McKim finds such pieces of theory.

> L. L. Thurstone, a pioneer in the development of psychological tests, writes: "As a result of factorial studies, during the last two decades, we no longer speak of visualizing as a single trait. We know some seven or eight primary factors that are quite distinct and which are all related to visual thinking." (EVT, p. 12)

If there are indeed independent visual thinking capacities, maybe they should also be assessed and trained independently in visual thinking education at Stanford. McKim experiments with a number of exercises akin to psychological tests (Fig. 1).

The endeavour to translate creativity theory into practical in-class exercises leads McKim also to consider Gestalt theory. One exercise he suggests is depicted in Fig. 2, showing only a couple of dots and small lines. However, for humans familiar with camels, the few dots suggest a specific "Gestalt" or resolution of the ambiguous stimulus material: There appears to be a camel.

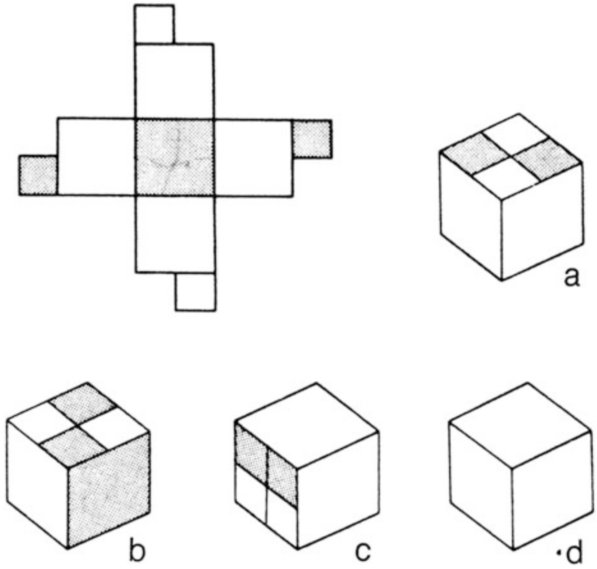



**Fig. 1** Some of the exercises, which McKim invokes to assess and train visual thinking skills, build on psychometric works concerning factors of the intellect, in particular regarding visual thinking capacities. In the exercise depicted here, students should find out that the figure shown in the upper left corner can be folded into shape *a* (image from EVT, p. 15)

As spectators seeing the dots in Fig. 2, we can witness our own tendency to interpret ("view") the scene in light of prior knowledge. Easily and automatically, we use this knowledge and familiar solutions to find answers for open questions. What is this? A camel. Constructing a novel solution (figure, Gestalt) is much more effortful and time-consuming. Could the dots be showing something else? Creativity—finding non-obvious solutions—is effortful. Note how it might be helpful to team-up with people who hold different viewpoints, people who have different experiences than we do. In the extreme case, they might not even know camels. Clearly, such persons with different viewpoints and experiences could help explore alternative interpretations. Maybe they can see a different Gestalt given the same ambiguous information.

In these and other cases, McKim advances John Arnold's legacy in a self-determined, imaginative and productive way. Starting off from Arnold's intention to incorporate factor-analytic studies in creativity education for engineers, McKim uncovers further theoretical resources, such as Thurstone's psychometric works, and the treatises of Gestalt theorists. McKim turns theoretical discussions into practical exercises and uses them to reflect on creative performance in general.

**Fig. 2** Some visual thinking exercises used by McKim are inspired by Gestalt psychology. An example is shown here, where observers typically detect a pattern in the dots and see a camel (image from EVT, p. 12)

## 2 Experiences in Visual Thinking: Training Basic Skills for Creativity

EVT comes in four major parts. First, there is a long introduction with theoretical frameworks. Then, McKim specifically trains visual thinking skills of the readers, in the order of (i) seeing, (ii) imagining and (iii) idea sketching. Sketching is trained from rough to refined, from 2D sketching to 3D model building.

Repeatedly, McKim emphasises that the overarching purpose of his book is to train creativity. Yet, many of the exercises he proposes are common-practice at art schools, to train the students' craftsmanship rather than highest levels of creativity, let alone innovation. For instance, this is one of the exercises McKim suggests for training perspective drawing:

> 1. Convergence is most easily observed in large objects (no smaller than a table). Select several large, horizontal, rectangular objects to draw in perspective.
> 2. To the best of your ability, make a small, freehand perspective sketch of one of the objects in the center of a sheet of newsprint.
> 3. Using a different-colored marker, extend all converging horizontal lines in your drawing to a vanishing point [ . . . ].
> 4. Repeat with several other objects. (EVT, p. 73)

How does this craftsmanship training in EVT facilitate creativity? It provides tools for creative thinkers to become most flexible and versatile in imagining novel solutions and getting them out into the world. McKim continues regarding perspective-drawing techniques:

> The visual thinker uses perspective primarily to record forms that exist only in his imagination. Consequently, in the next two exercises concentrate on seeing convergence, not in actual objects, but in rectangular solids conceived in your imagination and captured graphically. (EVT, p. 73)

Overall, a large number of training exercises in EVT appear to be directed at developing the students' technical skills, as they convey tools of the trade. How these training exercises relate to McKim's overall creativity education goals can be better understood in relation to his courses offered at Stanford Engineering. Here is an excerpt from the Stanford University Bulletin with courses and degrees 1962–1963. McKim offers the courses 112a, b and c:

> **112a. Rapid visualization**—Freehand perspective and shading techniques for rapidly visualizing design concepts. Emphasis is upon two-dimensional visual communication which is lucid and quickly executed. [ . . . ]
>
> **112b. Introduction to Product Design**—A study, through lecture and laboratory exercises, of the human values in product design [ . . . ]. Laboratory exercises consist of developing simple product concepts three-dimensionally, with rapid model making techniques. Prerequisite: 112a. [ . . . ]
>
> **112c. Product Design and Presentation**—A continuation of 112b, with emphasis shifted to the influence of mass production methods and materials upon design. Presentation techniques for communicating design concepts to others, especially to nondesigners, will also be considered. (Stanford University 1962, p. 114)

These descriptions sound familiar to present-day design thinkers, insofar as "rapid visualisation" is being the precursor to "rapid prototyping," which nowadays is considered a hallmark of design thinking. As Verganti et al. (2019) highlight in a discussion of design thinking approaches around the globe, the concept of design thinking has some "different interpretations" (p. 1); however a couple of characteristic elements can be identified across institutions, including an "intense use of prototyping as a rapid and effective source of communication and learning among stakeholders" (p. 2).

Notably, EVT is strongly concerned with skills needed for rapid visualisation (course 112a). It is sometimes concerned with the development of three-dimensional models (course 112b). The topic of communicating design concepts to others is only discussed in a couple of paragraphs in EVT (course 112c).

Amongst all university classes offered by McKim, courses 112a, b and c serve to establish very basic skills. Exercises related to design thinking, intended to train high levels of creativity and innovation, follow in another course series offered by McKim:

> **116a. Advanced Product Design**—Invention and development of new product concepts with emphasis upon methods for determining: unfulfilled human needs. Each design concept is developed into a working model. Prerequisites: 112a, b, c. [ . . . ]

> **116b. Advanced Product Design**—Continuation of 116a, with emphasis upon the influence of technology, especially "technological breakthrough," upon the formulation of new product concepts. Prerequisite: 116a. [ . . . ]
>
> **116c. Advanced Product Design**—Continuation of 116a, b, with emphasis upon developing a large, complex design to solve a "big" need, i.e., mass transportation or city planning. Prerequisite: 116b. (Stanford University 1962, p. 114)

Theoretical reflections of EVT sometimes allude to the advanced topics in McKim's courses 116a, b and c. However, these topics are not the focus of EVT training exercises. In summary, with respect to McKim's overall course content, EVT is concerned with *the basics of the basics*: predominantly with the content of course 112a. That is an important aspect in making sense of EVT as "a puzzle piece" in McKim's overall, much more comprehensive theoretical and educational works.

In this chapter, we do not endeavour to provide a complete discussion of all EVT content. Selectively, we will review theoretical frameworks discussed in EVT, which form part of the theoretical basis of design thinking practices up to the present.

The chapter provides a review of McKim's general theory of creativity (Sect. 3), his account of creativity as embodied cognition (Sect. 4), the concept of ambidextrous thinking coined by McKim (Sect. 5), the ETC process model: Express, Test, Cycle (Sect. 6) and the design of places for creative work (Sect. 7).

As in previous chapters on the theoretical background of design thinking, we will again highlight a number of central theoretical assumptions (A), definitions (D) and include some observations from a meta-perspective (M).

## 3 A Theory of Creativity

The topic of creativity is often mentioned in EVT. In particular, it is the overarching concept in the book's introduction. Here, McKim builds intensely on John Arnold's works in the field. In addition, McKim is very receptive towards Gestalt theory. With great interest, he acknowledges the book on visual thinking by Rudolf Arnheim (1969). Moreover, Max Wertheimer (1945) wrote about Productive Thinking, analysing acts of high-level creativity that often involve a change of viewpoint. McKim picks up on this notion. He uses both terms, "creative thinking" and "productive thinking," regularly.

According to McKim,

***A1) Creative thinking requires three conditions: (1) personal challenge, (2) productive information processing and (3) flexibility.***

Regarding the focus of EVT, McKim explains: "A major purpose of this book is to encourage [ . . . ] [the] third universal condition that fosters productive thinking: flexibility" (p. 2).

In this sense, McKim also emphasizes how visual capacities including drawing are important for creativity in all kinds of domains, even those where drawing is rarely taught. "Words are clearly not adequate to the thinking of a painter; as you will soon learn, words and numbers are also often inadequate to mathematical, scientific, and other non-artistic modes of [productive] thinking" (p. 3).

## 3.1 Personal Challenge as a Creativity Requirement

***D1) Challenge means that a person is highly motivated to change a given situation; she is passionate about solving a particular problem.***

As McKim puts it, “we think at our best when posed with a situation that we deeply desire to change” (p. 2). The notion of personal challenge includes some shifts away from John Arnold’s earlier treatment of the topic. Arnold had highlighted “drive” as a characteristic of highly creative people, meaning a general tendency of these people to work insistently and passionately on problems. McKim rather emphasises how people differ in their emotional responses to problems. A problem that person *A* perceives as highly challenging can leave person *B* completely untouched. Facing a different problem, people’s emotional reactions might be the other way around. “Challenge is a personal equation” (p. 2).

> The individual confronted with an unresolved situation that he finds fascinating and worthwhile to resolve stands a far better chance to develop his thinking abilities than the person presented with a puzzle he deems uninteresting. Of course, a meaningful challenge to one person may very well prove to be a bore to another. [ . . . ] Only *you* can identify the kind of challenge that will stimulate you to think deeply. (EVT, p. 25, emphasis in original)

***A2) To what extent a person feels challenged by a problem is a matter of individual emotional reactions to problem situations.***

Methodologically, this part of McKim’s theory sheds a novel light on need finding exercises. In design thinking, addressing human needs—often interpreted as addressing user needs—is considered an essential and characteristic undertaking. McKim himself emphasized the importance of comprehensively addressing human needs in his guest essay for the *Creative Engineering* manuscript (1959/2016). Moreover, he introduced need finding exercises in Stanford engineering classes (cf. courses 116 a–c; Roth 2015a), which inform design thinking up to the present. Yet, there are some “mysteries” about need finding methods in design thinking, which can now be resolved in light of McKim’s theory.

The typical procedure of need finding foresees that people working on a creative project go out into the field and meet others (potential users) for whom novel solutions might be designed. Thus, a multiplicity of “open user needs” are identified. The exact project mission is then decided by those persons who endeavour the creative project. These people are usually not the “users” themselves.

Today in design thinking, creative work is typically pursued by teams, not individuals. Most commonly, team members select the problem they will address in their creative project by voting for the one open need identified in user research that should become the team’s further work objective. Thus, team members decide based on what they find personally most promising, meaningful and inspiring. This procedure is sometimes criticised as not tapping the full potential of user research, because the intuition-driven and loosely structured decision procedure does not necessarily lead teams to work on “the most crucial need” from the users’ perspective. In fact, if the primary aim of the procedure was to find most important needs from the users’ point of view, having users vote might indeed make more sense than having design team members vote about the creative challenge to be tackled. By contrast, the design thinking approach used up to the present is still very well in line with McKim's theory of conditions that foster productive thinking. For the creative team to be successful, they must be personally motivated and feel challenged by a particular problem. This can be ensured best when the team decides for themselves what they find challenging and motivating.

***M1) The design thinking method of having teams self-select creative projects they want to pursue—inspired, but not determined by user needs—is fully in line with McKim's theory of people needing to work on problems they experience as personally meaningful in order to be most creative.***

Fortunately, of course, the goals of experiencing personal challenge and addressing key user needs are often closely aligned. It is by seeing fundamental unsatisfied needs in others, by experiencing empathy, that people gain motivation to make a change. A good example of this is provided by Bernie Roth.

> A four-person interdisciplinary team of Stanford Masters degree students were asked to create something that would change people's lives [...]. Eventually they happened upon several janitors that cleaned the building at night [...]. The students found out that the janitors had very little knowledge about financial matters and were being taken advantage of during almost every transaction [...]. The students undertook to develop and deliver Spanish language lessons about financial planning and ways to conduct financial matters [...]. One of the students was so inspired he went on to found a company, called Juntos, that allows people to use ordinary cell phones to learn about and deal with their finances. [...]
>
> I still have the original project notebook from this group. Whenever I look at the notebook I am moved to tears by the *empathy* the students felt for the janitors. It is easy to see why projects like these change students' life trajectories. (Roth 2017, p. 82f, our emphasis)

***M2) Empathy allows creative teams to feel personally challenged when facing crucial rather than incidental user needs.***

## *3.2 Productive Information Processing as a Creativity Requirement*

Productive information processing is a key theme in McKim's work—up to the present day. In EVT, the topic is introduced with general reflections: "Since thinking is essentially information-processing, we cannot expect productive thinking when information is incorrect, inadequate, or tucked away in an unavailable crevice of memory" (VT p. 2).

***A3) Creative thinking thrives on correct and adequate information that is readily available from memory.***

Beyond such general remarks, McKim pursues quite specific teaching aims. His training programme in EVT conveys specific, basic skills for productive information processing.

Throughout the book, McKim discusses the dimension of "concrete" versus "abstract" information processing. He highlights how attending to concrete details of sensations allows us to gather comprehensive information beyond stereotypes. It enables us to note details "outside the box" of prior concepts and expectations. By contrast, abstract thinking can crystallise the gist of a concept or viewpoint. Yet, when it lacks consciously made choices and flexibility, abstract conceptualizations are very often stereotypes that drive "thinking inside the box."

***A4) Concrete thinking is non-stereotypical; it drives thinking "outside of the box."***

***A5) Abstract thinking can crystallize the gist of a concept, but it can also advance stereotypical thinking "inside the box."***

McKim trained concrete information processing with regard to multiple sensory systems in his overall educational programme. At Stanford, he built the Imaginarium, where students practiced devoting attention to concrete perceptual experiences—across all sense channels, not only in the visual domain:

> When was the last time you gave all of your attention to the sensory experience of smelling an apple? [ . . . ] After several minutes in the Engineering Department Imaginarium, you could be doing just that [ . . . ]. The Imaginarium is a red, 16-foot geodesic dome, designed and outfitted by Prof. Robert McKim of the Mechanical Engineering (ME) Department here. [ . . . ] Created in 1972 [ . . . ], the Imaginarium is used in ME 101, "Visual Thinking," [ . . . ]. Slides and films are projected onto the white interior of the dome. Music, thunderstorm noises and numerous other auditory and touch stimuli are used. (Wentworth, Stanford Daily, 1978, p. 2)

In contrast to this plurality of sense-channels addressed in the Imaginarium, EVT is primarily concerned with visual thinking. The detailed treatment of visual skills in EVT can be understood as a prototypical training programme; the use of other sense channels could be trained in similarly refined ways to foster creative thinking. Overall, trainings progress from mindfulness of immediate sensations to similarly rich imaginations. Students learn to include all their senses when imagining something new.

> At one point participants [in the Imaginarium] imagine they're in an apple orchard. We inject the smell of apples through the air conditioning system [ . . . ] McKim said. (Wentworth, Stanford Daily, 1978, p. 2)

All in all, mindfulness of sensations emerges as a key concept in this training endeavour. One major reason why mindfulness is considered serviceable for creativity is because it facilitates concrete thinking outside the box.

***A6) Mindfulness of immediate sensations facilitates concrete thinking "outside the box" and thus also facilitates creative thinking.***

To diagnose his students' ability for concrete information processing, McKim invokes drawing exercises in EVT. Depending on outcomes, the diagnosis might be that a student is strongly inclined towards abstract, stereotyped thinking. The same drawing exercise, conducted repeatedly, could then serve to train the student's skills in concrete information processing:

> Taught always to name what they see, many students learn to label the visual stimulus too quickly, before they see it fully. For example, the word-dependent individual rarely sees trees in all their many shades of green and trunk-bark-limb-twig-leaf complexity. Instead, he sees trees as abstract visual concepts, vague green blobs on a stick. [ . . . ] Asked to draw a tree, the individual whose visual ability has atrophied can only draw a primitive green lollipop. (EVT, p. 24)

***A7) Drawing is a means to test and train people's concrete information processing ability (in the sample domain of visual thinking).***

The importance of "productive thinking" and "mindfulness" in McKim's overall framework of thought is further evidenced by his extensive and repeated mentioning of the topics in recent conversations with William J. Clancey.[1]

On January 31, 2018, McKim laid out to Clancey that "not all thinking is good thinking." For example, "going in circles" is not good. Losing concentration or attention is not good. Allowing the "chatter" in your mind (e.g., about what others think) is not good—it is "junk thinking." For example, McKim explained how such chatter would make it impossible to produce the rapid drawings he created. Moreover, allowing your biases to confine your ideas is not good. He referred to the section on "Relaxed Attention" in EVT as to characterize the opposite of chatter. Thus, chatter or unproductive junk thinking can be contrasted to mindfulness, flow and relaxed attention.

On January 29, 2019, McKim emphasized to Clancey that "we are always thinking." However, some thinking is just "bad thinking." Examples include thoughts that move in circles when worrying about something (obviously a prototypical instance of the mind's "chatter"). Bad thinking also occurs when ideas are based on clichés and stereotypes. All this bad thinking is not productive. By contrast, productive thinking is both creative and ethical/moral. Creative thinking breaks new ground, it is not based on clichés and stereotypes. Yet, creative thinking can be unethical or "morally blank." In that case, McKim does not consider it to be "productive." Thus, here he adds a distinction between creative versus productive thinking that is not specifically discussed in EVT. Yet, the importance of moral designs was already a major topic in his *Creative Engineering* guest essay (McKim 1959/2016; von Thienen et al. 2019).

On December 9, 2019, McKim expressed to Clancey and Jan Auernhammer that "it's most important not to allow the mind to wander off. Watch your mind, don't let it kick you around. Notice when the mind is unproductive: Going in circles, never ending, never producing anything. Silence that part of your mind."

These recent explanations are in strong continuity with McKim's earlier works, including EVT. Here, he lays out his rather broad conceptual understanding of "thinking," which then includes both productive as well as less productive mental activities.

---

[1]The following recollections are based on extensive notes taken by William J. Clancey during seven personal conversations with Robert McKim during 2016–2019.

> Irrational or sane, habit-ridden or brilliantly incisive, logical or illogical, awake or dreaming, we think with our entire being almost all the time. By this broad definition, most thinking is not "productive." We need not assume, as some writers do, that mental activity which merits being called "thinking" is necessarily good thinking. Indeed, most thinking that is eventually productive is preceded by frustrating, cycling, abortive, ill-informed, illogical, habit-plagued thinking that produces (at the time) very little of value. (EVT, p. 2)

McKim also trains readers to monitor their imaginative activities. When thought cycles become apparent, readers should learn to silence these imaginative impulses and instead direct their thoughts into more productive directions:

> The scenarios of many daydreams are enormously predictable; they are "the reverse of a present frustration," [ . . . ]. "If broke, we fantasy winning the sweepstakes. If jilted, we wallow in fantasied revenge." The repetitiveness of these compensatory daydreams testifies to their inability to solve problems. While the active visual thinker directs his fantasies towards expression in reality, the compensatory daydreamer escapes from reality into fantasy, where he cycles passively and endlessly.
>
> Not all daydreaming falls under the heading of escape-to-fantasy, however. Many visual thinkers use a form of daydreaming to think productively. (EVT, p. 95)

Similarly, McKim submits:

> Look inward, become aware of your imagination, and learn to control it productively. If you are aware of your inner imagery but are unable to control it (if you are prone to drift in cyclic and unproductive daydreams, for example), then learn to extend your awareness into other modes of imagery and, again, learn to direct your imagination toward productive ends. (EVT, p. 83)

EVT also spells out a theory of attention (Sect. 4.2), where McKim uses the term "passive attention" to describe an individual whose thought content is driven or even "dictated" by the environment. This contrasts to a productive thinker, who maintains control over his own thinking by means of metacognitive oversight. The productive thinker devotes "voluntary attention."

Given the strong continuity in theorising, even recent explanations of McKim can help to obtain further terminological clarity.

***D2) Productive thinking advances creative (novel and effective) solutions that are ethical.***

***D3) Chatter is thinking that yields no constructive ideas, such as cyclic thoughts about the opinions of others or rumination regarding personal worries.***

***A8) The thought processes of a person can be non-productive in three major was: (1) when the person does not strive for ethical, creative solutions; (2) when she becomes distracted by chatter or a loss of attention; (3) when the person generally lacks necessary skills to advance ethical, creative solutions.***

***A9) The process of productive thinking, prior to the achievement of final solutions, is characterized by long phases of the mind staying intentionally "on topic," and by mindfulness for concrete experiences beyond clichés or stereotypes.***

The concern of McKim for mindfulness was later continued by Rolf Faste at Stanford Engineering. Faste also authored a book manuscript under the headline of

"Zengeneering."[2] It explores in detail the role of "Zen" mindfulness for creative and worthwhile engineering.

More recently, the design thinking research group of Manish Saggar (2017) has continued this tradition of theorizing. They have investigated the difference between unproductive going-in-circles ("rumination") versus productive design reflections in fMRI scans.

## *3.3 Flexibility as a Creativity Requirement*

A major purpose of McKim's book EVT is to help people become more flexible in their thinking. This is to be achieved by practising different thinking strategies, where each approach renders some actions easy, but it may be hampering with regard to other actions. In his explanation of the topic, McKim borrows an analogy from David Straus: The strategy repertoire of a creative thinker is like the toolbox of a carpenter. What a poor carpenter the person would be who only knew how to handle a hammer. A hammer is very practical for some purposes. Yet, the carpenter will need different tools for other purposes. Similarly, an engineer who always invokes the strategy of analytical thinking could solve some problems very well, but could barely handle others. To be proficient in creative problem solving without being limited to very specific kinds of problems, the creative thinker needs to be proficient in a large strategy repertoire, like the carpenter who needs to be proficient with a diversified tool kit:

> Once he [the carpenter] has mastered the use of a tool, it becomes almost an extension of his hand. [ . . . ] His knowledge and skill with his tools . . . determines a substantial part of his overall ability as a carpenter. (David Straus, quoted in EVT, p. 161)

McKim emphasizes the importance of exercise and practical skill for the development of flexibility. When a person working on a creative project is able to see different meta-options she has—different tools she could use—this is already good. Yet, much exercise may be needed before she is actually able to pursue each meta-option in practice—before she masters the various tools so well that they basically extend her physical abilities.

***D4) Flexibility is a superordinate ability to choose between various, complementary strategies of thought and action, which the person is able to pursue proficiently.***

According to McKim's summary, EVT trains 30 overall strategies, each based on numerous methods and exercises. His list gives a good overview of the book's content: Relax, devote attention, experiment with drawing materials, purge, think directly in 3-D, re-centre (which might be called "change point of view" nowadays), pattern-seek, define, imagine, project, recall, seek an analogy, dream or daydream,

[2] http://www.fastefoundation.org/about/zengineering.php

foresee, subjectify, analyse, re-proportion, modify, clarify, rotate, manipulate, look inside, generate alternatives, test, cycle, repeat, change idiom, incubate, intuit, stop thinking.

Of course, McKim is not the first person to endeavour such strategy compilations. Amongst the many authors concerned with creativity, Alex F. Osborn prominently compiled somewhat similar lists, as presented and discussed in Arnold's *Creative Engineering*. The comparison is illuminating. Osborn's strategy list comprises the following approaches: "Put to other uses? [...] Adapt? [...] Modify? [...] Minify? [...] Substitute? [...] Rearrange? [...] Reverse? [...] Combine?" (Osborn, cited in Arnold, 1959/2016, p. 98). This compilation is concerned with how to re-think things, how to generate ideas for new things based on what is already given. By comparison, McKim adds numerous meta-strategies for creative work, such as relaxation, devoting attention, daydreaming, using intuition or stopping to think.

Generally, the topic of flexibility was already emphasised in Arnold's (1959/2016) *Creative Engineering*. McKim elaborates the subject and provides a novel structure. Arnold began his treatment of the topic with a discussion of "flexibility" as a key construct in the psychometric works of Joy Paul Guilford. There, a person's flexibility was rather narrowly assessed by asking people to name as many alternative uses for existing objects as the person could think of. To Arnold, flexibility is important in many more ways. He generally understands it as the ability of a person to consider meta-options, including different potential points of views, different work approaches, different solutions etc. (cf. von Thienen et al. 2017). Arnold names various examples of how creative thinkers can be flexible, but he does not provide a system. McKim adds a huge number of further examples beyond those discussed by Arnold in *Creative Engineering* and systematises them into three different categories.

***A10) Thinking can be flexible in three major ways: (1) in levels of thinking: from deliberate/conscious to automatic/non-conscious, (2) in thinking operations, such as analysis vs. synthesis or diverging vs. converging, and (3) in the use of different representation systems for information: verbal, mathematical, visual, tactile, acoustic, emotional etc.***

Regarding the first category, McKim explains:

> Flexibility in levels of thinking is demonstrated by thinkers who know that it is sometimes advisable to stop thinking consciously about a problem, to relax, to take a walk, to sleep on it—in short, to allow thinking to proceed unconsciously. Productive thinkers are also alert to recognise ideas that emerge from unconscious levels. (EVT, p. 2)

Methods that McKim trains on this behalf include relaxation exercises borrowed from psychotherapy and meditation, stretching and the writing of a dream diary, amongst others. (For present-day research findings concerning this topic, cf. the chapter "Neurodesign Live", in this book, specifically the neurodesign lecture input of Mathias Benedek.)

The second type of flexibility required for creativity concerns thinking operations:

> Most thinkers are disposed to use a limited set of favorite thinking operations. The logical thinker likes to operate his thinking by rules of logic, step-by-step, in a single direction. The intuitive thinker, by contrast, appears to take "mental leaps," often in surprising directions. While acknowledging a genetic influence in this personal bias toward certain mental operations, we can also see that education that rewards certain thinking operations, ignores others, and even penalizes as a few, is also bias inducing. (EVT, p. 2f.)

With regard to these biases, EVT intends to provide an antidote by training thinking operations often neglected in formal education. One can easily see how strategies such as relax, re-centre, imagine, daydream, incubate, intuit or stop thinking from McKim's list are rarely promoted elsewhere at universities, especially at engineering faculties. In the end, flexibility in the use of strategies or thinking operations is desired. "An important purpose of this book is to encourage the reader to enlarge his working repertoire of thinking operations and to learn the value of moving from one operation to another" (p. 3).

Regarding flexibility in representation systems, McKim uses changing terminology. Next to writing about representations in different systems, he also uses the terms "vehicles of thought" or "languages of thought." To aid clarity, we will only use the phrase "representation system" henceforth. In this respect, once again, McKim seeks to promote flexibility. Further details about McKim's theory of representation systems and his ideas concerning their flexible usage are discussed in Sect. 4.4.

## 4 Creativity as Embodied Cognition

Beyond McKim's description of three basic requirements for creativity—personal challenge, productive information processing and flexibility—McKim also reflects on the physiological underpinnings of the phenomenon. These reflections of McKim are specifically meaningful for recent developments in the field of design thinking, which take place under the headline of "neurodesign." Here, the bodily basis of design thinking is being explored (Auernhammer et al. 2021; von Thienen et al. 2021).

In present-day laboratory studies of creativity, very often the brain lies at the centre of physiological scrutiny. While participants work on creativity tasks, brain activities are monitored by means of EEG-recordings, fMRI or fNIRS. From McKim's perspective, the brain is just one part among many others in the human body, which matters for creative performance. His stance would nowadays be described under the headline of "embodied cognition." In this domain, present-day scholars discuss how the entire body of an animal shapes its cognitive processes. This is also a key topic for McKim across his whole book. "The entire nervous system (not just the brain) is involved in thinking" (EVT, p. 2). "We think with our

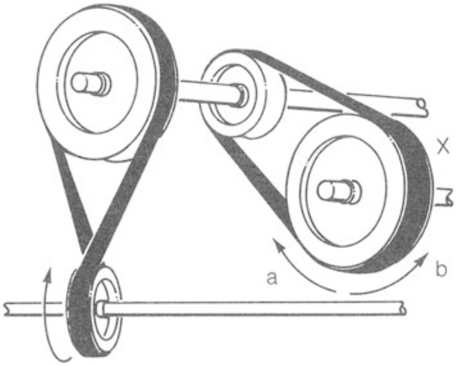



**Fig. 3** One exercise in visual thinking asks readers to determine the direction in which one pulley will turn given interventions on another pulley (image from EVT, p. 16)

entire being" (ibid.). "Psychic (mental) functions cannot be readily separated from somatic (bodily) ones" (p. 1).

***A11) Creative performance is a matter of the whole body, not just the brain.***

EVT includes ample exercises for people to train their bodily skills and it provides encouragement for readers to engage in physical activities—all in the service of creativity.

***A12) Bodily skills (such as accurate perception or drawing), physical activities (such as walking, relaxing or 3d-model building) and physical environments (including materials that promote different kinds of engagement with the environment) are essential determinants of people's creative capacity and creative performance.***

All upcoming sections will elaborate this perspective. Whatever topic McKim turns to in EVT, the role of the whole body for creative performance is always highlighted.

Even when a problem is to be solved mentally (i.e. "in the brain"), McKim draws attention to the role of our body morphology—beyond the brain—for the information processing that takes place. In one example (Fig. 3), McKim depicts two pulleys. He asks:

> Which way (a or b) will pulley 'X' turn?
>
> Did you trace the motions of the pulleys with your finger, or feel some sort of inner muscular involvement, as you came to the correct conclusion that pulley "X" goes in direction b? (EVT, p. 16)

As humans, many of us solve this puzzle by mentally simulating operations with fingers, hands and arms. These operations are based on our human body-morphology. If we had different appendages for the handling of artefacts—if we had trunks like elephants or bills like birds instead of hands—our mental operations would be different in order to solve the problem.

## *4.1 A Theory of Relaxed Attention*

In considerable depth, McKim especially elaborates how muscle tonus (relaxation) impacts emotions, attention processes and productive versus non-productive information processing. McKim holds that:

***A13) Relaxed attention is most favourable for creative, productive thinking.***

> Relaxation is important to thinking generally, because we think with our whole being, our body as well as our brain [ . . . ]: uptight body, uptight thoughts. Be reminded, however, that the totally relaxed individual cannot think at all [ . . . ]. [S]ome muscular tension is needed to generate and attend mental processes. Some tension, but not too much: relaxed attention. (EVT, p. 33)

In his overarching theory of creativity, McKim holds that it is important to develop flexibility in one's levels of thinking: from controlled, conscious, deliberate to automatic, non-conscious, non-deliberative cognitive processing. For highest levels of creative performance, creators need to be ready to harness both kinds of information processing. Again, he highlights that these are whole-body engagements, not just brain-specific processes. A typical example of non-deliberative processing occurs during sleep.

***A14) To facilitate creative breakthroughs, the creative individual needs to be ready to process information in varying body-states, from energetic and controlled work on a task to automatic, non-conscious information processing during phases of relaxation with attention off-task (e. g., taking a shower, going for a walk, sleeping).***

> **The paradox of ho-hum and aha!**
>
> Relaxation involves loosening up, letting go, and finally—ho-hum—going to sleep. Attention involves focusing energy, finding excitement in discovery—aha!—and being very much awake. Ho-hum and aha!—what can these seemingly opposed modes of consciousness have in common? [ . . . ] After a period of relaxed incubation, which can take place in the shower or on a peaceful walk as well as sleep, attention is not uncommonly riveted by the "aha!" of sudden discovery. [ . . . ] While the subconscious incubation requires relaxation, a sudden flash of insight requires attention or is lost. (EVT, p. 33)

Here, McKim expresses another claim regarding work phases where the creator does not think about his or her creative project in consciously controlled ways.

***A15) When creators work on long, complex problems, breaks or resting periods most effectively increase chances of breakthrough insights when relaxation is achieved.***

From the perspective of present-day (neuro-) design thinking research, also another aspect is notable in McKim's discussion: Two out of three examples he gives for situations that facilitate automatic, non-conscious problem processing involve relaxed, bilateral, fluid motion: going for a walk and taking a shower. Only the example of sleep describes a rather motion-less state. Notably, McKim's examples are highly consistent with more recent research findings, which indicate a strong facilitating effect of relaxed, bilateral, fluid motion on creative thinking (von Thienen 2018).

McKim is furthermore concerned with interrelations of body-states and emotions. He holds that:

***A16) There is a bi-directional causality between body-tension and fear: fear causes tension; body-relaxation reduces fear.***

> By far the most fundamental cause of hypertension is fear. The fearful or insecure person tenses his body because he believes that he will soon face a real or imagined attack or catastrophe. At work, he overreacts and burns energy needlessly, or does not act at all—in each instance, to avoid failure. At home in bed, he fusses and worries; his body tense, he cannot go to sleep.
>
> Unable to relax, the fearful individual also finds it difficult to maintain attention. Every distraction is interpreted as a potential threat or an opportunity for relief. Easily diverted, he becomes prone to the conflicting mental agenda and immobile tension that characterize the indecisive. (EVT, p. 34)

McKim notes that many people try to counter excessive tension with alcohol or other drugs. "Indeed, so prevalent is tension that large industries cater to letting go: alcohol, drugs" (p. 34). While McKim does not seem to believe much in relieving effects of alcohol or other drugs, he is fully convinced of the positive impact of bodily relaxation exercises: "Physical-relaxation techniques provide an excellent way to break the cycle of fear, worry, and tension" (p. 34).

In terms of McKim's more recently used terminology, one can say that

***A17) Excessive body-tension and fear provide a physiological basis of "chatter," "junk-thinking," or altogether unproductive thinking.***

To counter unproductive thinking, McKim suggests bodily exercises.

> Holding the heavy human head over a desk for long periods while looking rigidly straight ahead at paperwork is a comparatively recent behavior that places an extremely unnatural demand on neck and shoulder muscles. These areas should be relaxed periodically, and always just before intensive visual/mental activity. (EVT, p. 35)

Ever since this theoretical acknowledgement of body states impacting creative performance, physical activity has been a typical element in design thinking warm-ups prior to creative work proper. Bernie Roth recalls how such physical activities were initially considered awkward in Stanford's School of Engineering, but gradually became accepted.

> There are movement activities that directly use the mind-body connection to stimulate learning and creativity. In the Design Division, we have been teaching these activities for a long time. Originally, these were considered somewhat New Agey. [ . . . ] The president's office could not see any justification for an engineering design class being in the women's gym for warm-up exercises. Fortunately, those days are long past. (Roth 2015b, p. 179f.)

***M3) Body motion has been introduced as a typical element of design thinking warm-ups to foster a flexible muscle tonus in the whole body, and to facilitate relaxed attention in subsequent creative work.***

The ability to achieve body states at highest levels of relaxation is considered favourable in several regards.

> Deep muscle relaxation prepares the individual to sleep—perchance to dream—or, if mental alertness is retained, to imagine more vivid and spontaneous visual fantasies than can usually be obtained with normal muscle tonus [ . . . ]. (EVT, p. 36)

***A18) Deep muscle relaxation leads to sleep and thus increases chances of dreaming, when alertness is not maintained.***

***A19) Deep muscle relaxation leads to enhanced (more spontaneous and more detailed) imagination, when alertness is maintained.***

Yet, again, McKim emphasizes the importance of flexibility, also with regard to muscle tonus. Deep relaxation is one extreme that creative individuals should be capable of, but abilities of tensing the body are as important. Body tenseness is understood as a physiological prerequisite for focused attention. As McKim explains: "Devotion of attention is the focusing of energy. The vehicle for transmitting human energy is muscular tension" (EVT, p. 36).

***A20) Muscular tension is a physiological basis of building up and focusing attention.***

> By relaxation, you let go inappropriate muscular tensions that divert energy from what you are doing; by attention, you direct and devote your energy, freely and dynamically, to discovering more and more about a single object, idea, or activity that interests you. Old habits, however, may initially make the task of maintaining the state of relaxed attention difficult. Excessive tension reappears; the mind wanders. (EVT, p. 38)

Against this background, McKim provides exercises to help readers "clear the ground of consciousness so that the physical and mental and emotional awareness inherent in relaxed attention can be maintained for longer periods of time" (p. 38).

## 4.2 A Theory of Attention

The ability of people to persist with on-task attention is considered a prerequisite by McKim for productive thinking (cf. Sect. 3.2). Here as much as in other cases, he endeavours to provide (neuro-)psychological accounts of cognitive processing in general, and creative thinking in particular. Today, the bio-psychological basis of creativity is a core topic in the emerging field of neurodesign (Auernhammer et al. 2021; von Thienen et al. 2021); McKim has laid important groundwork in this field.

In detail, McKim spells out a theory of attention, closely intertwined with his discussion of body-tonus.

***A21) Different states of attention to distinguish include: forced attention, immersed attention, passive attention, preattention and voluntary attention.***

***D5) Forced attention occurs when the person is instructed to pay attention to a task, or the person instructs herself to attend a task, which she does not find interesting per se.***

***A22) Forced attention can only be maintained for short periods of time; it is effortful to maintain and does not allow the individual to tap her full creative potential.***

> Externally or internally demanded, *forced attention* usually occurs for brief moments only, and must continually be reinforced.
>
> Paying attention because you should or ought to is clearly less pleasant, and less effective, than devoting attention because you want to. (EVT, p. 36)

Here, McKim's theory of attention underpins his theory of creativity, where he introduces "personal challenge" as a pre-requisite for high levels of creative performance (Sect. 3.1).

***A23) When a task does not interest the person, she does not feel personally challenged and can devote forced attention only; under such circumstances, the person cannot unfold her full creative potential.***

The situation is very different when a task does interest the person.

***D6) Immersed attention occurs when the individual is highly interested in a task and gets so absorbed in the activity that she loses self-conscious reflections on a meta-level regarding the situation.***

***A24) Immersed attention is experienced as pleasurable and attention is not easily diverted away from the task; it can be observed regularly in playing children.***

> The individual who attends because he wants to is not easily diverted. *Immersed attention* is natural absorption in developing an idea, contemplating an object, or enjoying an event. Watch a child pleasurably engrossed in stacking blocks to obtain a clear image of *immersed attention*. (EVT, p. 36)

Very different from immersed attention, is a state that McKim addresses as "passive attention."

***D7) An individual pays passive attention when she only reacts to whatever stimuli appear in her environment.***

***A25) With passive attention, the person tends to pursue each task only for a limited amount of time, and tasks are not consciously self-determined, because attention wonders from one objective to another cued by the environment.***

> Immersed attention should not be confused [ . . . ] with *passive attention*, which is being easily absorbed, willy-nilly, in whatever comes. The passively attentive child who "seems to belong less to himself than to every object which happens to catch his notice" presents a formidable challenge to his teacher. (EVT, p. 36)

In light of McKim's more recent terminology, passive attention can be related to the concept of "unproductive junk thinking." Here the person occupies herself with topics that draw attention away from a project, which the person could otherwise pursue productively.

The next concept of attention to distinguish is "preattention."

***D8) Preattention means that a person pursues a routine task mostly by means of automatic processing, with relatively little conscious reflection required.***

***A26) Complicated, novel tasks cannot be solved by means of preattention; they require full attention.***

> *Preattention* is another natural form of attention. Absorbed in thought, for example, you suddenly realize that you have somehow negotiated your automobile through miles of turns and traffic without conscious awareness: you have been preattending the driving task. Preattention is comparable to an automatic pilot that attends routine events but cannot cope with the unusual. Should a highway emergency occur while you are preattending [ . . . ], you must come to full attention to cope with it. (EVT, p. 37)

Then, by contrast, the most important form of attention McKim distinguishes in the context of creativity is "voluntary attention."

***D9) Voluntary attention occurs when the person immerses in a task only to such a degree that self-conscious reflections on a meta-level are maintained, which allow the individual to change foci of attention wilfully.***

***A27) Voluntary attention is best suited for visual thinking activities.***

> Of the kinds of attention discussed so far, immersed attention would seem at first best suited to visual thinking. What could be better than being able to "lose oneself," to become wholly immersed in what one is doing? Emphatically better is a quality of attention in which sense of self is not lost and consciousness is not taken over entirely by what one is attending. I will call this kind of attention *voluntary attention*. The individual who attends voluntarily is able to change the focus of his attention quickly, at will. To do this, his consciousness cannot be wholly immersed; he must be sufficiently self-aware to be able to decide. (EVT, p. 37)

Here, McKim adds discussions about attention mechanisms to an account of flexibility advanced by Arnold before, where he had discussed one aspect of flexibility from a perspective of "personality."

> Flexibility [ . . . ] is also the ability, that can be consciously developed, that allows you to be both an observer and a participator at the same time or in alternation. It is most desirable to have this duality of personality be constant in time if the observer half is not acting as a judge or evaluator [ . . . ]. Perhaps the alternating roles would be the safest at first. This would allow you to step back every so often and review what you have done to date and to reconnoiter and determine the best path to continue along. (Arnold 1959/2016, p. 86)

McKim explores how persons can achieve the kind of "flexibility in personality" that Arnold had described in highly creative persons. Like Arnold, McKim emphasizes the possibility of enhancing flexibility by means of practice. In McKim's framework, this informs his statements about attention.

***A28) Voluntary attention can be trained.***

Moreover, McKim spells out conditions under which voluntary attention develops, or can be maintained. Thus, students can train to develop and maintain voluntary attention, by seeking its favourable conditions.

***A29) Voluntary attention (i) can only be devoted to one topic at a time, (ii) requires that you take interest in the topic and (iii) can be sustained only through ongoing, dynamic processing of the topic.***

> Like the art of relaxation, skill in voluntary attention can be learned. The first principle to learn is that you can fully attend only one thing, or related group of things, at a time. [ . . . ] [Then comes] the second principle of voluntary attention: find interest in what you are attending, or your attention will wonder, become divided, or have to be forced. [ . . . ] [T]he third principle of voluntary attention is that attention is dynamic. Whenever mind and eye become immobile, attention diminishes and vision blurs. (EVT, p. 37)

Here we can witness the origin of the design thinking motto "stay focused on topic," sometimes followed by the explanation "one conversation at a time." This motto grounds in insights regarding human physiology. Our mind (in more recent terminology: the working memory) is not made to pursue different unrelated topics or tasks consciously at the same time:

> You can fully attend only one thing, or related group of things, at a time. True, you can preattend one thing (of a routine nature) and attend another. But try to attend fully two unrelated conversations at a time, and you will find that you can do so only by alternating your attention between the two. You will also find that your attention naturally favors the conversation that most interests you [ . . . ]. (EVT, p. 37)

***A30) Splitting up attention across several tasks or topics at a time decreases performance on each single task and hampers productive thinking altogether.***

Thus, creative persons should seek to devote their full attention to one important matter at a time, instead of trying to split up attention. This is the "one topic," the "one conversation" for design thinkers to focus on, where immersive experiences are to be sought. Notably, this does not mean at all that design thinkers should stay fixed on a particular topic from the beginning of a creative project to its end. This would be absolutely disastrous for creativity, as flexibility in one's focus of attention and openness to seemingly irrelevant information have been found by research to be essential for high levels of creative performance (von Thienen 2019). Yet, the motto "stay focused on topic," building on McKim's theory of attention, also implies something very different.

***M4) The design thinking motto "stay focused on topic" means in McKim's terms "devote voluntary attention": Seek immersion in one objective at a time, maintain meta-cognitive oversight, be ready to flexibly shift your focus of attention deliberately (not in purely passive reactions to ever-changing environmental stimuli).***

Finally, McKim distinguishes between "internally" versus "externally" directed attention.

Internally directed attention allows the person to access her own "inner" imagery and to use it for productive purposes. "Look inward, become aware of your imagination" (EVT, p. 83). Internally directed attention can also serve to explore bodily sensations. "Close your eyes and sit quietly for several minutes. Allow your attention to systematically explore the muscle sensations of your body" (p. 35).

This contrasts to externally directed attention, where the person is mindful of her surroundings, including objects in the environment. An example discussed above is the seeing of a tree. In the respective exercise, McKim instructs readers to look closely and pay attention to the "many shades of green and trunk-bark-limb-twig-leaf complexity" (p. 24).

Both internally and externally directed attention are highly important to McKim. He trains them regularly. In particular, the chapter "seeing" includes many tasks where readers practice externally directed attention. In the chapter "imagining," multiple exercises call for internally directed attention.

***D10) With internally directed attention the person focusses on mental imagery or on proprioception.***

***D11) With externally directed attention the person focusses on her environment.***

Indeed, the topic is so important to McKim that he even designs environments specifically to facilitate internally versus externally directed attention. Notably, from one purpose to the other, different environments can be required. Internally directed attention benefits from quiet, secluded environments: "Inner stimuli, often fragile, are easier to attend in an environment in which external stimuli (such as distracting noises or interruptions) are absent" (EVT, p. 85). By contrast, externally directed attention thrives from stimuli in the environment that elicit interest, or materials that facilitate active engagement with the surroundings (see Sects. 7.1 and 7.2).

***M5) Environments for creative work should facilitate both internally versus externally directed attention. Typically, different kinds of environment are needed for the two ends.***

## *4.3 A Theory of Memory*

Next to his theory of attention, McKim also spells out a theory of memory. Once again, he provides an embodied cognition account. According to this view, what we remember is a matter of our whole body. In particular, muscle tonus and relaxation play a key role in McKim's memory conception.

The topic of memory is important indeed in the context of creativity. Already historically old creativity theories acknowledged the fact that novel ideas are in some way informed by what the person knew before. In one traditional theory, creative ideas are defined as a novel re-combination of old ideas. John Arnold had also included this aspect in his definition of creative thinking.

> The creative process is primarily a mental process whereby one combines and recombines **past experience**, possibly with some distortion, in such a fashion that the new combination, pattern, or configuration better solves some need of mankind. (Arnold 1959/2016, p. 66, our emphasis)

When past experience is essential to the creative thinking process, then—in terms of (bio-)psychological theory—memory functions are involved. From present-day perspectives, such an account has lost nothing of its topicality. Research finds similar brain areas recruited when people remember the past or engage in creative thinking (Beaty et al. 2018; see also the input of Mathias Benedek in the chapter "Neurodesign Live").

***M6) McKim moves beyond a psychological theory of creativity; by discussing the role of the whole body in relation to attention, memory and creative thinking he provides a bio-psychological theory of creativity.***

With regard to memory, McKim highlights its essential importance for creative performance: "We cannot expect productive thinking when information is [...] tucked away in an unavailable crevice of memory" (VT p. 2).

***A31) Abilities of memory retrieval partially determine people's creative capacities.***

In the section on externalized thinking (Sect. 7.1) and prototyping (Sect. 7.2) McKim lays out how people can use material culture in order to extend their memory. For instance: "Idea sketches are [ . . . ] a kind of visible graphic memory" (p. 121). He also points out how material culture extends our memory functions, so that we can conduct mental operations that would be impossible without material aids.

> Drawing provides a function that memory cannot: the most brilliant imager cannot compare a number of images, side by side in memory, as one can compare a wall of tacked-up idea sketches. (EVT, p. 10)

***A32) Material culture permits mental operations that human memory alone (unaided by material culture) would not support.***

Beyond the use of material culture, McKim also addresses perception skills and practices as highly relevant for memory performance. Schooling perception ("mindfulness") is a key approach he takes in order to help people improve their memory retrieval capacities.

> **visual memory**
>
> Ability to retain visual imagery is difficult to measure. One can never be sure that a low test score is the result of poor memory; it could as well be the result of inaccurate perception. Indeed, **vigorous perception and faithful remembering are closely allied**. The more actively you perceive [ . . . ] designs, the more likely you will be able to reproduce them from memory. (EVT, p. 14, our emphasis)

McKim invites readers to try the following exercises.

> Close your eyes and recall an apple [ . . . ]. After a minute or so, open your eyes and ask yourself: "Did I see a colored apple? Was it a specific apple? What was the apple resting on?"
>
> Most people, when attempting to recall an apple, either experience blank or inobedient imagery or a stereotyped red apple that floats in space. (EVT, p. 91)

Based on his memory theory, McKim asks readers to reflect on their conscious experiences when eating apples. He notes how conscious experiences depend on people's focus of attention. Likely, a lack of voluntary attention devoted to apples while eating them, and correspondingly a lack of comprehensive and accurate perception, explains a bad performance in the "remember-an-apple-test."

> When you last munched an apple, for example, were you fully conscious of its nuances of color, flavor, scent, coolness, crispness, and texture? Likely not. More probably, you were talking to someone or thinking of something else. If my assumption is correct, your image of an apple in the previous exercise was as lacking in sensory detail as your usual conscious experience of apples. (EVT, p. 91)

***A33) Capacities of memory retrieval depend on previous conscious experiences; only what is consciously experienced first can later be easily retrieved from memory.***

***A34) Paying voluntary attention to an object or situation, and exploring it actively across multiple sensory modalities (mindfulness), improves the recall of multimodal details concerning the object or situation from memory later on.***

While keen visual perception is relatively easy to train, McKim emphasizes that people often find it much harder to be mindful of other sensory experiences. Many of them are commonly processed non-consciously. Cultural blocks antagonize a balanced conscious exploration of all sensory modalities.

> Nonvisual sensory modes are particularly repressed because they are especially related to feelings of pleasure, disgust, and pain. The olfactory pleasure of perfume (and disgust at the smell of spoiled food), [...] the kinesthetic pleasure of dancing (and ache of sore muscles), the auditory pleasure of music (and nerve-jangling noise of the city): these feelings that accompany the nonvisual senses are particularly intense. Because we naturally avoid pain and, obeying cultural strictures, also commonly avoid pleasure, we tend to repress much sensory experience. Sensory experience that is not actively and consciously assimilated is also not readily remembered. (EVT, p. 92)

To help people recall sensory experiences that were not actively and consciously assimilated at the time of the initial experience, McKim suggests a method, which he calls *relaxed multimodal retrieval*.

> Now consider the rationale for a retrieval method that will enable you to recall more vivid and complete memory images. I will call this method "relaxed, multimodal retrieval."
>
> Why relaxed retrieval? When consciousness is relaxed, as it is in hypnosis, for example, long-term memories are more readily recalled. (EVT, p. 91)

The method combines two interventions. The first is relaxation.

> The importance of relaxed attention [...] to visual recall can be explained in terms of cognitive structures. Unlike videotape, cognitive structures encode information in every sensory mode and in the mode of feeling. Much of this intersensory and feeling input is assimilated subconsciously. [...]
>
> As with videotape, cognitive structures can be replayed accurately only in the same mode that they were recorded. Thus you must relax consciousness to replay memories partially recorded subconsciously. (EVT, p. 91)

The second intervention is multimodal retrieval.

> Memory retrieval is also enhanced when recall is multimodal—that is, when all the sensory modes of imagination and the mode of feeling are called into the playback. (EVT, p. 91f.)

Here is an example of the method, applied to enhance the recall of an apple.

> Close your eyes and relax; direct your attention inward [...]. Now imagine that in your hand you have a delicious, crisp apple. Feel the apple's coolness; its weight; its firmness; its round volume; its waxy smoothness. Explore its stem [...]. Now bite the apple; hear its juicy snap; savor its texture, its flavor. Smell the apple's sweet fragrance [...]. With a knife, slice the apple to see what's inside. As you continue to explore the apple in detail, return occasionally to the larger context; see your hand, feel the soft breeze [...]. (EVT, p. 92)

***A35) Memory performance is partially determined by the person's physiological body state, in particular their level of relaxation and cognitive control.***

***A36) When a person did not actively and consciously assimilate a perception by the time of the original experience, chances of recall can be increased through relaxation next to multi-modal retrieval techniques.***

***D12) Relaxed multimodal retrieval is a method that aims to facilitate the recall of content that was not consciously processed by the time of the original experience.***

Of course, McKim also trains mindful perception in order to improve memory performance. Here, multimodal perception is key.

> Repeat the previous exercise with a real apple instead of an imaginary one. Savor the apple slowly and pleasurefully, with all of your senses. [ . . . ] After eating it, recall the apple in all sensory detail. (EVT, p. 92)

***A37) Training mindful, multimodal perception is a means to improve memory performance and thereby creative capacity: Only those experiences that a person can retrieve from memory in one way or other can inform her creative solutions.***

## *4.4 A Theory of Representation Systems*

Related to McKim's theories of attention and memory is also his account of representation systems. Once again, he explores the role of different sensory-modalities and why it is important for creative thinkers to be versatile in accessing them all.

As in other fields, McKim builds on works of his predecessor John Arnold, where he adds both developments of theory and practice. This was clearly in line with Arnold's hopes and expectations, who had asked McKim to develop visual thinking classes in addition to Arnold's already established courses.[3]

Notably, Arnold taught quite often methods for the creative process that included a strong invocation of verbal information processing. For instance, he taught students to start off from feelings about a problem domain (e.g., frustration, a feeling that "something is wrong"). Then they should probe different verbal formulations of the problematic situation, until a promising problem view and a respective, creative project was found (e.g., Arnold 1959/2016, p. 94). Thus, Arnold taught students to translate emotionally represented problems into verbally represented problems.

Verbal representations allow uniquely fine-tuned explorations of potential project avenues. Up to the present, design thinking uses the power of language to explore different problem accounts, and to unleash pinpointed creative endeavours. Methodologically, this power of language is harnessed for instance by formulating different How-Might-We questions or Point-of-View statements (d.school 2010). Another recent example is provided by Kelley & Kelley:

> For example, in retail environments, we've discovered that if you change the question from "how might we reduce customer waiting time?" To "how might we reduce **perceived** waiting time?" it opens up whole new avenues of possibility, like using a video display wall to provide an entertaining distraction! (Kelley and Kelley 2013, p. 23, emphasis added)

[3]Personal notes of William J. Clancey of a conversation with Robert McKim on January 31, 2018.

In this example, a single word in the problem description—"How might we reduce (perceived) customer waiting time?"—entails a huge difference for subsequent project trajectories, for creative missions and likely solutions (what in design thinking theory is often called the "solution space"). Language seems to be an almost ideal medium to make such precise distinctions.

***M7) Language allows pinpointed differentiations of multiple potential creative projects in a problem domain; minor changes in verbal accounts of a problem open up greatly differing solution spaces.***

Yet, how about other ways to represent information? Arnold had already added a couple of drawings here and there in his treatises, before McKim began to elaborate the concept of visual thinking.

In *Creative Engineering*, a discussion by Guilford comes closest to anticipating a theory of information representation systems.

> [It is important to note] the kind of content or material, or the form in which [. . . ] information exists: figural, symbolic, or semantic. Figural content is information in concrete form, as perceived through the senses or as recalled in the form of images. [. . . ] Symbolic content is in the form of signs, which have no significance in and of themselves. Examples are letters, numbers, musical notations, and so on. Semantic content is in the form of meanings to which words are commonly attached, hence it is most notable in our verbal thinking. (Guilford 1959/2016, p. 153)

McKim concerns himself much more intensely with representation systems in EVT. His discussion goes beyond Guilford's short overview in several important regards, including the number of representation systems that are distinguished. Already in his guest essay in *Creative Engineering*, McKim had highlighted the importance of emotions or feelings for human creative design activities (cf. von Thienen et al. 2019—where the topic was discussed under the headline of 'felt design responses'). Thus, unsurprisingly, McKim adds emotions/feelings as another representation system. Furthermore, when information can be processed via the visual sense channel, then of course it can also be processed via other sense channels. "Cognitive structures encode information in every sensory mode and in the mode of feeling" (p. 91). Here, McKim's theory of memory and his theory of representation systems overlap.

> A well-known thinking vehicle is language [. . . ]. Other vehicles of thinking are non-verbal languages (such as mathematics), sensory imagery, and feelings. (EVT, p. 3)

According to McKim's treatment of the topic . . .

***A38) Representation systems are characterized in a twofold way: (1) how information is processed cognitively and (2) how information is represented externally.***

Examples of representation systems are provided in Table 1.

Here is an example concerning the visual sense channel, where McKim introduces the concept of "visual imagery" (Fig. 4).

> Visual thinking is carried on by three kinds of visual imagery:
>
> (1) the kind that we *see* [. . . ]
> (2) the kind that we *imagine* [. . . ]
> (3) the kind that we *draw* [. . . ]. (EVT, p. 6, emphasis in the original)

**Table 1** Examples of representation systems

| Representation system | Sample cognitive process | Sample externalization |
|---|---|---|
| (Verbal) Language | Listening to a conversation, reading | A spoken or written sentence |
| Mathematics | Calculating | A mathematical proof |
| Visual imagery | Seeing | A sketch or sculpture |
| Auditory imagery | Hearing | A played song |
| Tactile imagery | Experiencing softness | Products made of specific materials |
| Kinaesthetic imagery | Sensing the body in motion | Dance |
| Emotion/feelings | Experiencing pleasure | Gesture |

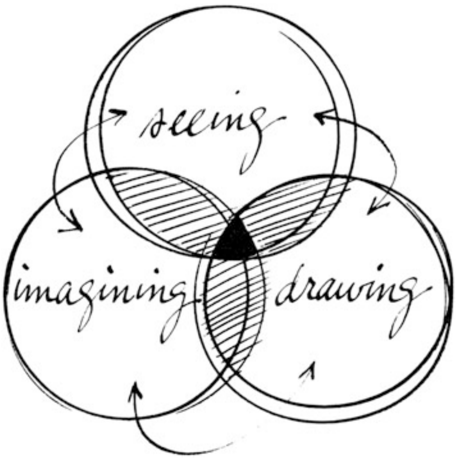



**Fig. 4** With this Venn diagram, McKim visualizes "the interactive nature of seeing, imagining and drawing" (image re-printed from EVT, p. 6)

Notably, these three kinds of imagery correspond to the major chapters in EVT: Seeing, imagining, idea sketching.

Visual imagery covers all cognitive processing based on the visual sense channel.

***D13) Representation systems can be identified on the basis of sensory modalities (e.g., seeing, hearing) and cognitive processing systems (e.g., language processing, mathematical processing).***

When a person perceives something in a particular representation system, it can be something found in nature (a tree, a stone etc.) or something man-made.

By contrast, externalizations in representation systems are necessarily man-made. They are (usually intentional) expressions of thought in some medium that can be perceived with one's senses. Prototypical examples are physical, man-made artefacts to convey problem-views or solution ideas in the creative process.

> Consider the sculptor who thinks in clay, the chemist who thinks by manipulating three-dimensional molecular models, or the designer who thinks by assembling and rearranging cardboard mockups. Each is thinking by seeing, touching, and moving materials, by externalizing his mental processes in a physical object. (EVT, p. 40)

Externalizations can take many different forms. For instance, "visual ideas can be expressed by acting them out, talking about them, writing them down, constructing them directly into a three-dimensional structure—and drawing them" (p. 116).

***D14) An externalization is a (typically intentional) expressions of thought in a medium that can be perceived by the senses.***

***D15) The sensory modality and/or cognitive processing system used to perceive an externalization identifies the representation system that is being deployed.***

As McKim's respective theorising is essential for his discussion of prototyping and prototyping materials, this topic is treated in further detail in Sect. 7, which covers McKim's account of how to design places that facilitate creative work.

Clearly, in everyday life, representation systems are often not used disjunctively. When listening to another person, we typically engage in verbal information processing, at least when the other person's language is understandable to us. There is also additional auditory information regarding the tone of the voice and the "melody of speech" (intonation), next to possibly other sounds in the background. Moreover, recognising an angry or gentle voice can result from emotional information processing. Similarly, visual stimuli do not normally entail disjunctively visual thinking. Here, once again, McKim highlights the role of memory.

> Perceptual reality [...] [i.e. the way in which you perceive reality] combines what you know with what you see, and that knowing is polysensory. You perceive a chair: polysensory memories merge; you perceive a chair that is solid, pleasant to touch, and soft to sit in. (EVT, p. 70)

***A39) When we perceive the world, representation systems are typically not used in isolation and disjunctively; already the visual perception of a single object usually activates several representation systems (here: memories concerning different sensory modalities) in parallel.***

Yet, when confronted with problems to solve, McKim emphasizes that people often select specific representation systems to tackle the task, which can be more or less helpful. He invokes problem exercises to help people become aware of the representation systems they personally prefer and choose intuitively. By contrast, people often neglect certain other representation systems that might be helpful at least for the solving of some other problem types. Most people have strong preferences and are by no means equally facile in different systems.

> Observe your mental processes as you attempt to solve this problem: "a man and a girl, walking together, step out with their left feet first. The man walks three paces while the girl walks two. When will both lift their right feet from the ground simultaneously?" [...]
>
> Did you, for example, talk to yourself about the problem sub-vocally? If so, the vehicle of your thinking was language. Or did you walk two fingers of each hand [...] or feel vague walking sensations in your muscles? If so, your thinking vehicle was sensory imagery. [...] The answer to the puzzle [is]: Never. (EVT, p. 3f.)

McKim, together with his colleague James Adams at Stanford Engineering, used such puzzles to illustrate the importance of selecting suitable representation systems for the understanding of problems and finding solutions. Regarding this same puzzle of two persons walking, Adams remarked:

> This is a good problem to solve with visual thinking. The live experiment with another person, a drawing, or a musical rhythm analogy will all work well. The mathematical approach will work, although it is somewhat circuitous. Verbalisation, once again, will not get you very far. (Adams 1974, p. 65)

For other problems, different representation systems can be more fruitful. Thus, the appeal is to use representation systems mindfully, to acquire proficiency in different systems and to be flexible in one's choices.

***A40) Representation systems differ in the problem-solving opportunities they engender; different representation systems allow people to solve different kinds of problems.***

Notably, once again a full-body perspective is invoked regarding problem-solving. Specifically, problem-solving by means of sensory imagery is described as a "full-body undertaking." In the puzzle concerning two persons walking side-by-side, solution approaches in which people move fingers like feet on a table, or even endeavour a two-person live experiment, engender insights by means of body motion.

***M8) The theory of representation systems pursues an embodied cognition approach; the role of the body—from sensory organs, over body states to the body in motion—is analysed in relation to creative problem solving.***

One of the reasons why McKim finds it utterly important for people in a creative project to invoke many different representation systems, is because he holds a respective (bio-)psychological theory about the emergence of creative breakthrough ideas. Here, the basic notion is that creative breakthroughs often obtain when knowledge from a seemingly disparate field is brought to bear on a problem that is currently to be solved—a belief that has received much support from recent research (von Thienen 2019; cf. also the discussion of "processing seemingly irrelevant information" in the chapter "Neurodesign Live").

McKim discusses pertinent cognitive processes under the headline of "hidden likenesses," which need to be discovered. Notably, expectations are high regarding creative breakthroughs that obtain from the discovery of such hidden likenesses. "The discoveries of science [and] art are explorations—more, are explosions of hidden likenesses" (EVT, McKim agreeing with and quoting Bronowski, p. 106). "It is the same act in original science and original art" (p. 106.).

One example is a famous creative breakthrough that August Kekulé achieved in the field of chemistry. He noted and explored the potential likeness of a snake biting its tail (thus forming a ring), and the benzene molecule. Against expectations, the molecule turned out to have a ring structure. (This example is discussed in further detail in Sect. 5).

A more mundane example helps to lay out the presumed role of different representation systems for the discovery of hidden likenesses.

> In the verbal arts, a hidden likeness is encoded in a simile, analogy, or metaphor. Similes and analogies point to likenesses explicitly (for example: "The Renaissance was like the opening of a flower"); metaphors do so implicitly ("the Renaissance blossomed.")

> On the usual conscious level of language, of course there is no likeness between flowers and the Renaissance. The hidden likeness is on a deeper level, beyond words, **where sensory and emotional memories associated with the two words overlap**. (EVT, p. 106, emphasis added)

By using the full spectrum of available representation systems—including especially the often neglected representation systems of sensory and emotional processing—creators increase their chances of discovering hidden likenesses. This, in turn, should make creative breakthroughs much more likely. Once again, however, relaxation abilities and more generally flexibility in thinking levels will also be needed.

> Access to vivid sensory and affective memories, to that portion of memory containing material for the discovery of vivid and illuminating hidden likenesses, often requires the relaxation of conscious control. (EVT, p. 107)

***A41) Versatility in different representation systems, plus flexibility in levels of thinking, strongly increases the chances of a creator to develop breakthrough insights.***

***A42) In biopsychological terms, hidden likenesses are discovered when memories concerning seemingly different topic domains get activated jointly, based on similarities of sensory and affective experiences in the domains.***

The concept of hidden likenesses informs design thinking up to the present. It underlies, for instance, the method "analogous empathy" described in the Bootcamp Bootleg (d.school 2010, cf. Fig. 5).

Representation systems will be treated in further detail in an upcoming review of Conceptual Blockbusting (Adams 1974) in this series on design thinking history.

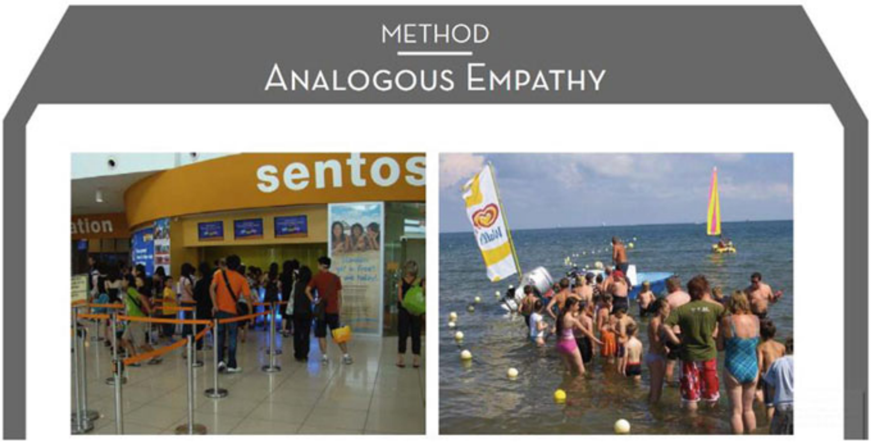



**Fig. 5** With the present-day design thinking method "analogous empathy," creators discover and explore "hidden likenesses" between two or more seemingly different topic domains [image reprinted from d.school (2010, p. 12)]

## 5 The Concept of Ambidextrous Thinking

Ambidextrous thinking is a concept coined by McKim in his discussion of visual thinking, which becomes central for the history of design thinking. Later on, Rolf Faste—a successor of Robert McKim at Stanford's Product Design Department—will advance former "visual thinking" classes towards a curriculum on "ambidextrous thinking." This title serves to emphasise even more the role of diversified sensorimotor engagements beyond the well-explored channel of visual information processing for purposes of creative engineering.

> ME 313, Ambidextrous Thinking, was created in 1988 to meet the needs of incoming Masters degree students in the programs of Mechanical Design, Manufacturing Systems Engineering and Product Design. [ . . . ] "Ambidextrous" means the ability to use both hands [ . . . ] and by extension, use of the whole body, in creative thinking. [ . . . ] ME313 grows out of a course called Visual Thinking which has been required of all undergraduate Mechanical Engineering students for over thirty years. "Ambidextrous Thinking" was chosen as the name because it alludes to more than visual thinking [ . . . ]. (Faste 1994, p. 1)

Years later, the concept of ambidextrous thinking and respective curriculum practices were advanced under a novel headline once again: design thinking. Yet, this part of design thinking history will be reviewed in another chapter of this series.

McKim's concept of "ambidextrous thinking" was inspired by ideas of Jerome Bruner, Abraham Maslow, Ulric Neisser and John Arnold. McKim combines their ideas in a novel framework of thought and practice.

Jerome Bruner's *On Knowing: Essays for the Left-Hand* (1962) discussed ancient symbolisms of the left versus right hand. According to this symbolism, the right hand is associated with "the doer":

> The right is order and lawfulness, *le droit*. [ . . . ] Reaching for knowledge with the right hand is science. [ . . . ] [T]he right hand represents discipline, logic, objectivity, reason, judgement, knowledge, skill, and language. [ . . . ] [T]he symbolic right hand holds the tools necessary to develop, express, and realise ideas, to bring them into the world of action. (EVT, p. 18)

By contrast, symbolically the left hand is associated with "the dreamer":

> Though the heart is virtually at the center of the thoracic cavity, we listen for it on the left. Sentiment, intuition . . . Should we say that reaching for knowledge with the left hand is art? [ . . . ] Developing the symbolism further, the left hand represents openness, receptivity, subjectivity, playfulness, feeling, motivation, and sensory and imaginative processes [ . . . ]. The symbolic left hand is open to fresh impressions, hunches, and subconscious levels of thinking [ . . . ]. (EVT, p. 18)

According to this symbolic view of left versus right hand, neither one will achieve great creative solutions alone. Novel and promising ideas need to emerge from the left, but to put them into action requires skills of the symbolic right hand. Accordingly, Bruner proposes more than multidisciplinary teams with symbolically left and symbolically right-handed team members, or "institutionalised cultural bridges" (EVT, p. 18). According to Bruner, there would have to be "an internal transfer from left to right" (ibid.) in each creative individual. McKim picks up on this notion and elaborates it to a comprehensive concept of ambidextrous thinking.

> Bruner's call for an internal transfer from left to right hands implies a need to integrate the artist and scientist within each one of us [ . . . ]. The individual who is able to bridge the inner messages of his left hand over to his form-giving, outward-oriented right hand, is, to carry the left right symbolism one step further, ambidextrous in his thinking. Truly creative people in every field are ambidextrous—that is, capable of receiving with the left and transferring to and expressing with the right. (EVT, p. 18f.)

***D16) Ambidextrous thinking means that a person is proficient in diverse thinking strategies and she combines them in effective ways: from symbolically "left-handed" approaches (such as being spontaneous, open to dreams, playful and intuitive) to symbolically "right-handed" approaches (such as following organised, well-reasoned and educated work strategies).***

***A43) In order to achieve great creative outcomes, there is not only a need for diverse teams, but each creative individual needs to be capable of diverse thinking strategies; each individual needs to be capable of ambidextrous thinking.***

Up to the present, this outlook is pursued in design thinking education. While teams are assembled to be diverse, there is not a lot of role segregation in practice. All team members make personal experiences in the field (fostering "left-handed" cognitive processing). All team members also engage in synthesis work, often including analyses in a $2 \times 2$ matrix or using other organised approaches (fostering "right-handed" cognitive processing).

To McKim, this theoretical framework of ambidexterity provides a rich background against which he offers, and experiments with, practical trainings. His students are engineers, well-versed in symbolically right-handed activities, such as mathematical calculations or model building. To balance these skills, McKim emphasises symbolically left-handed activities in the curriculum. Whether people are encouraged to train acute perception or daydreaming in the Imaginarium, whether they are asked to take a relaxing bath, doodle in their notebook or conduct stretching exercises as recommended in EVT, or whether there is even a probing of drug effects on creative performance (Harman et al. 1966)—an overarching intention is to induce more symbolically left-handed processes in addition to right-handed cognitive processing. In particular, McKim encourages more intuition-driven, spontaneous, not consciously controlled ideation processes.

While the terminology of ambidextrous thinking may seem unique, the underlying theoretical framework is in fact a classic one (Clancey 2011; von Thienen and Meinel 2019). Many authors have made similar distinctions, akin to the symbolic left versus the symbolic right, which need to work together in order to advance masterful creative outcomes. Table 2 provides a brief overview of terms used by different authors in the design thinking tradition.

Once embracing Bruner's notion of left versus right hand, McKim elaborates the concept of ambidextrous thinking especially based on the works of Abraham Maslow, who had been another guest expert in John Arnold's *Creative Engineering* seminar. McKim discusses the same claims and content that Maslow had personally presented in the 1950s at Stanford, though EVT provides references to more recent

**Table 2** Different authors have described two kinds of creativity approaches, one associated with creative leaps and heightened creativity, the other associated with technical sophistication and a "polishing" of details [adapted from von Thienen and Meinel (2019)]

| | Creative leaps, heightened creativity | Sophistication and polishing |
|---|---|---|
| John Arnold (1959) | Inspired creativity approaches | Organized creativity approaches |
| Robert McKim (1959) | Felt design responses | Reasoned design responses |
| Abraham Maslow (1959) | Primary creativeness | Secondary creativeness |
| Jerome Bruner (1962) and McKim (1972) | Symbolic left hand | Symbolic right hand |
| Rolfe Faste (1994) | Right mode thinking (alluding to the right brain hemisphere) | Left mode thinking (alluding to the left brain hemisphere) |

writings of the author. Maslow does not use the terms "left hand" versus "right hand," but instead writes about "primary" versus "secondary" creativeness.

In Maslow's description, secondary creativeness is typically exhibited by adults, not young children. A classic example would be an effective scientist who is a rather "rigid" or "constricted" person. Someone who exhibits secondary creativeness deals with the world "logically, objectively, and in orderly fashion" (EVT, p. 19). Syndromatically, an adult who is capable of secondary creativeness only "has lost intimate contact with senses, feelings, and his inner fantasy life" (ibid.). Secondary creativeness alone does not yield creative leaps. It is more a matter of polishing, fine-tuning and making gradual step-by-step progress. This contrasts to primary creativeness.

> Maslow, in describing "primary creativeness," agrees with Bruner's statement that "the great hypotheses of science are gifts carried by the left hand." According to Maslow, primary creativeness "comes out of the unconscious." It is the result of [our] ability "to fantasy, to let loose, to be crazy, privately." Primary creativeness "is very probably a heritage of every human being and is found in all healthy children." [. . .] Conscious primary creativeness, according to Maslow, is "lost by most people as they grow up." Most people, that is, whose society demands reality-adjusted thinking only, and whose education has been almost exclusively "right-handed." (EVT, p. 19)

Here, McKim finds further theoretical support for his endeavour to integrate more dreaming activities in the strategy repertoire of engineers, in the service of creativity. McKim continues in his review of Maslow's remarks.

> We all nightly experience primary creativeness in our dreams: "in our dreams, we can be . . . more clever, and wittier, and bolder, and more original . . . with the lid taken off, with the controls taken off, the repressions and defences taken off, we find generally more creativeness . . . ." (EVT, p. 19)

Like Bruner, Maslow also points to the necessity of integration—a message that McKim endorses wholeheartedly. "A truly integrated person can be both secondary and primary; both mature and childish. He can progress and then come back to reality, becoming then more controlled and critical in his responses" (Maslow quoted by McKim in EVT, p. 19).

One reason why this framework of ambidextrous thinking becomes so important in EVT, is because it interplays straightforwardly with McKim's theory of representation systems. Here, it underpins the importance of visual thinking for high levels of creative performance. When people use the visual representation system, they are in touch with their senses (at least the visual sense channel), which is said to advance primary creativeness/symbolically left-handed thinking. By contrast, when people predominantly use representation systems of mathematics or verbal languages, this is assumed to advance secondary creativeness/symbolically right-handed thinking.

> The verbal thinker, especially, tends to think in this second-hand way: he skilfully manipulates symbols but rarely makes full contact with his own primary resources. Visual thinking is a marvellous antidote for this sterile, one-sided kind of thinking. Or more correctly, visual thinking with its symbolically left-handed, primary-process origins, is a vital complement to symbolically right-handed, secondary-process thinking-by-words-and-numbers. (EVT, p. 21)

Maslow describes a prototypical example of overreliance on verbal thinking and resulting "mere" secondary creativeness. He portraits a scientists who spends his academic career pre-dominantly by working with texts: reading and writing. In this form of academic life, primary, sensorimotor experiences in the world are barely sought. Thus, primary creativeness does not get stimulated.

> As Maslow suggests, the individual [scientist] who is capable only of "secondary creativeness" [...] stands on other people's shoulders, thinking about the written thoughts of someone who, in turn, was writing about an idea that he had read—and so on. (EVT p. 21)

***A44) Visual thinking is a symbolically left-handed activity, which facilitates primary creativeness (i.e. heightened creativity; creative leaps).***

***A45) Verbal and mathematical thinking are symbolically right-handed activities, which facilitate secondary rather than primary creativeness (i.e. technically sophisticated solutions mostly in existing paradigms).***

Against this background, the unique relationship between design thinking and libraries can be reconsidered in theoretical terms. In an empirical research study, design thinking experts had named libraries amongst the "top three environments" that would antagonize design thinking (von Thienen et al. 2012). Moreover, existing design thinking facilities—even when located at universities—typically do not encompass large "university-typical" libraries. McKim's reflections provide a theoretical background, which helps to elucidate present-day thoughts of design thinkers about libraries: An environment that is predominantly filled with texts can make it difficult for visitors to make first-hand experiences immersed in the world, as one is rather reading second-hand about the experiences of others. Texts and mathematical treatises court verbal and mathematical processing, as opposed to immersive sensorimotor experiences in the world. At the same time, McKim's overarching purpose was to encourage flexibility, i.e. the use of all representation system in balanced ways. This might argue in favour of libraries to be used for some time, carefully balanced with immersive polysensory experiences at other times.

According to the theory of ambidextrous thinking . . .

***M9) Environments need to promote sensorimotor engagement and symbolic processing in carefully balanced ways in order to promote both primary and secondary creativeness (ambidextrous thinking), to foster highest levels of creative performance.***

***M10) Environments that predominantly provide texts, such as libraries, bias towards symbolic information processing; to encourage ambidextrous thinking, they need to be complemented by other environments that foster poly-sensory experiences in the world.***

***M11) The theory of ambidextrous thinking elaborates creative mastery as a phenomenon of embodied cognition; the individual is said to achieve highest levels of creative performance only when she seeks out, and integrates, sensory-motor experiences with symbolic information processing.***

In EVT, McKim also turns to history and reviews case examples of outstanding innovators to find characteristic patterns in their approaches. Before him, in a similar manner, John Arnold had reviewed works of famous creative persons to identify distinctive work patterns. McKim emphasizes two regularities: In the cases he reviews, all innovators benefitted from visual thinking in their work, and they used visual approaches as part of ambidextrous thinking strategies:

> In chapter 1, scientists Fleming, Watson, Kekulé, and Einstein and engineers Tesla and Houbolt are revealed as eminently ambidextrous. Kekulé's dream of a snake biting its tail, for example, is left-handed, while his verification of this insight in his laboratory and within the theoretical framework of chemistry is the work of his disciplined right hand. (EVT, p. 19)

In the case of the chemist Kekulé, for instance, a description of the creative process was provided by the chemist himself. Kekulé had provided an account of how he had tried to figure out the structure of the benzene molecule for a long time. Then, sitting in front of a fireside, in a state of dreaming he experienced the visual imagery of a snake biting its tail. This engendered Kekulé's idea that the benzene molecule might have a ring structure, which he later verified in chemical experiments. Analysed in the framework of ambidextrous thinking, and McKim's theory of creativity more generally, this episode displays a number of characteristic elements. Kekulé relaxes. He dreams. He experiences visual imagery. Thoughts emerge from automatic/non-conscious levels of processing (not only from deliberate thinking with attention "on task"). All this is essential for Kekulé to achieve a creative leap. However, a symbiosis is required between these symbolically left handed activities, and the symbolically right handed rigour of a capable scientist. It takes ambidextrous thinking to achieve the creative breakthrough.

> Again, it is not a question of one or the other: sensory imagination and symbolic thinking are complementary, each performing mental functions that the other cannot. [. . . ] Specifically, the creative thinker is ambidextrous: he uses his symbolic left hand as well as his right [. . . ]. Learning to think visually is vital to this integrated kind of mental activity. (EVT, p. 22)

## 6 The ETC Model for Creative Work: Express, Test, Cycle

In addition to more general reflections, as concerning the concept of ambidextrous thinking, McKim also provides immediately practical advice. One notable contribution is his "ETC model" to facilitate creative processes. The acronym stands for Express (Sect. 6.1), Test and Cycle (Sect. 6.2).

As one of the first visualisations in our work tradition, the ETC model introduces bold graphic circles to highlight the essentially iterative nature of creative work. Figure 6 compares McKim's ETC model to a more recent design thinking process model.

Markedly, the ETC model is only concerned with a very brief passage in the overall creative process, namely with the stages of ideation and testing prototypes. Clearly, this does not indicate McKim's overall treatment of creativity was this limited—it was not. In his Advanced Product Design courses, McKim introduced elaborate need finding exercises, where participants went out to meet potential users, for whom novel products might be designed. In this context, he advanced methods that are used up to the present day for creative process phases prior to ideation. Moreover, courses such as Product Design and Presentation (112c) offered by McKim carefully considered methodologies to advance final prototypes towards real-world products. Here and in Advanced Product Design, the concern was to make a big impact in the world, which is nowadays treated in the final

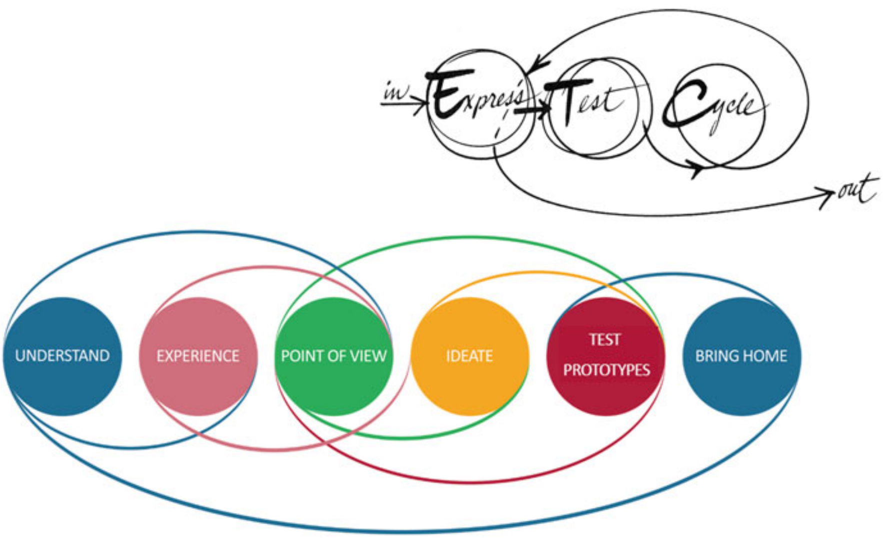



**Fig. 6** The ETC model is only concerned with the stages "ideate" and "test prototypes" of a recent-day design thinking process model. Graphically, in the ETC model, circular lines connecting different process phases underscore the essentially iterative nature of creative work. This graphic element is used up to the present to communicate the need for iteration in creative processes

"bring home" phase of creative projects. Thus, early and late stages of the creative process are simply not the core topic of EVT and the ETC model. Even so, McKim's theoretical treatments reveal unmistakably, how important objectives of "understanding," "experiencing," probing "points of view" and "bringing home big ideas" are for his overall account of creativity.

Regarding the objective of *understanding*, McKim emphasises the importance of developing "correct," "adequate" accounts of situations, in order for thinking to be productive. "Since thinking is essentially information-processing, we cannot expect productive thinking when information is incorrect, inadequate, or tucked away in an unavailable crevice of memory" (EVT, p. 2). He continues, "Each reader must seek these [ . . . ] conditions without much aid from this book: [ . . . ] information requirements vary with each problem" (p. 2). At the same time, EVT provides theoretical reflections and practical advice in numerous sections, as to the difference between productive versus non-productive thinking, how readers can recognise unproductive thinking phases, and how they can redirect their own thoughts towards more fruitful trajectories.

The objective of *experiencing* is a key topic throughout EVT. McKim explains how immersive experiences with great perceptual awareness regarding all human sense modalities are essential for high levels of creative performance. Without this mindfulness, thinking is bound to abstract, symbolic processing, which all too often merely reproduces stereotypes. Individuals who only use a few representation systems, where specifically sensory-motor systems and feelings are disregarded, cannot expect to escape language-bound, culturally conveyed traditional concepts that advance thinking inside the box. "Taught always to name what they see, many students learn to label the [ . . . ] stimulus too quickly, before they see it fully" (EVT, p. 24). Thus, asked to draw a tree, they "can only draw a primitive green lollipop" (ibid.)—a tree stereotype. McKim seeks to help students escape the rut of stereotyped symbolic processing, by gaining immersive experiences in the world and learning to be mindful about the here-and-now.

Similarly, *points of view* are a re-current, often addressed topic in EVT. The term McKim uses most regularly in this context is "recentering." He explains how personal knowledge and training impact the way in which we see the world. "A dentist and a psychologist see the same smile differently" (p. 83). Moreover, communities have a strong formative effect upon perception, and emotional blocks prevent us from seeing things differently. Here, McKim adds psychological theories of perception concerning a topic discussed in his *Creative Engineering* guest essay before (where he had addressed cultural need hierarchies; cf. McKim 1959/2016; von Thienen et al. 2019).

> To judge whether your own vision has been stereotyped by fear, be aware of your emotions with regard to "unacceptable" images. For example, be aware of your feelings when your clothing is somehow conspicuous. [ . . . ] More important, ask how far you could depart from the visual norm of fashion without having real reason to fear losing friends, losing your job, or even being "put away" in a mental institution. Social coercion patterns perception more powerfully than we are usually aware. (EVT, p. 45)

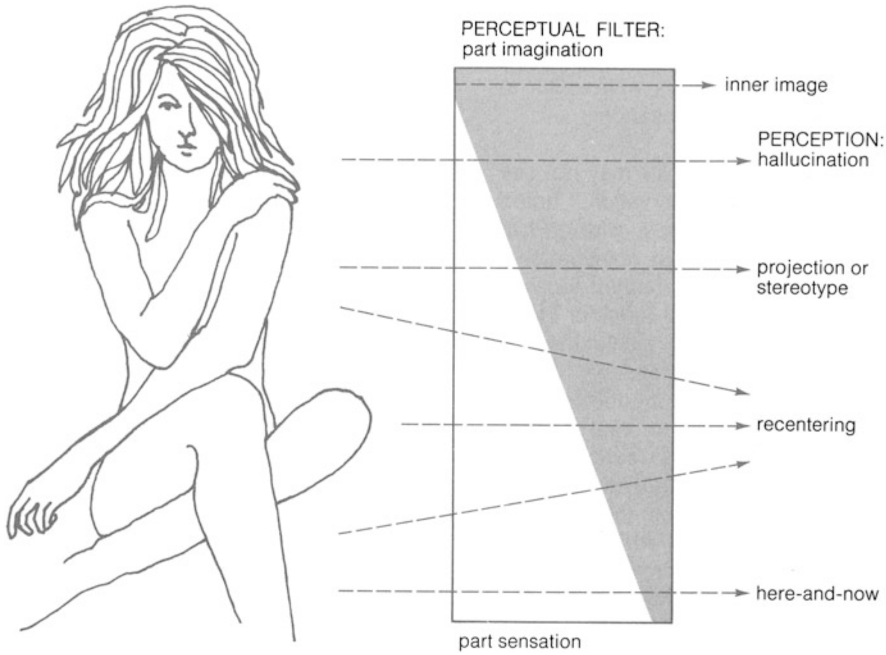



**Fig. 7** Recentering, the act of exploring a novel point of view, is very close to mindfulness of the here-and-now. There are many ways to recenter. By contrast, when a person perceives based on stereotypes, or when she hallucinates, her perceptions are dominated by imagination (image reprinted from EVT, p. 44)

Against culturally pre-determined views, McKim holds: "Healthy perception is not stuck in a cocoon of cultural conditioning; it is open, flexible, and alive" (p. 45).

> The key concept is *flexibility*. The person who can flexibly use his imagination to recenter his viewpoint sees creatively. The person who cannot budge his imagination to see alternative viewpoints, by contrast, experiences only a one-sided, stereotyped vision of reality. (EVT, p. 44)

Figure 7 provides a graphical illustration of how McKim understands recentering, i.e. the healthy and flexible exploration of different possible viewpoints. Notably, recentering is very close to mindfulness of the here and now. The individual uses some imagination to explore different possible points of view. However, these different viewpoints are all rather reality-adjusted; they are all viable. There is a large distance to hallucinations, where perceptions are dominated by imaginations that are not reality-adjusted. Moreover, recentering is flexible; there are many ways (arrows) of recentering. This contrast to perception following the single trajectory of a dominant stereotype.

> Recentering is characterised by the flexible ability to change from one imaginative filter to another. The recentering perceiver might, for example, see the naked lady as would a sculpture (perhaps assessing the formal quality of her pose), as would an advocate of women's liberation (she's being exploited), then as the lady herself (I feel a bit chilly), and so on. (EVT, p. 44)

***D17) Recentering means to perceive something from a novel viewpoint.***

Methodologically, to train people's abilities of recentering, McKim invokes exercises such as "making the familiar strange" or verbal "re-labelling"—approaches used occasionally in design thinking up to the present.

Regarding the *bring home* phase in creative projects, McKim provides many pages of examples in EVT that depict and compare externalisations/models/prototypes of successful creators from earlier and later work stages. He emphasises how prototypes usually evolve from rough to refined. Quite often, there is a trajectory from 2D sketches to 3D models. Final solutions need to consider many details of appeal and usability, such as the sensory feeling of the materials used, the exact positioning of knobs etc.—topics already elaborated in McKim's *Creative Engineering* guest essay (McKim 1959/2016; von Thienen et al. 2019).

***M12) The ETC model only covers the phases in a creative project concerned with ideation and testing prototypes; McKim's overall work, however, covers the full palette of process phases distinguished in present-day design thinking processes models, from understanding a problem to bringing home big ideas.***

Amidst all phases and objectives in creative work comes the ETC model: Express, Test and Cycle. As in present-day design thinking compilations, the model is introduced together with dedicated methodological suggestions regarding each phase, structurally very similar to the Bootcamp Bootleg (d.school 2010).

To understand suggested methods of the ETC model theoretically, especially in the express phase, it is important to bear in mind that McKim uses the model to translate the concept of ambidextrous thinking into educational practice. Here, the major methodological question emerges how creators can bridge their symbolically left and symbolically right hand. How is it possible to receive inspiration from automatic, non-deliberate cognitive processes and then create something tangible that facilitates deliberate creative work?

To recall, this is the concept of ambidextrous thinking, which McKim sets out to translate into practical exercises and methods for education in class: "The symbolic left hand is open to fresh impressions, hunches, and subconscious levels of thinking" (p. 18). "The symbolic right hand holds the tools necessary to develop, express, and realise ideas, to bring them into the world of action" (ibid.). "The individual who is able to bridge the inner messages of his left hand over to his form-giving, outward-oriented right hand, is [ . . . ] ambidextrous in his thinking. Truly creative people in every field are ambidextrous—that is, capable of receiving with the left and transferring to and expressing with the right" (p. 19).

## 6.1 Express

"'Ex-press' means to **press out**. Idea-sketching is a way to express visual ideas, to literally press them out into tangible form" (p. 116, emphasis in original). When interesting ideas emerge in the mind, McKim highlights their elusive and quickly changing character. The creative person needs to take immediate behavioural action in order to not lose track of the idea.

Creating rough sketches seems to be an ideal technique to capture visual ideas: Rapid Visualization.

McKim describes the experience:

> ...the model for idea-sketching is an inner event visible only in the mind's eye, rarely fully formed, and easily lost to awareness. The visual thinker who uses drawing to explore and develop ideas makes many drawings; idea-finding and formation is not a static, "one picture" procedure. He also draws quickly, ideas rarely hold still; they readily change form and even disappear. (EVT, p. 116)

***A46) An emerging idea is dynamic and indefinite; the individual needs to externalize it rapidly in some representation system, before it vanishes from awareness.***

The objective of having to be highly sensitive to one's own imagery and extremely fast in order to record novel ideas is also underpinned by a distinction McKim invokes, where he emphasizes different methodological necessities in earlier versus later phases of idea development.

> Graphic ideation has two basic modes: exploratory and developmental. In the exploratory mode, the visual thinker probes his imagination with his marker, seeking to touch and record the vague and elusive imagery that usually accompanies the conception of a new idea [...]. In the developmental mode, the visual thinker gradually evolves a promising, though initially embryonic, concept into mature form. (EVT, p. 116)

***D18) Exploratory ideation is concerned with the recording of emerging ideas; major methodological challenges include (a) recognizing novel ideas in one's constantly changing imagery and (b) being fast enough to record ideas before they are lost to awareness.***

***D19) Developmental ideation is concerned with the maturation of novel ideas; major methodological challenges concern the achievement of sophistication regarding an idea.***

During exploratory ideation, the individual can choose among many different representation systems to record emerging ideas. McKim encourages readers to be mindful of different options they have. Even when novel ideas appear in the form of visual imagery, they can be captured in different formats. "Visual ideas can be expressed by acting them out, talking about them, writing them down, constructing them directly into a three-dimensional structure—and drawing them" (p. 116).

***A47) Different representation systems can be used to capture emerging ideas.***

The necessary speed to record novel ideas can be obtained by creating sketches, instead of detailed representations. Sketches can be engendered in many different representation systems. Body-motion, verbal accounts, 3D models or 2D drawings can all be engendered in sketch-form.

> What are the characteristics of a sketch? Actors perform "sketches" that are customarily short and informal; writers "sketch out" their ideas in outline form and in rough, preliminary drafts; sculptors make rapidly executed "three-dimensional sketches" before proceeding to the final expression of their idea. In whatever form it takes, a sketch is typically (1) self-intended or directed to a small in-group, (2) concerned more with chief features than with details, and (3) performed spontaneously and quickly. Sketches that record the excitement of idea generation and formulation also often possess a vitality and freshness lacking in the final communication. (EVT, p. 116)

***A48) To capture emerging ideas in any representation system, it is best to use rough sketches instead of detailed representations.***

***D20) A sketch is the representation of an idea or conceptualization in a form that is (1) meant for use by oneself or one's team only, (2) concerned more with chief features than with details, and (3) it is performed spontaneously and quickly.***

Furthermore, any procedure of capturing emerging ideas thrives on psychological safety, which allows the creator to devote full attention to emerging ideas only. There need not be any "chatter" in the creator's mind as to what others might think, or what they might need to be told in order to understand and like an idea. The only concern for a creator to care about—the only focus of his voluntary attention—needs to be his own creative undertaking.

> Being his own audience, the graphic ideator enjoys certain freedoms [ . . . ]: he can sketch freehand, quickly and spontaneously, leaving out details that he already understands that he believes might concretize his thinking prematurely [ . . . ]; he feels free to fail many times on the way to obtaining the solution. (EVT, p. 117)

***A49) (Graphic) Ideation is to be conducted in a state of psychological freedom or safety, where the creator does not think about perspectives of others; this helps individuals maintain voluntary attention on the ideation objective (not on social concerns); it helps individuals represent ideas before they get lost, and ultimately it increases productivity.***

Psychological freedom or safety has also been a topic in design thinking research, where similar concerns have been highlighted as those described by McKim (Leifer and Auernhammer 2021).

(Graphic) ideation contrasts to (graphic) communication. Methodologically, communication concerns should be addressed in later process phases.

***A50) (Graphic) Communication is to be conducted with a focus of attention directed towards social objectives; here, the key question is how to best present an idea so that other understand (and possibly like) it.***

> Graphic ideation is not to be confused with graphic communication. The former is a formative process concerned with *conceiving and nurturing ideas*; the latter is an explanatory process concerned with *presenting fully formed ideas to others*. Graphic ideation is visually talking to oneself; graphic communication is visually talking to others. Graphic ideation precedes graphic communication in most instances: the visual thinker must first discover and develop an idea worth communicating. (EVT, p. 117)

Just like social communication concerns, self-critical reflections should also be silenced in the ideation phase.

> *Defer judgement*. Attempting to express and to judge ideas simultaneously is comparable to trying to drive a car with one foot on the accelerator and the other on the brake. (EVT, p. 118)

In this regard, McKim's discussion is very similar to that of Arnold in *Creative Engineering*—even up to the references he provides, to Guilford, Osborn and Schiller.

***A51) To facilitate ideation, individuals need to defer judgement.***

***D21) An individual defers judgement during her own ideation process when she does not engage in critical reflections regarding herself, her ideas and her externalizations.***

In this regard, McKim also mentions the importance of some basic skills in the externalisation process, such as drawing skills to capture visual ideas. Lacking skills easily induce judgemental thinking, and they can also have other negative consequences.

> The importance of drawing skill to the full expression of visual ideas must not be overlooked. Inadequate drawing ability has three negative effects on the *E*xpress phase of ETC: (1) a clumsy sketch usually evokes judgemental processes that restrict or stop idea-flow, (2) ideas that cannot be adequately recorded in sketch form are often lost, and (3) attention devoted to problems of drawing is attention diverted from idea-generation. (EVT, p. 119)

***A52) Insufficient externalisation skills hamper the ideation process; they (i) induce judgemental thinking, (ii) lead to a loss of creative ideas as these are not captured fast or adequately enough and (iii) they hamper "voluntary attention," which should be uniquely devoted to ideas and not to (difficulties of) the externalisation process.***

Yet, conducted in favourable psychologic conditions and with suitable skills, the externalization process itself facilitates ideation. Notably, this includes great flexibility on the key dimension of concrete versus abstract thinking.

> [There are] two important attributes of graphic ideation. First, the sketches are relatively "rough." They are not intended to impress or even to communicate; instead, they are a kind of graphic "talking to oneself." Second, [ . . . ] [i]dea-sketching, likely thinking itself, moves fluidly from the abstract to the concrete. (EVT, p. 10)

***A53) One indicator of productive ideation is a fluent movement between concrete and abstract treatments of the topic, which can be identified in idea sketches.***

An example of graphic ideation in contrast to graphic communication is provided in Fig. 8.

Overall, the phase of *E*xpression in the ETC model is concerned with several ends.

***A54) The aim of the Expression phase in the creative process is to (i) identify ideas as they come to mind, (ii) externalise them adequately, so as to not forget about them and to (iii) facilitate the emergence of further ideas.***

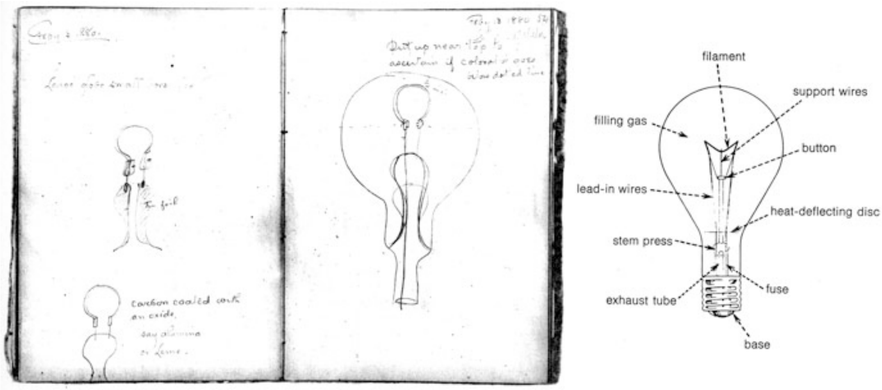



**Fig. 8** The drawing on the left shows a notebook of Thomas Alva Edison, as an example of graphic ideation, depicting steps "in the birth of an idea" (EVT, p. 117). The drawing on the right is taken from a General Electric catalogue as an example of graphic communication (both images reprinted from EVT, p. 117)

From present-day design thinking perspectives, McKim emphasises quite strongly cognitive processes of the individual in the moment of recording ideas. Today, most commonly ideas are not recorded in moments of social withdrawal, but rather in situations of a team searching for good ideas jointly. Notably, this is clearly a situation McKim finds fully compatible with his account, as he specifically lays out how initial idea-sketching can be conducted in small "in-groups"—like design thinking teams.

With his reflections, McKim places a "magnifier" on a cognitive process that does occur individually—at the time of EVT and just as much today. When jotting down ideas for the first time, an individual takes action, and she does so as part of an ongoing cognitive processes, which can be studied as *her* cognitive process. McKim provides methodological advice for the person as to what can be important in this very brief moment when a novel idea takes shape in one's mind. The message sounds like a triviality accepted as a matter of course by present-day design thinkers: Sketch your idea out quickly, before you forget about it. Yet, much beyond seeming trivialities, McKim's studies into exploratory ideation have led him to endeavour comprehensive reflections on, and experimentation with, prototyping materials (Sect. 7.2). After all, different materials and equipment can be more versus less helpful for people to create rapid idea sketches. The sophisticated knowledge design thinkers enjoy today regarding the use and impact of different prototyping materials emerged, in theoretical terms, from McKim's theory of ambidextrous thinking and his studies into (materially facilitated) ideation.

***M13) McKim's account of ideation is concerned with individual cognitive processes, which take place during the first recording of ideas, regardless of whether people search for novel solutions alone or in teams.***

***M14) McKim's concepts of ambidextrous thinking and ideation have furthered extensive knowledge regarding the impact of prototyping materials on cognitive processes—knowledge that design thinkers use in practice up to the present.***

## *6.2 Test and Cycle*

The move from idea *E*xpression to *T*esting is characterised by a shift in one's mindset, thinking mode or viewpoint:

> Once you have expressed a number of ideas [. . . ], you are ready to evaluate them. Judgement, deferred in the *E*xpress phase of ETC, is fully exercised in the *T*est phase. Now is the time to be self-critical, not before. [. . . ]
>
> The most crucial imaginative act in the *T*est phase is moving from the viewpoint of creator to the viewpoint of critic. As you view your sketches, imagine yourself in the role of a constructively critical person [. . . ]. (EVT, p. 121)

***A55) To facilitate testing, the individual needs to endorse the outlook of a constructive critic and needs to engender critical judgements.***

Here, McKim also introduces a treatment of different creative process phases as relating to different mindsets, viewpoints or thinking modes. This outlook is maintained up to the present in design thinking education. For instance, the d.school Bootcamp Bootleg does not speak of "process phases" at all, but of different "modes" during the process.

***M15) When present-day design thinking treatises (like d.school Bootcamp Bootleg) address different phases of the creative process as different process "modes," this mirrors McKim's treatment of the topic in EVT. Here, McKim emphasizes how creators need to change their viewpoint/outlook/thinking mode from one process phase to the next.***

Methodologically, "testing involves (1) seeing your sketches fully and imaginatively, (2) comparing sketches, (3) evaluating each idea in relation to present criteria, and (4) developing new criteria" (p. 121):

> The first step in the *T*est phase of ETC is to display all of your idea sketches side-by-side. Once displayed, your graphic memory is fully available for the active operations of testing. [. . . ]
>
> Place all your idea sketches on a wall, table, or floor. Step back for an overview. As you view your idea-sketches, attempt to see them as fully and imaginatively as possible, recentering the way you see into a variety of viewpoints. (EVT, p. 121)

Figure 9a shows a visual display as used in architectural practice and education at the time of EVT.

McKim also notes how critical assessments benefit from piece-by-piece presentations of ideas. The recentering that he asks for in the test phase is methodologically facilitated, to a considerable degree, by the grouping and regrouping of ideas in different ways. Thus, McKim's consideration regarding the *T*est phase can be seen as anticipating methods such as "saturate and group" as described in the Bootcamp Bootleg (d.school 2010, Fig. 9b).

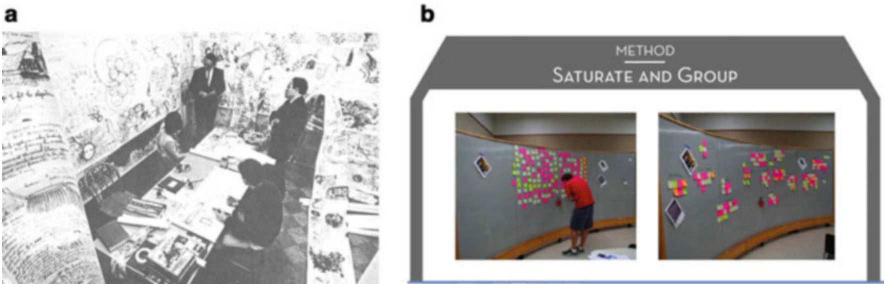



**Fig. 9** (**a**) Visual displays common around 1970 (image reprinted from EVT, p. 120). (**b**) Visual displays common in present-day design thinking sessions [image reprinted from d.school (2010, p. 14)]

> Physically grouping and regrouping the sketches usually facilitates comparison. Moving your sketches out of the order in which they were expressed and into new juxtapositions also often causes ideas to be seen afresh. (EVT, p. 121)

As an educator and practitioner, McKim immediately considers how equipment and classroom designs can best facilitate the *T*est phase. He comes close to inventing Post-it™ Notes (invented at 3M shortly after the publication of EVT). Certainly McKim's recommendations in EVT created a ready use for sticky notes, once they became available on the market.

> Note how the format of your idea-log influences your ability to compare. A bound notebook makes comparison clumsy; a continuous scroll of sketches prevents side-by-side comparison. Comparison, essential to the act of evaluation, is facilitated by a loose-leaf format that permits you to juxtapose and group [ . . . ] freely. (EVT, p. 121)

***A56) To test ideas, it is helpful to display all available options side-by-side; grouping and re-grouping helps to develop novel views on the material and to develop criteria for evaluation.***

***A57) Using small, separate paper leafs (like present-day Post-it™ Notes), each depicting just one brief idea, facilitates the process of evaluating large amounts of material; the loose leafs can easily be grouped and regrouped.***

Another important objective in the *T*est phase is to deploy criteria in order to evaluate different options. A crucial aspect in this endeavour occurs on a meta-level. *T*esting also means learning which criteria to invoke. What is a worthwhile problem to address? Which needs should the solution address?

> Testing, of course, implies criteria. In the early rounds of ETC, criteria are usually imprecise, incomplete, and implicit. Initial criteria are also frequently inaccurate. The final function of the *T*est phase is to review criteria and to state them more exactly. [ . . . ] As you formulate and refine your criteria, record them in writing. The revised statement of criteria is an invaluable aid in the next round of ETC. (EVT, p. 121)

***A58) The overarching aim of the test phase is to develop an ever better understanding of the criteria that one's solution shall meet (which problem is to be solved with a novel solution and what does the solution need to achieve, in precise terms?).***

Recent design thinking practices are closely in line with the objectives McKim describes here as part of the ETC model. Both practices and methodologies evolve in the legacy of the ETC approach.

A good example is the Stanford Design Thinking Virtual Crash Course (d.school 2012), which offers an introduction to design thinking in just 60 min. In pairs of two, participants develop solutions for each other, e.g. to enhance the partner's gift-giving experience. In a first testing round, each participant has about a handful of solutions to test with a partner. The major aim here is not to present seemingly perfect solutions already, but to find better criteria for what should be developed in the first place. Then participants iterate and return to ideation. Now they understand even better what the partner needs, and novel solutions can benefit from this refined set of criteria.

In terms of methodologies, "Design Principles" described in the Bootcamp Bootleg provide a good example of approaches in line with McKim's ETC model. "Design principles" are "statements of criteria" that, according to McKim, should be refined in the *T*est phase.

Here is a description of the method "Design Principles" in the Bootcamp Bootleg:

> You, as the designer, articulate these principles, translating your findings—such as needs and insights—into design directives. These principles give you a format to capture abstracted, but actionable, guidelines for solutions, and communicate your design intentions to others. (d.school 2010, p. 25)

***M16) The use of iteration to engender learnings about "what is worth developing" outlined in the ETC model is a core element of design thinking up to the present. McKim wrote about "test criteria" that should be refined over time; in the Bootcamp Bootleg they re-appear in the form of "design principles."***

After *T*esting, the next step in the ETC model is to *C*ycle. Thus, people engaged in creative activity can expect to iterate process phases a couple of times before they have developed a solution that seems ready for public release. Notably, each iteration engenders novel learnings, so going back does not mean to start from square one. Moreover, creators shall develop a metacognitive oversight regarding the process. Decisions as to where the project shall continue—how far to move back when iterating?—can be taken in increasingly deliberate ways. Of course, with a longer process model (e.g., from understanding to bringing home) it can be decided in an even more fine-grained way how far creators want to move backwards when they iterate, and to which earlier phase exactly they want to return:

> The first round of idea sketching rarely produces an idea that fully meets your test. After evaluating your first concepts, you are ready to return to idea sketching. At this point, it is often valuable to pause and consider the next strategy you will use in search of a solution. *C*ycling, the third step in ETC, is more than a return to another round of idea expression; it is a return with an idea generating strategy mind. [...] An individual who decides to

> develop one concept in considerable detail has decided on a strategy. Another who opts to generate more ideas before delving into detail with one has decided on another strategy. (EVT, 121f.)

***A59) Major aims of cycling in the creative process are to (i) develop an increasingly better understanding of what solution to develop in the first place: criteria for a worthwhile solution (ii) to get better and better at delivering the worthwhile solution and (iii) on a meta-cognitive level, to gain oversight over the creative process, allowing mindful and pointed choices of where to move next, or where to move back, in the creative process.***

## 7 The Importance of Places: Or—Embedded Cognition

In present-day introductions, design thinking is often said to build on three pillars: creative processes, creative people and creative places, the so-called 3 Big P (see Fig. 10). Indeed, few other approaches to the teaching of creativity and innovation include such thorough knowledge about the impact of places on creative performance, and few dedicate as much care to the design of places for the specific purpose of facilitating creativity.

In the history of design thinking, McKim achieved major milestones regarding our theoretical understanding of places. He also introduced many lasting "best practices" in the design of places for purposes of creativity and innovation.

Before McKim, Arnold had already addressed the impact of places in *Creative Engineering*, but his discussion had remained rather brief. Most notably, Arnold discussed (1) place arrangements that help teams maintain high levels of energy in long creative teamwork sessions, and (2) psychological safety as a social condition at workplaces to unleash peoples' creative potential.

To maintain high levels of energy, Arnold had recommended providing . . .

> one less chair than the number of people attending the [creative team] session. This means that one man stands or sits on the edge of a desk or even on the floor. Should any man seated in a chair get up to move around or leave the room for any reason the unseated man quickly takes the vacated chair and so there is a **continual, though imperceptible movement throughout the session, therefore no one becomes physically or mentally fixed**. (Arnold 1959/2016, p. 111, our emphasis)

Like McKim, Arnold had highlighted the impact of body posture and motion on psychological states, including peoples' creative abilities.

Beyond this, Arnold had described social and psychological conditions that need to obtain at the workplace in order for people to be most creative. Ideally, "external standards of evaluation are completely absent. You have **no fear of being thought or being called a fool**" (Arnold 1959/2016, p. 108, our emphasis).

McKim continues to explore the impact of places, and he also seeks solutions that work well in practice. Yet, McKim's account is considerably more comprehensive


**Fig. 10** Design thinking builds on three pillars: (knowledge concerning) creative people, creative processes and creative places, the so-called "3 P" [image adapted from D-School (2020) (https://hpi.de/en/school-of-design-thinking/design-thinking/what-is-design-thinking.html)]

and systematic. Most of his suggestions are common practice in design thinking today.

Overall, McKim discusses "places" in a conceptual framework that nowadays would be headlined as "embedded cognition." Here, the idea is that environments are so crucial for the cognitive processes and behaviours of individuals, that it makes no sense to study individuals alone, detached from environments (Clancey 2018). McKim wholeheartedly endorses such a view.

He emphasizes how different tools, such as pen and paper, and people's abilities of using them define to a large extent people's behavioural options and their on-task performance. "Once he has mastered the use of a tool, it becomes almost an extension of his hand" (p. 161). "His knowledge and skill with his tools ... determines a substantial part of his overall ability" (ibid).

Moreover, actions taken with suitable tools are understood as "enhanced cognitive processes." Thus, McKim speaks of "drawing to extend one's thinking" (p. 10).

> Drawing not only helps to bring vague inner images into focus, it also provides a record of the advancing thought stream. Further, drawing provides a function that memory cannot: the most brilliant imager cannot compare a number of images, side by side in memory, as one can compare a wall of tacked-up idea sketches. (EVT, p. 10)

This is a major purpose, if not *the* most important purpose, McKim provides to explain why people should be drawing. For the most part, during the creative process, drawing does not serve the purpose of communicating fully formed ideas to audiences, but it facilitates the creative thinking process itself.

Moreover, the environment provides strong cues for the individual. For instance, "the materials used are important: inflexible materials tend to cause rigidity in thinking." (p. 40). Thus, environments need to be designed very carefully, in order to provide cues that facilitate intended cognitive processes, such as creative thinking.

Finally, environments shall support the flexibility a creative thinker needs to move between relaxation and energetic attention, between attention directed inward or outward, between phases of single-person pursuits versus teamwork.

## *7.1 Environments to Facilitate Externalized Thinking*

Straightforwardly, McKim encourages thinking by manipulating materials:

> Consider the sculptor who thinks in clay, the chemist who thinks by manipulating three-dimensional molecular models, or the designer who thinks by assembling and rearranging cardboard mockups. Each is thinking by seeing, touching, and moving materials, by externalizing his mental processes in a physical object. (EVT, p. 40)

In present-day terminology, one major advantage of working with physical models instead of mental representations only is that it reduces the load of the working memory. The person does not need to put as much cognitive effort into the maintenance of a mental simulation and therefore has more capacities for other cognitive operations, such as being creative.

Going beyond this, authors like Bamberger and Schön (1983) have argued that in notable cases creative constructions could not occur without tangible form. Conceptions develop in a dynamic interplay of perceiving, reconceiving and doing.

As McKim explains, "externalized thinking involves actively manipulating an actual structure much as one would manipulate that structure mentally" (EVT, p. 40).

The approach of carrying out thinking in the world ("externalized thinking") is often discouraged by conventional education, as McKim says. Thus, students need to re-learn how to facilitate productive thinking by means of working with materials.

> Although you have been educated to do otherwise, link perception, thinking, and action as closely together as you possibly can. Cut; fold; touch; test; hold the pieces together in a new way. Externalize your thinking, as if the process were described accurately by one word, "perceive-think-act." (EVT, p. 40f.)

Notably, the word "perceive-think-act" corresponds to the structure of EVT with its three chapters of seeing-imagining-idea sketching, to explore the realm of visual thinking. Thinking in other modalities, in other representation systems, could be elaborated accordingly.

***D22) Externalized thinking means to engage in the triple-activity of "perceive-think-act" at once or in rapid iteration, in order to arrive at novel, worthwhile solutions.***

***D23) Internalized thinking means to not use "perception" and/or "action" out of the repertoire of "perceive-think-act" in order to arrive at novel, worthwhile solutions.***

***A60) In the realm of visual thinking, the headline "perceive-think-act" translates to "see-imagine-sketch idea" in the context of creative projects.***

When an idea is not only pondered in the mind, but also physically expressed, clearly this has a number of advantages. For instance, the person can take a break and does not have to be afraid of forgetting the idea, as it is captured for later. "Idea sketches are a remarkable extension of imagination, a kind of *visible graphic memory*" (p. 121). McKim also addresses a number of further advantages.

> Externalized thinking has several advantages over internalized thought. First, direct sensory involvement with materials provides sensory nourishment—literally "food for thought." Second, thinking by manipulating an actual structure permits serendipity—the happy accident, the unexpected discovery. Third, thinking in the direct context of sight, touch, and motion engenders a sense of immediacy, actuality, and action. Finally, the externalized thought structure provides an object for critical contemplation as well as a visible form that can be shared with a colleague or even mutually formulated. (EVT, p. 40)

***A61) Artefacts created in the course of externalized thinking can be created in any medium or representation system and are typically created intentionally.***

***A62) Compared to internalized thinking, externalized thinking has a number of advantages: it provides memory aids, both short-term and long-term; it nourishes thinking with sensory details; it promotes serendipitous discoveries; it reveals opportunities for action; it facilitates the critical assessment of an idea; it helps to compare different solutions side-by-side; it enables communicating ideas to others—shared artefacts are a vital means for co-creation of ideas in teams.***

Naturally, this concept of externalized thinking encourages a corpus of theorising and practices concerning prototyping materials.

## *7.2 Prototyping Materials and Space-Design*

In remarkable detail, McKim considers the advantages and disadvantages of various materials that can be used for prototyping, or "rapid visualization" by the time of EVT. Overall, he recommends easy-to-use materials:

> Materials that involve the visualizer in difficult techniques [...] will absorb his energy and divert his attention away from thinking. Time-consuming techniques also impede rapid ideation, since ideas frequently come more quickly than they can be recorded. [...] The best materials for visual thinking are direct, quick, and easy to use. (EVT, p. 30)

***A63) Prototyping materials to facilitate ideation need to be (i) so easy to use that creators can devote all their voluntary attention to idea generation (instead of being distracted by difficulties of the prototyping process), and (ii) they need to be so quick that creators can express their ideas before forgetting about them, even when ideas emerge rapidly one after the other.***

McKim also recommends using inexpensive materials: "From the wide variety of papers available, the less expensive is advised, especially for the beginner. Costly paper tends to inhibit thinking" (p. 31).

***A64) Prototyping materials impact the creative thinking process (e.g., expensive paper inhibits thinking; rigid materials lead to rigid thinking).***

McKim considers a number of materials with their relative advantages and disadvantages, such as the following:

> Clay, the traditional sketch material of the sculptor, has many disadvantages to weigh against its basic advantage of malleability. Clay's soft plasticity tends to limit, and even to define, the kinds of forms that can be visualized; it directs ideation to surface considerations; it is heavy, messy, and time-consuming. Styrofoam is an important alternative to clay: it is relatively stiff, can be easily formed into a hollow structure, and can be glued. (EVT, p. 31)

Based on such considerations, McKim provides material lists to help equip environments for creative thinking.

Notably, there is a strong continuity between McKim's considerations and suggestions formulated by Schools of Design Thinking today. Thus, the d.school (2011) also provides a materials list to help equip design thinking environments, and it strongly resembles McKim's original compilation. Figure 11 provides a side-by-side comparison.

Beyond basic prototyping materials, McKim also recommends using technical equipment in the creative thinking process: "In addition to the inexpensive materials so far listed and described, the visual thinker should consider acquiring optical equipment to be used as tools for visual thinking" (EVT, p. 31). Thus, for instance, he recommends "**cameras**, useful for making 'record shots'" (ibid., our emphasis). Again, the continuity to present-day design thinking equipment is obvious. Figure 12 depicts methods in the design thinking Bootcamp Bootleg (d.school 2010), which also invoke cameras for making record shots.

McKim also advises: "**Organized storage** should be provided close to each work area to diminish distracting clutter." (EVT, p. 31, our emphasis). Today, the Schools of Design Thinking standardly offer such storage (Fig. 13).

Moreover, McKim reflects on work surfaces. Of course, paper can be placed on tables, horizontally. McKim also emphasizes that vertical surfaces can and should be used for capturing ideas:

> To alleviate back tension, and also to provide for the important element of change, a **stand-up, vertical drawing surface** should be available: a blackboard, easel, or wall-mounted roll of paper. (EVT, p. 31, our emphasis)

***A65) Providing work areas with horizontal and vertical planes (e.g., tables and whiteboards) encourages motion and change; it also helps to maintain body states that facilitate energetic work over long workdays (e.g., no back pain).***

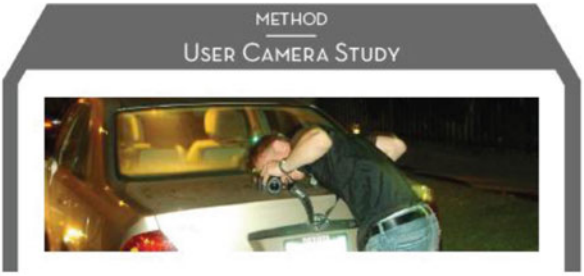
| Materials List in EVT (1972) | d.school Materials List (2011) |
|---|---|
| **introductory list of materials**<br>Markers:<br>1 nylon-tip pen (black)<br>1 ballpoint pen (black, medium point)<br>5 Magic Marker or Eagle Prismacolor felt-tip markers (assorted colors). Note: when buying felt-tip markers, consider warm grays (Magic Markers #2 and #4 or Prismacolor 8971 and 8974, for example) for quickly rendered shading effects.<br>3 Prismacolor pencils (assorted colors). When buying colored pencils, avoid the hard kind; Prismacolor's color range, intensity, and texture are difficult to beat.<br>1 Conté stick (black #3) | **The idea is to use low-resolution nimble materials that can be manipulated quickly.**<br><br>**Writing Implements**<br>Fine point black sharpie<br>Thick, color sharpies, assorted<br><br>**Scale Experiential**<br>sheets<br>large rolls of butcher paper |
| Paper:<br>1 large newsprint pad (approximately 18″ × 24″)<br>1 tracing pad (approximately 14″ × 17″, with one sheet of grid paper)<br>Eraser:<br>1 Pink Pearl<br>Tools:<br>1 mat knife<br>1 inexpensive pair of scissors<br>1 wooden ruler with brass insert (24″)<br>Special Materials:<br>1 small tube or bottle of finger paint<br>1 roll of glazed shelf paper (white, 18″ wide) | **Tools**<br>hole punch<br>scissors<br>stapler (with staples)<br>hot glue/glue guns<br>rulers |

**Fig. 11** Ever since EVT, it is common practice in design thinking to discuss equipment in support of the creative thinking process, especially to facilitate rapid prototyping. Left: excerpts of a materials list compiled by McKim in EVT. Right: Excerpts of a materials list compiled by the d.school (2011)

Once again, such vertical surfaces are now to be found everywhere at the Schools of Design Thinking, as an alternative to working on tables (Fig. 14).

McKim also concerns himself with suitable arrangements for groups, so that all team members can engage equally in group activities:

> It can be easily demonstrated, for example, that five people sitting in a straight line cannot interact verbally as well as can five people sitting in a circle. [. . . ] Clearly, **an inter-active group needs to be able to work over a shared visual image**, suggesting modifications, and changes, making erasures, and so on. (EVT, p. 32)



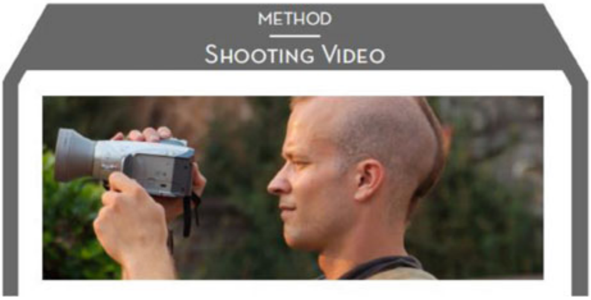




**Fig. 12** In line with recommendations in EVT, design thinkers at present still use cameras for making record shots in the creative process [images reprinted from d.school (2010, pp. 8 and 42)]

**Fig. 13** As recommended in EVT, environments for design thinking still provide organized storage for prototyping materials close to work areas (photo from the HPI D-School)


**Fig. 14** Stand-up, vertical drawing surfaces are a characteristic element of design thinking environments today, in continuity with EVT suggestions (photo from the HPI D-School)

***A66) In teamwork, furniture and spatial arrangements should court the team to form a circle; everyone needs to have good access in terms of sight and touch to the team's work area.***

In the passage above, McKim reflects on group activities that involve sketches. In some other cases, drawing may not be the best approach for teams to jointly visualise and develop ideas. Sometimes, it can be more favourable to work with three-dimensional models. A respective example discussed by McKim concerns Nobel Laureate James D. Watson and his colleagues, who worked on the structure of the DNA molecule. "A complex structure such as the DNA molecule is difficult to visualize in imagination or on paper" (EVT, p. 8). Instead, "Watson and his colleagues visualized this complex structure by interacting directly with a large three-dimensional model" (EVT, p. 8).

Thus, environments for creative activity also need to facilitate joint model building.

***A67) To facilitate creative work, environments needs to support both 2-dimensional visualizations and 3-dimensional model building, all from rough to refined.***

**Fig. 15** A design thinking team today, engaged in externalized thinking by means of rapid prototyping. The design thinking environment, which facilitates the activity, resembles spatial setups suggested in EVT for creative teamwork (photo from the HPI School)

Figure 15 shows a group of design thinkers acting much as McKim suggested: Standing not in a line, but rather in a circle around a table, where they can all jointly see and develop ideas by means of rapid prototyping, using externalized thought and a bias to action. Thus, they are engaged in an inseparable synthesis of "perceive-think-act" (EVT, p. 41).

***M17) From considerations regarding different prototyping materials, over optical equipment (such as cameras) and organizing storage to horizontal versus vertical work planes—McKim has provided ample recommendations for the design of creative places that design thinking environments use up to the present day.***

## *7.3 Facilitating Flexibility with Spatial Designs*

While much of a creative project consists in energetic work, McKim generally emphasises the importance of flexibility. This notably includes flexible shifts between work phases at high levels of energy versus phases of dedicated relaxation (cf. Sect. 4.1). He emphasises how environments for creative work need to facilitate

**Fig. 16** EVT highlights the importance of designing environments where people can shift, flexibly, between active creative work versus relaxation. Correspondingly, environments for design thinking typically include cosy corners, as the one shown here, where design thinkers can retreat and relax (photo from the HPI D-School)

this kind of flexibility. "The visual thinker should also have access to **a quiet place where he can relax** and turn his thoughts inward—or stop thinking entirely: a reclining chair, a couch, or even a relaxing bath" (EVT, p. 32, our emphasis).

***A68) Environments for creative work need to facilitate flexible shifts between phases of (i) active, energetic concentrated work on a task and (ii) relaxation.***

Again, present-day design thinking environments are carefully constructed to facilitate this kind of flexibility. While at Stanford even a room has been designed to look and feel like a sauna for people to retreat, at the D-School in Potsdam several cosy corners are provided. Some offer huge couches in protected areas where individuals can even take a nap, others offer an easy chair (as in Fig. 16).

To recall, the overarching aim of EVT is to train flexibility. "A major purpose of this book is to encourage a [ . . . ] universal condition that fosters productive thinking: flexibility" (EVT, p. 2). Consequently, also in his discussion of environments for creative work, McKim emphasises the importance of flexibility. Spatial arrangements should not be static, and they should not be the same for everyone. Environments for creative activity need to be changeable, so that people using the space can adapt it to their preferences and purposes. Environments need to help people become as flexible as possible, and creative individuals need to develop a habit of actively establishing environments conductive to their pursuits. In this context, McKim also emphasises how individuals can react differently to environments. Each person needs to develop an individual sensitivity towards how the room affects him or her:

> The visual thinker should also consider the subjective nature of his environment. [ . . . ] The visual thinker who is emotionally comfortable in and stimulated by the [ . . . ] character of his environment [ . . . ] will be more productive than the visual thinker who is rubbed wrong by his surroundings. (EVT, p. 32)

Once again, McKim invokes a historical and biographical approach to emphasise how important it is for creators to be mindful of the environment, and to self-create environments that are conductive to one's projects:

> Dr Johnson needed to have a purring cat, orange peel, and plenty of tea to drink . . . Zola pulled down the blinds at midday because he found more stimulus for his thought in artificial light. Carlyle was forever trying to construct a soundproof room, while Proust achieved one. Schiller seems to have depended on the smell of decomposing apples which he habitually kept concealed in his desk. (EVT, McKim quoting McKellar, p. 32)

***A69) Expert creators have developed a high degree of sensitivity towards how the immediate environment impacts their creative processes; they actively seek out favourable environments and re-design spaces, so as to render them most conductive towards their own creative processes.***

These concerns for flexibility in spatial designs have been pursued and elaborated ever since EVT. In their comprehensive compendium on spatial designs for creative work, Doorley and Witthoft (2012) emphasize as one principle: "Make a flexible space. Create a space that adapts to the needs of the people who use it" (p. 270). Moreover, as Leifer and Steinert (2011) point out, innovation is generally about making changes, and "space has emerged as a key factor to facilitate change" (p. 156). In order for spaces to facilitate innovation, aka change, innovation spaces need to be flexible themselves: "The key concept for the spatial setup is flexibility (adaptive/agile work places)" (p. 156).

Beyond McKim's original suggestions for spatial designs in EVT, the concern for flexibility has been pursued even further. Nowadays, design thinking spaces even involve mobile walls and furniture on wheels, so as to provide the greatest possible flexibility for people to redesign rooms on the fly, according to need.

> The key concepts [for space-design] include:
> – Use flexible room separators instead of fixed walls [ . . . ]
> – All furniture is easily movable and modular to serve multiple, often previously unexpected purposes. (Leifer and Steinert 2011, p. 156f.)

Moreover, design thinking research has found that experienced design thinkers indeed adapt and change their work environment much more regularly than design thinking novices (Weinberg et al. 2014). In an observational study, teams of design thinking beginners set up their work spaces in the beginning. Then, with only one exception, "the initial spatial setting remained untouched for the duration of the innovation project, although all furniture was easy to move" (Weinberg et al. 2014, p. 915).

Thus, design thinking novices do not exhibit flexibility in their own environmental designs. One spatial setup is rigidly maintained. This contrasts to design thinking experts.

> Teams [of design thinking experts] divided their workspace into two separate parts [ . . . ]. During their teamwork sessions the teams switched frequently between two or more spatial settings [ . . . ]. Working on analysis and synthesis was quite [often] done at the high table while sitting on high chairs or standing in front of the whiteboard. Brainstorming and ideation was most often done either sitting or standing in front of one or two whiteboards. For team reflection the teams preferred to use the circular sitting area. (Weinberg et al. 2014, p. 916f.)

In this study, design thinking experts demonstrate awareness for the need discussed by McKim to shift flexibly between different work modes, such as highly concentrated work at the whiteboards versus more relaxed moments of team reflection. As encouraged by McKim in EVT, these different work modes are supported by corresponding, suitable changes in the environment.

McKim's biographical approach also highlights the initiatives of well-known creators, who redesign their environments so as to better address their own needs. Similar initiatives are observed among design thinking experts in the study by Weinberg and colleagues.

> In contrast to the design thinking beginner's teams the design thinking expert teams used individual artefacts to 'decorate' their team space. These items fall into two categories: individual decorating items (e.g. plants and a carpet) and items intentionally brought in by team members related to their innovation challenge [ . . . ]. (Weinberg et al. 2014, p. 916)

Thus, design thinking experts appear to make changes in the work environment mindfully, so as to facilitate each and every phase of the creative process with dedicated spatial setups, very much in line with McKim's suggestions in EVT (Fig. 17).

**Fig. 17** Experienced design thinking teams adjust their work spaces regularly to changing needs in the course of different creative process phases. Differing spatial setups are invoked for concentrated work phases as opposed to moments of relaxation and reflection [images reprinted with permission from Weinberg et al. (2014)]

Overall, McKim's *Experiences in Visual Thinking* has provided a cornucopia of theoretical frameworks and practices, which have been formative for design thinking as a unique approach to creativity and innovation.

## References


Adams, J. L. (1974). *Conceptual blockbusting*. Stanford, CA: Stanford Alumni Association.

Arnheim, R. (1969). *Visual thinking*. Berkeley: University Press.

Arnold, J. E. (2016). *Creative engineering*. In W. J. Clancey (Ed.), *Creative engineering: Promoting innovation by thinking differently* (pp. 59–150). Stanford Digital Repository. Retrieved from http://purl.stanford.edu/jb100vs5745. (Original manuscript 1959).

Auernhammer, J. K. M., Sonalkar, N., & Saggar, M. (2021). NeuroDesign: From neuroscience research to design thinking practice. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research*. Cham: Springer.

Bamberger, J., & Schön, D. (1983). Learning as reflective conversation with materials: Notes from work in progress. *Art Education, 36*(2), 68–73.

Beaty, R. E., Thakral, P. P., Madore, K. P., Benedek, M., & Schacter, D. L. (2018). Core network contributions to remembering the past, imagining the future, and thinking creatively. *Journal of Cognitive Neuroscience, 30*(12), 1939–1951.

Bruner, J. (1962). *On knowing. Essays for the left hand*. Cambridge: Harvard University Press.

Clancey, W. J. (2011). Relating modes of thought. In T. Bartscherer & R. Coover (Eds.), *Switching codes: Thinking through new technology in the humanities and the arts* (pp. 161–183). Chicago: University of Chicago Press.

Clancey, W. J. (Ed.). (2016). *Creative Engineering: Promoting innovation by thinking differently—by John E. Arnold*. Retrieved from http://purl.stanford.edu/jb100vs5745 (Original manuscript 1959).

Clancey, W. J. (2018). Spatial conception of activities: Settings, identity, and felt experience. In T. Hünefeldt & A. Schlitte (Eds.), *Situatedness and place: Multidisciplinary perspectives on the spatio-temporal contingency of human life* (pp. 81–110). Cham: Springer Nature.

d.school—Hasso Plattner Institute of Design at Stanford. (2010). *Bootcamp bootleg*. Retrieved from https://hpi.de/fileadmin/user_upload/fachgebiete/d-school/documents/01_GDTW-Files/bootcampbootleg2010.pdf

d.school—Hasso Plattner Institute of Design at Stanford. (2011). *Materials list*. Retrieved from https://dschool-old.stanford.edu/groups/k12/wiki/56b69/Materials_List.html

d.school—Hasso Plattner Institute of Design at Stanford. (2012). *Stanford design thinking virtual crash course*. Retrieved from https://www.youtube.com/watch?v=-FzFk3E5nxM

Doorley, S., & Witthoft, S. (2012). *Make space*. Hoboken, NJ: Wiley.

Faste, R. (1994). Ambidextrous thinking. In *Innovations in mechanical engineering curricula for the 1990s*. New York: American Society of Mechanical Engineers. Retrieved from http://www.fastefoundation.org/publications/ambidextrous_thinking.pdf

Guilford, J. P. (2016). The psychology of thinking. In W. J. Clancey (Ed.), *Creative engineering: Promoting innovation by thinking differently* (pp.152–166). Stanford Digital Repository. Retrieved from http://purl.stanford.edu/jb100vs5745. (Original manuscript 1959).

Harman, W. W., McKim, R. H., Mogar, R. E., Fadiman, J., & Stolaroff, M. J. (1966). Psychedelic agents in creative problem-solving: A pilot study. *Psychological Reports, 19*(1), 211–227.

Kelley, T., & Kelley, D. (2013). *Creative confidence*. New York: Crown Publishing.

Leifer, L. J. & Auernhammer, J. K. M. (2021). *Psychology of design* [research project in the Hasso Plattner Design Thinking Research Program 2019/2020]. Retrieved from https://hpi.de/dtrp/projekte/projekte-201920/psychology-of-design.html

Leifer, L. J., & Steinert, M. (2011). Dancing with ambiguity: Causality behavior, design thinking, and triple-loop-learning. *Information Knowledge Systems Management, 10*, 151–173.

Maslow, A. H. (2016). Emotional blocks to creativity. In W. J. Clancey (Ed.), *Creative engineering: Promoting innovation by thinking differently* (pp.188–197). Stanford Digital Repository. Retrieved from http://purl.stanford.edu/jb100vs5745. (Original manuscript 1959).

McKim, R. H. (1972). *Experiences in visual thinking*. Belmont, CA: Wadsworth Publishing.

McKim, R. H. (2016). Designing for the whole man. In W. J. Clancey (Ed.), *Creative engineering: Promoting innovation by thinking differently* (pp.198–217). Stanford Digital Repository. Retrieved from http://purl.stanford.edu/jb100vs5745. (Original manuscript 1959).

Osann, I., Mayer, L., & Wiele, I. (2020). *The design thinking quick start guide. A 6-step process for generating and implementing creative solutions*. Hoboken: Wiley.

Plattner, H., Meinel, C., & Weinberg, U. (2009). *Design thinking. Innovation lernen. Ideenwelten öffnen*. München: Mi-Wirtschaftsbuch.

Roth, B. (2015a). Design thinking in Stanford. In C. Meinel, U. Weinberg, & T. Krohn (Eds.), *Design thinking live* (pp. 250–251). Hamburg: Murmann.

Roth, B. (2015b). *The achievement habit*. New York: Harper Collins.

Roth, B. (2017). Design thinking in Stanford. In C. Meinel, U. Weinberg, & T. Krohn (Eds.), *Design Thinking live. 30 perspectives on making innovation happen* (pp. 80–86). Hamburg: Murmann.

Saggar, M. (2017). *Examining the role of design reflection and associated brain dynamics in creativity* [research project in the Hasso Plattner Design Thinking Research Program 2019/2020]. Retrieved from https://hpi.de/dtrp/projekte/projekte-201718/examining-the-role-of-design-reflection-and-associated-brain-dynamics-in-creativity.html

Stanford University. (1962). *Stanford University Bulletin. Courses and Degrees 1962-63*. Retrieved from https://stacks.stanford.edu/file/druid:cp135qt4613/1962-1963.pdf

Verganti, R., Dell'Era, C., & Swan, K. S. (2019). Call for papers in the *Journal of Product Innovation Management*, special issue: Design thinking and innovation management: Matches, mismatches and future avenues.

von Thienen, J. P. A (2018, September 10). *Design thinking, the body and creativity: Exploring some bridges*. Talk at the Symposium Neuroscience and physiological perspectives on design thinking and creativity, Potsdam, Germany. Recording retrieved from https://www.tele-task.de/lecture/video/7013

von Thienen, J. P. A. (2019). *Introduction to neurodesign*. Talk in the Neurodesign Lecture: physiological perspectives on engineering design, creativity, collaboration and innovation. Retrieved from https://www.tele-task.de/lecture/video/7701

von Thienen, J. P. A., & Meinel, C. (2019, June 20–22). *Balancing child-like and adult approaches in creative pursuits: The sense-focus model of creative mastery*. Talk at the European Collaborative Creativity Conference EC3, Bologna.

von Thienen, J. P. A., Noweski, C., Rauth, I., Meinel, C., & Lang, S. (2012). If you want to know who you are, tell me where you are: The importance of places. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research: Studying co-creation in practice* (pp. 53–73). Heidelberg: Springer.

von Thienen, J. P. A., Clancey, W. J., Corazza, G. E., & Meinel, C. (2017). Theoretical foundations of design thinking. Part I: John E. Arnold's creative thinking theories. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research. Making distinctions: Collaboration versus cooperation* (pp. 13–40). Cham: Springer.

von Thienen, J. P. A., Clancey, W. J., & Meinel, C. (2019). Theoretical foundations of design thinking. Part II: Robert H. McKim's need-based design theory. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research. Looking further: Design thinking beyond solution-fixation* (pp. 13–38). Cham: Springer.

von Thienen, J. P. A., Szymanski, C., Santuber, J., Plank, I. S., Rahman, S., Weinstein, T., Owoyele, B., Bauer, M., & Meinel, C. (2021). Neurodesign live. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research*. Cham: Springer.

Weinberg, U., Nicolai, C., Hüsam, D., Panayotova, D., & Klooker, M. (2014, September 2–4). *The impact of space on innovation teams*. 19th DMI: Academic Design Management Conference, London.

Wentworth, M. (1978). Going past the moon, into the galaxy—Imaginarium users probe 'mind's eye.'. *Stanford Daily, 174*(37), 2.

Wertheimer, M. (1945). *Productive thinking*. Chicago: University of Chicago Press.

# Part I
# Effective Design Thinking Training and Practice

# Designing as Performance: Bridging the Gap Between Research and Practice in Design Thinking Education

**Jonathan Antonio Edelman, Babajide Owoyele, Joaquin Santuber, and Anne Victoria Talbot**

**Abstract** The adoption of Design Thinking as an innovation method has grown from traditional design circles to a broader range of industries and professions looking to become more innovative. The growth seen in industry has also influenced a rise in Design Thinking research and education with a strong focus on team-based design. In the last 10 years, design research programs have yielded a rigorously vetted body of new knowledge in the study of team interactions in high performing teams. Despite research-informed and data-driven insights, the impact of these outcomes in the realm of Design Thinking education remains marginal, and the development and application of new DT methods, tools, and frameworks often lack a rigorous empirical foundation. In an effort towards bridging the gap between research and practice, this chapter presents new research-based training methods for team-based design. These training packages are built on the research outcomes from the Stanford Center for Design Research and the Hasso Plattner Design Thinking Research Program, as well as contemporary work in cognitive science. The training packages take the form of *performative patterns* (Edelman et al. Design thinking research. Springer International, Cham, 2020). *Performative patterns* are micro-interactions that can be articulated into warm-ups, drills, and exercises for training purposes. Findings from this research demonstrate the effectiveness of the approach for both students of Design Thinking practice, and coaches.

## 1 Introduction

> Experience without theory is blind, but theory without experience is mere intellectual play.
> Immanuel Kant (1724–1804)

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### 1.1 The Research-Practice Gap

This chapter is written with two communities in mind: the research community and the practice community. Because we are concerned with bridging the research practice gap, we have made an attempt to present our research and outcomes in a manner that both communities will find value and inspiration. It is our hope that this chapter creates the steps toward creating a dialogue that will bring the knowledge and expertise of both communites together to promote excellence in design and the study of design.

Design Thinking (DT) has become a widely used method to produce creative outcomes in different contexts, cultures, and disciplines. DT is applied worldwide in a variety of settings and formats, from industry to the social sector and education. As an innovation paradigm, Design Thinking is currently undergoing an exciting and critical transformation. Ad hoc content and practices, based on anecdote and experience, are increasingly being displaced by new content and practices grounded in empirical evidence and rigorous theory.

At least two forces drive this transformation, one force having its source in academia and the other in industry. From academia, the demand has been for Design Thinking to communicate the same rigor and theoretical depth required by other academic disciplines; from industry, the demand is for robust, reliable, and verifiable methods. In both cases, new research and the transfer of this research to the community of practice is crucial to the ongoing growth and success of Design Thinking. For researchers, understanding and accepting design as a valid domain of scholastic inquiry is required; for industry, having reliable methods that support evidence-informed decision making to dedicate resources towards developing new products and services is required. In light of these factors, it would make sense that it is in the interest of both the academia and industry to embrace one another and share knowledge and practice to create a flourishing and sustainable Design Thinking community.

Nonetheless, our experience as design practitioners, teachers, and researchers point to a gap in the Design Thinking community. On one end of the spectrum of popular understanding of research and practice, we have theorists who count words and gestures in the hope of finding meaningful patterns that indicate team performance. On the other end of the spectrum, we have practitioners who are often encouraged to make it up as they go along in the hope of creating a useful design intervention. Unfortunately, the impact of research outcomes in the practice of Design Thinking remains marginal. The development and application of new DT methods, tools, and frameworks often lack the foundation of rigorous research, and research insights seldom get implemented to inform practice.

This state of affairs is not unique to the design community; indeed, it appears to be endemic to most fields. In the paper "How to Develop an Impactful Action Research Program: Insights and Lessons from a Case Study" (Lakiza and Deschamps 2019) Lakiza and Deschamps state that "no matter how relevant the work of theorists is, practitioners often disregard it as too theoretical to be applicable in their precise situation." Several other authors also highlight the research-practice gap as "the failure of organizations and managers to base practices on best available evidence" (Rousseau 2006).

Our investigations have suggested that the research-practice gap results in the confluence of three factors:

1. Issues are arising regarding the dominance of affective outcomes over skill-based and cognitive outcomes in design thinking training contexts. (Taheri et al. 2016)
2. Difficulties experienced by academics in translating findings into tangible solutions in DT education and industry. (Edelman et al. 2012)
3. The inability of design thinking practitioners and program managers in using research findings to improve their team performance (Meinel and Leifer 2020)

In order to address these factors, and thereby create a bridge that links research and practice, the authors of this chapter have developed a collection of training materials based on research on high performing teams. This research—the foundations of the approach—has been outlined in the previous publication in this series (Edelman et al. 2020), and is drawn from research done at the Center for Design Research and the Hasso Plattner Institut, as well as new findings in cognitive science and media studies. The collection of training materials we present has been tested in several scenarios, and while a work in progress, we offer an overview of our research and training packages called ***Designing-as-Performance***.

The fundamental premise of the Designing-as-Performance (D-a-P) approach is that *designing* is a performative act, and that design sessions are a performance of a corpus of *behaviors with mediating objects*. We call these behaviors with mediating objects ***performative patterns***. Performative patterns are micro-interactions that are distilled from observing high-performance teams at work. Performative patterns can be articulated and taught through training routines comprised of relevant theory (frameworks) and repeated practice of well-crafted drills and exercises. Furthermore, performative patterns serve as shared models (both mental models and interactive models) that enable design teams to perform well.

## 2 Theoretical Foundations

### *2.1 The Three Learning Outcomes: Affective, Cognitive and Skill-Based*

The paper "An educational perspective on design thinking learning outcomes" (Taheri et al. 2016) investigated current Design Thinking education through the lens of an educational model of learning outcomes. Taheri and her colleagues studied Design Thinking learning outcomes under three primary categories: Affective Outcomes, Cognitive Outcomes, and Skill-Based Outcomes, based on work by (Bloom 1987; Gagné 1984). Taheri observes that in most Design Thinking educational contexts, there is a strong bias towards ***Affective*** Outcomes and a lack of emphasis on ***Cognitive*** and ***Skill-based*** outcomes.

In response to Taheri's insights concerning current Design Thinking education, the work we present in this chapter—*Designing-as-Performance*—emphasizes Cognitive and Skill-Based modalities as a supplement to current DT educational practice. Designing-as-Performance builds on previous research by designing skill-based and cognitive outcomes to augment the overemphasized affective outcomes in DT training. Our position is that although affective outcomes are necessary, they are not sufficient.

The issue here is that a large sampling of Design Thinking training is offered in quick workshops, which seem to be aimed at providing an introduction that focuses on affective outcomes such as 'creative confidence.' In our experience, it is relatively quick and easy to give encouragement in a short workshop, and indeed participants come away feeling good about themselves. However, as time passes, this effect wears off, and the realization that they have neither sufficiently developed skills nor have the theoretical frameworks that can support more depth to their work.

In order to bring clarity to the current state of education in Design Thinking, we offer an analogous situation, developing expertise in diving off the 3-meter board. If an athlete is primarily coached with affective tools, such as 'you can do it' or 'you just have to be confident' or at worst, 'just jump, and you will figure it out,' most athletes and coaches would not expect a substantial outcome. While necessary, the affective approach in sports training is not sufficient for high performance. Physical skills for which supervised repetition and practice are required, as is an understanding of body mechanics and physics, are also necessary for success.

To draw a fine point on this, the so-called rules of brainstorming are an example of affective tools in the guise of cognitive and skill-based tools. For example, 'come up with many ideas' is equivalent to a coach telling a diver 'jump higher!' Or 'encourage wild ideas' is analogous to a coach telling a diver 'now do a lot of twists and turns!'. We have witnessed the equivalent to 'just jump and you will figure it out' in many DT training scenarios. Part of the problem can find its roots in the training of trainers themselves. Very often, DT coaches have had to make it up as they go along, and while some coaches are experienced practitioners because theoretical instruction is virtually non-existent in DT coaches training, they have little material to draw on. This paucity of grounded theory leaves students on their own to devise solutions and methods for radical and or meaningful change without a solid foundation in the mechanics of design and team interactions. After their experience from a short workshop, beyond feeling good about themselves and free to make things up, many students of DT lack the creative confidence the training claims to instill, as shown in Fig. 1.

For these reasons, we have supplemented currently and commonly used DT education practices with materials that cultivate cognitive and skill-based outcomes. Our goal is concerned with the radical transformation and innovation of design thinking education. To make this goal actionable, we set the objective as the "development of new training material in the form of work packages to make designing accessible to designers and digital engineers." These packages were prototyped to meet three learning outcome criteria: Affective, Skill-based and Cognitive.

The impact of Designing-as-Performance goes beyond training DT practitioners; it also enhances the training of the trainers or DT coaches. In a coaches' certification course, we surveyed coaches and asked what kinds of things do they do when coaching teams. The responses were overwhelmingly weighted towards affective coaching, like helping teams with motivation and getting along. The good news is that after an advanced coaching workshop that included skill-based and cognitive-based materials, they reported a broader range of coaching repertoire.

## 3 Extended and Distributed Cognitive Models: Beyond Cartesian Thinking

While Designing-as-Performance remedies the current bias for affective outcomes in DT training, it also addresses flaws in the cognitive model upon which Design *Thinking* is based. DT training and literature emphasizes the generation of ideas based primarily on text—such as words written on post-its—and verbal communication—design conversation—as the driving factor of team success. Research has shown that while this approach is necessary, it is neither sufficient nor based on a contemporary cognitive model. Rather than a primarily brain-based cognitive activity, we see team-based design activities as an exemplar of *extended* and *distributed* cognition.

In light of this, we will introduce two concepts: **extended cognition** and **distributed cognition**. By 'extended cognition,' we mean that 'thinking' is a loop that engages the brain, the body, and the media (tools and representations) with which we work. By 'distributed cognition,' we mean that 'thinking' in teams is shared and distributed across team members, in the same way, that music-making is distributed amongst players in a jazz ensemble or that action is distributed amongst the players in a sports team. These terms and their usage follow contemporary work in cognitive science (Tversky 2019; Kirsh 2010; Hutchins 1995; Clark and Chalmers 1998).

We have observed that most DT concepts and training are based on a Cartesian model of cognition, in which 'thinking' is a mental activity that occurs in the brain. Much of DT research also tacitly uses the Cartesian model as it overwhelmingly relies on the analysis of transcripts to identify 'ideas' and their development in a design session. Interestingly, the very notion of 'idea' as an *internal mental entity* is itself a Cartesian invention. Indeed, the popular notion that designers make 'ideas into objects' constitutes a misdirect, which can lead neophyte designers astray. Designers create 'experiences with things' (Kirsh 2013). While 'ideas' can have great power, they are generalizations. Designers do not create generalizations as such. The power of design in its many faces is more often than not in the realization of specific experiences for users. Research suggests that high-performance teams are not, in fact, on a quest for many 'ideas.' Instead, high-performance teams act out a series of interconnected scenarios or 'enactment' (Edelman 2011) in which they enact short hand experiences called 'marking' (Kirsh 1996, 2011).

Thinking, in a traditional 'Cartesian' model, happens in the brain. However, in a contemporary cognitive model, cognition includes more than the brain: motion and gesture are critical to thinking, as are the types of tools that we use, which includes the characteristics of the media that we use to think and communicate (Tversky 2019). While there are several labels for this kind of cognition, we have chosen to use the term '**extended cognition**' to describe a model that accounts for thinking to be a loop that includes the brain, the body, and the tools that we enlist when we think. This model implies that cognition is embodied (Varela et al. 1993). Our analysis of design teams at work follows this model by taking into account not only language as a proxy for 'brain' cognition but also gesture and the kinds of shared media used by designers at work.

Seeing the work of design as a kind of extended cognition accounts for why enactment and marking is a hallmark of high-performance teams. It is much easier to 'think' with the body and the right things than it is with the mind alone (Tversky 2019). Off-loading memory and processes into the body and the right kinds of shared representations and tools frees a designer to be imaginative, which is to *walk through and experience* how the world could be different than it is.

Extended cognition can be observed to be **distributed** amongst members of a team. High-performance teams, whether they are design teams, sports teams, or jazz ensembles, break up complex transformational routines (like running a play in sports, or improvising in music) into *small radically distributed interactions*: parts are handed off and developed moment to moment, place to place. In high-performance design teams, we see gestures copied, extended, and combined amongst team members; we see how semi-imaginary environments are transformed piece by piece as if in a dreamscape; we see new and unexpected experiences unfold and emerge as the high-performance design team performs radically distributed micro-interactions.

## *3.1 Training in Performative Disciplines*

Traditionally, performative disciplines have relied on a combination of theory and structured practice that reinforce desirable behaviors that are critical for performative excellence. In the case of sports (Porter 1974; Schmidt and Lee 2014), the understanding of theory and body mechanics and repeated application of this understanding in multiple use case scenarios (warm-ups, individual skills, team drills) are critical for high performance. In the same manner, musical performance (Harnum 2014) enjoys a long tradition of training, which is comprised of musical theory, body mechanics, skills, drills, and free play as requirements for outstanding performance.

The common thread that unites jazz training and sports training: improvisation and development of cognitively distributed and extended skills, which are comprised of offers, methods of picking up these offers, and transforming the offers and handing them off again. Our research approach thus integrates research in (a) musical performance training and (b) sports training. Literature about and educational practice in sports and music suggest the following:

- Designers may benefit from relevant theory and structured practice of design behaviors in the same way that other performative disciplines benefit from instruction in theory and structured practice of domain-specific behaviors
- These behaviors are repeatable and understandable
- These behaviors can be articulated into drills and exercises
- Repeated practice of well-crafted drills and exercises build fluency and expertise

Because Designing-as-Performance proposes that *design activity is a performative act* like improvisation in Jazz and team sports like Football (American or World), we have appropriated several elements from these performative disciplines as a basis for training: Warm-Ups, Individual Skills, and Team Drills.

## 4 Designing-as-Performance

Designing-as-Performance proposes that the design activity is a performative act, like improvisation in Jazz ensembles, team sports like football, or a surgical team in the operating room. In each case, we observe a series of carefully coordinated interactions with instruments (e.g., musical instruments, balls and bats, and surgical instruments), in each case we observe that things do not always go according to plan; in each case, we observe that success is predicated by a collection of shared models of interaction (both behavioral and theoretical) that are repeatedly practiced by team members that enable them to anticipate planned or unplanned steps proactively. Team members, whether in music, sports, or surgery, show up and *perform* their roles. *Performance* is characterized by bodies engaged in coordinated activities with things, situated in a place that affords reaching an end (whether the end is free play and exploration or a concrete goal makes no difference).

Jazz musicians understand the *macro-structures* of their performance, beginnings, middles, and ends in which different activities are shared. Likewise, athletes understand that different plays are performed on different parts of the field and at different times. It is the same for surgical teams. While being fluent in instantiating the right kinds of interactions in the larger arc of a performance, many interactions also take the form of *micro-interactions*: handoffs passes, exchanging vital information explicitly and tacitly.

In the case of high-performance teams in design, we have observed that the same factors hold. Team members understand where they are in the arc of their performance, or the macro-interactions. Are they in an analytic phase (calling out what is there in the current state of affairs) or affirming a new solution? Are they in a generative phase (disrupting what is there, tentatively addressing new possibilities, or sketching them)? Are they dealing with what could be called UI, UX, or systems-level issues? High-performance teams know what kinds of questions are appropriate to ask in the phase in which they are performing and what kind of answers correlate to these questions.

On the micro-interaction side, high-performance teams know how to play 'roles' like 'disruptor' and 'integrator' and how to 'hand off' so that the next team has a better chance of moving the inquiry along. They share a repertoire of interactive patterns or plays that allow them to go beyond what any one of them could imagine, and then bring it home in the form of a novel object-interaction. If all of this seems abstract, do not worry. The following sections will shed light on the interaction mechanics of high performing teams.

## *4.1 Performative Patterns*

The real power of team-based design is unleashed when the tasks are distributed in an appropriate way amongst the team members. The approach we propose is to articulate team creative collaboration as *a set of micro-interactions that break down cognitive tasks into small steps*.

These micro-interactions are called **Performative Patterns**.

In team sports, a fundamental Performative Pattern is the *play*. Plays are predetermined interactions that determine where players and the ball will be in a given time frame and within limits. The time frame depends on the sport and on the play. The limits are often co-determined by the opposing team in the form of coverage. Thus, a *play serves as a container for previously undefined content* (e.g., the unfolding of the play in the context of the coverage) that allows the ball to be effectively be sent to and caught at a place where no one is at the time of release. In basketball, where the action changes at a phenomenal rate, plays are called out dynamically and in rapid succession, execution of which is only possible if the teams have practiced not only the plays but transitions between plays.

In Jazz, analogous situations abound. For example, a typical performative pattern is 'call and response.' Call and response require that players trade short melodic phrases, repeating sub-phrases or fragments and transforming and building on them. This is not done willy-nilly. The craft of improvisation in an ensemble is knowing what kind of phrases and fragments will be fruitful to hand off and how to transform them, as described by Thomas Brothers regarding the jazz legend Louis Armstrong (Brothers 2014). As in basketball, Jazz improvisation can be a rapidly changing landscape, and a reliance on a well-practiced and shared interactive repertoire is required for a successful performance. In Jazz, musically inventive routines constitute performative patterns that *serve as container for previously undefined content*, which comes in the form of melodic or harmonic co-invention.

What is a Performative Pattern in team-based design?

Here we offer a working definition:

*A performative pattern in design is a set of defined iterative micro-interactions that serve as a container for previously undefined content.*

Simply stated, performative patterns are designed to enable design teams to cycle through a succession of instantiations of new experiences by way of mapping what exists, disrupting what exists, and creating a re-configuration. Performative patterns are structured interactions that work best when rapidly iterated. Each performative pattern addresses a different aspect of high-performance team behaviors. In the early stages of training, designers are directed to practice a performative pattern in isolation from other performative patterns. In later stages of training, performative patterns are combined. Combinations are modeled on the observed behaviors of high-performance teams.

The content, or subject matter, of a performative pattern, is not defined. Performative patterns are configured to accommodate a wide range of design subjects, including products, services, and systems. In the same way that plays in sports or riffs and inventive operations in music break the development process into small chunks, the micro-interactive steps of each iteration of a performative pattern break the design process itself into smaller phrases or fragments. Furthermore, performative patterns provide a guide for what needs to be handed off to the next team member and what the 'receiver' can do with the design fragment before passing it on. Because cognition is radically distributed amongst design team members (each with different experiences, points of view, etc.), the outcomes are not determined in advance. Instead, the new object-interactions emerge from the iteration of the performative pattern. Each endpoint of a pattern serves as the starting point of the next iteration. This affords teams to go far beyond preconceived notions and into the creation of new and unexpected experiences.

Training in performative domains often has similar elements: affective, cognitive, and skill-based training. In high-level sports training, we observe that sports psychology, body mechanics, and physical training are all considered part and parcel of cultivating high-performance outcomes, and the desired end of training is to combine these separate elements in a single athlete and team. In music, we find the same elements: interventions for developing confidence (e.g., overcoming stage fright or feeling confident in their compositional style), training in music theory, and physical training. Here again, excellence is assumed as an integration of the three elements in a single player and ensemble. In both these domains, the physical training is grounded in frequent and seemingly endless repetitions that take the form of bespoke warm-ups fit for specific activities, practice of a repertoire of individual skills that are appropriate for their instrument, and team/ensemble drills that cultivate coordination of the parts within the greater enterprise of scoring in sports or creating a compelling musical experience.

In design training, we have appropriated several elements from other performative disciplines as a basis for training: Warm-Ups, Individual Skills, and Team Drills. Specific examples of these training modalities will be introduced in the context of each of the four performative patterns discussed below.

The following are four examples of the performative patterns we developed and tested: MEDGI, Dimensions of Engagement, Analytic and Generative Questions/Answers and Media Models. We have chosen these four examples because they are all foundational to D-a-P, and have been tested in several venues.

### 4.1.1 MEDGI

M-E-D-G-I is an acronym that stands for Mapping, Educing, Disrupting, Gestalting and Integrating, and serves as a primary performative pattern. MEDGI is both a macro and a micro pattern in that it describes both long term project development arcs and moment to moment development team interactions. The MEDGI Re-Design Method was developed as a result of over 10 years of research at Stanford and the HPI into how small design teams create new concepts. It has been taught and tested in several institutions and on several contents.

The five steps of MEDGI were distilled from observing high-performance teams in action and analyzing their interactions. The thrust of MEDGI is to move an existing object-interaction to a state of potentiality and then reform it into a new object-interaction.

On the macro level, **Mapping** activity is laying out current object-interactions and their accompanying narratives on a time and space map. Much more than simple 'understanding,' Mapping entails creating a shared representation of the current state of affairs. Another salient difference between 'understanding' and Mapping is that 'understanding' in DT often stops at having a linguistic account for what exists. While the generality of a linguistic representation has the power to cover many situations, it can lack the specific and situated characteristics of an object-interaction or experience that often yield insights that lead to well-crafted design interventions. Mapping ensures that the representation of the state of affairs is externalized and somewhat persistent. A map allows team members to point to and to refer to specific points in time and space that they can then address. Furthermore, because the map is an external representation, a map affords reduced cognitive loading and can free up cognitive processes and allow room for imagination.

On the micro-interaction level, Mapping refers to not only stating the state of things at specific moments in time and in space but also to enacting these moments, which is to say bringing an *experience* to the table, instead of just a description. For example, instead of a designer exclusively stating that 'you hold the bottle and twist the cap,' the designer would act that out too, either as a full enactment or as a marking. These specific gestural maps constitute offers that enable other team members to pick the gestural cues up and transform them. Mapping can also be done with sketches.

**Educing** refers to identifying and highlighting what works and what does not work, and pain and pleasure points. On a macro level, educing often means encoding the map problem and success areas, literally identifying and highlighting them for the team to see. As in Mapping, this step ensures that very little important and shared information is kept or lost in memory because it is held in an external representation.

On the micro-level, Educing refers to enacting what works and what doesn't work, pain and pleasure points, on an experiential level. As in Mapping, this entails more than a verbal account of what works and what does not work, Educing asks the designer to act out the moments in the object-interaction that could be reduced or augmented. For example, the struggle to twist the bottle cap off, or the pleasure of a clever mechanism that allows a user to feel mastery. Here again, as in each step of MEDGI, the gestural cues constitute offers that enable the other team members to transform them.

**Disrupting** refers to suggesting a change to the state of affairs in an object-interaction, and take the form of questions like, 'what happens if...?' On a macro level disruption can take the form of suggesting the introduction of whole new technologies, or sweeping changes that could result of combining different, seemingly unrelated fields. For example, 'what are some of the things that could happen if we could hear brain waves?' in the field of neuroscience.

On a micro level, in an analogous manner to Mapping and Educing, Disrupting refers to acting out the force of change. For example, making a gestural enactment of throwing something that was previously static. In Disrupting, there is little or no explicit notion of a solution; disrupting is a move towards exposing the potentiality of an object-interaction.

**Gestalting** refers to 'roughing in' a new object-interaction. On a macro level, Gestalting is seen as a general picture of the field of possibilities that could result from the Disruption in the previous phase.

On a micro level, Gestalting is the enactment of a broad picture with few details articulated. Gestures are generally not fully enacted, but marked in a gestural shorthand (Kirsh 2011).

**Integrating** refers to when the new state of affairs comes together, crystallized in a new articulation. On a macro level, Integrating entails the thorough definition of specifications for manufacture and distribution, detailed attention to touchpoints for compelling user experience and interaction, as well as systems integration.

On a micro level, Integrating entails noting experiential factors such as touch-points (e.g., buttons and adjustors, pay points) and new potential names for the product or service. Unlike Gestalting, in which enactment is characterized by broad marking, Integrating tends towards full enactment.

In the course of researching and teaching team-based design, we have frequently observed that poorly performing teams are either not aware of what phase in which they are acting or not in agreement about what phase they are in. This observation holds true on both the macro and micro levels of place in the process. The remedy for this is to explicitly provide a framework (for strong cognitive outcomes) as well as the repetitive practice of acting (for strong skill-based outcomes) in a phase appropriate manner.

### 4.1.2 Dimensions of Engagement

The Dimensions of Engagement constitute an architecture for redesigning products and services from a systems point of view (Edelman 2011). Each dimension delineates at what level—incremental, mid-level, and radical—interventions can be accomplished. The Dimensions of Engagement emphasize the interdependence of two elements of redesign: **objects** and their **context.** The implication of this is that designers create both objects and the context in which the objects operate when they redesign.

For example, when a designer designs a **smartphone,** she designs **a whole set of interactions**—usability, scenarios and networks—not merely the smart phone-as-object itself as proposed by the great Italian designer Achille Castiglioni. Great design is characterized by a harmonious agreement that unites each level of engagement to the others. A relevant example of this is the development of the Apple iPod in the context of the network of content acquisition and delivery that constitutes the iTunes system. Apple's aim was to create a new, seamless experience that was a radical change from the disjointed way in which people acquired, transferred and listened to music. This re-design of object-interactions depended on getting the three levels of the Dimensions of Engagement to work together seamlessly: the **core function** of the new way of enjoying music in the context of the social and technical **network**, the general **form** factors and functions (which constitute **depth**) in the context of **use-case scenarios**, and the **touchpoints** (e.g., buttons and adjustors) in the context of **usability** (See Fig. 1).

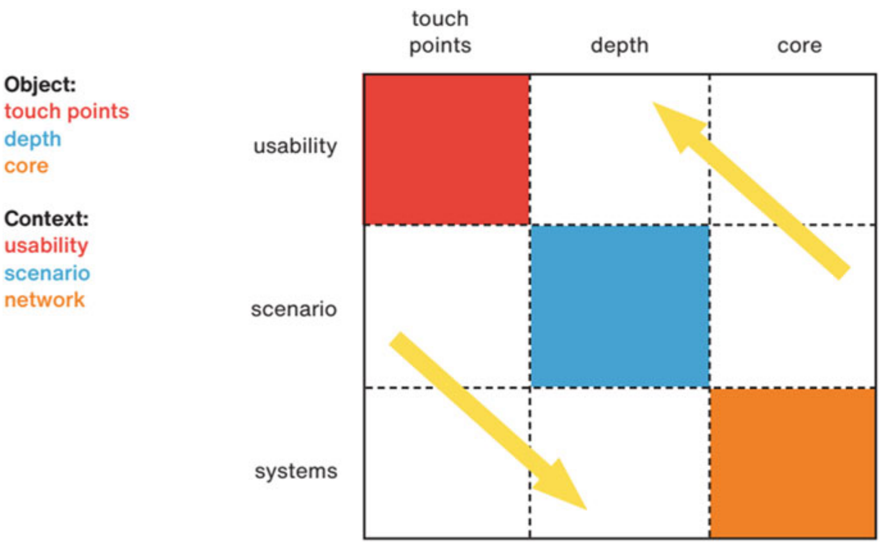


**Fig. 1** Dimensions of Engagement Matrix adapted from Edelman et al. (2012)

We have observed, both in research settings, that and training settings that poorly performing design teams are often either not aware of the levels of a product service architecture, or they are not aware on which level they are working or transitioning to and from, or are not in explicit or tacit agreement about whether they are dealing with touchpoint/usability issues or core/network issues. Dimensions of Engagement provide a shared model of team interaction that allows negotiation and anticipation of areas for development. Mastery of the theoretical aspects of the Dimensions of Engagement leads to better cognitive outcomes of instruction, the repetitive practice of gestural articulation, handing off, receiving and transforming object-interactions on the different levels of the Dimensions of Engagement leads to more robust team interactions and skill-based outcomes.

### 4.1.3 Analytic Questions/Answers and Generative Questions/Answers

Exploring our design teams engage in asking the right questions we build on work by Ozgur Eris (Eris 2003). Eris studied the kinds of questions that designers ask when they are working in teams. He found that a combination of **Deep Reasoning Questions** and **Generative Design Questions** are needed for successful design outcomes.

Deep Reasoning Questions (DRQs) are characterized by inquiry concerning specification, comparison, and verification. DRQs are analytic questions that address what is actual and often what is feasible. DRQs ask questions like, ‘what are the dimensions?’ or ‘will this work?’.

Generative Design Questions (GDQs) are concerned with generating a field of possibilities. GDQ’s are generative questions that address a range of potential outcomes. GDQs ask questions like, ‘what happens if we change the user?’ or ‘what are the ways we can change the process?’.

In practice, we have found that the highly articulated terms ‘Deep Reasoning Question’ and ‘Generative Design Question,’ as well as their acronyms ‘GDQ’ and ‘DRQ’, are difficult for design students to remember. We have chosen to simplify them and hence refer to them as Analytic Questions and Generative Questions, respectively.

Furthermore, while Eris does not explicitly give a name to the kinds of answers that are appropriate to the questions, we have adopted the convention of calling them Analytic Answers and Generative Answers. These distinctions are very useful in training scenarios as an agreement between the form of a question and an answer has an impact on team performance.

Significantly, there is a strong correspondence between Eris’s questions and the five phases of MEDGI. In fact, we are led to consider the underlying orientation of Analytic Questions/Answers and Generative Questions/Answers to be the backbone of MEDGI. The first two phases of MEDGI, Mapping and Educing, are purely analytic; they ask and answer ‘what is there now?’ and ‘what works and doesn’t work?’ respectively. The next two phases, Disrupting and Gestalting, are generative; they ask ‘what happens if?’ and provide sketchy answers of potential directions to explore. The final phase of MEDGI is Integrating, which is an Analytic phase when what was potential is made concrete and actual; Integrating asks and answers 'exactly how is that going to be?'

In both research and training situations, we have observed that a common phenomenon in low performing teams happens when players ask analytic questions during a performance phase when generative questions are a better fit, and vice versa. Moreover, on many occasions, we have noted that players will inadvertently answer an analytic question with a generative answer and vice versa. Both of these instances demonstrate tacit or explicit a misalignment in the team as to where they are in the process or a lack of awareness of the impact of the characteristics of questions on design inquiry. The remedy for this is explicit instruction in the nature of questions and answers in design performance (resulting in better cognitive outcomes) and repetitive practice in asking phase appropriate questions and answering them accordingly (resulting in better skill-based outcomes).

#### 4.1.4 Media Models

Designing-as-Performance is predicated on the model that cognition is both extended and distributed. In respect to distributed cognition, the arc of the design process is broken into smaller phrases or fragments. In respect to extended cognition, the elements that constitute performance are (1) theory and thus language, (2) gestural and behavioral interactions, and (3) the shared objects or representations that design teams enlist when they are redesigning (Edelman and Currano 2011).

The two previous three performative patterns have concentrated on frameworks for phase appropriate interactions, with an emphasis on linguistic and gestural performance. The Media Models framework posits that the tools and representations designers use can be considered cognitive prostheses, augmenting, and shaping how designers speak and behave. Media Models as a performative pattern emphasizes gestural performance in relation to objects and the behaviors that are associated with them. The Media Models framework classifies the tools and representations designers use and share along the axes: concrete to abstract and pluripotent to differentiated.

We have found that the media (tools and representations) designers use and share can encourage Analytic Questions/Answers and Generative Questions/Answers as well as the kinds of gestures (both scope of gesture and the quality of gesture) that are performed in response to the media.

The Media Models framework provides design teams with a theoretical foundation for understanding and making informed choices about the kinds of shared models that will support phase appropriate (MEDGI) extended and distributed cognition, in other words, *performance*.

The chart below presents the Media Models framework with representative instantiations of the same handheld device, a material analyzer. Quadrants 1 and 4 are well-defined, while Quadrants 2 and 3 are loosely-defined. Quadrants 1 and 4 are associated with Analytic Cognition; Quadrants 2 and 3 are associated with

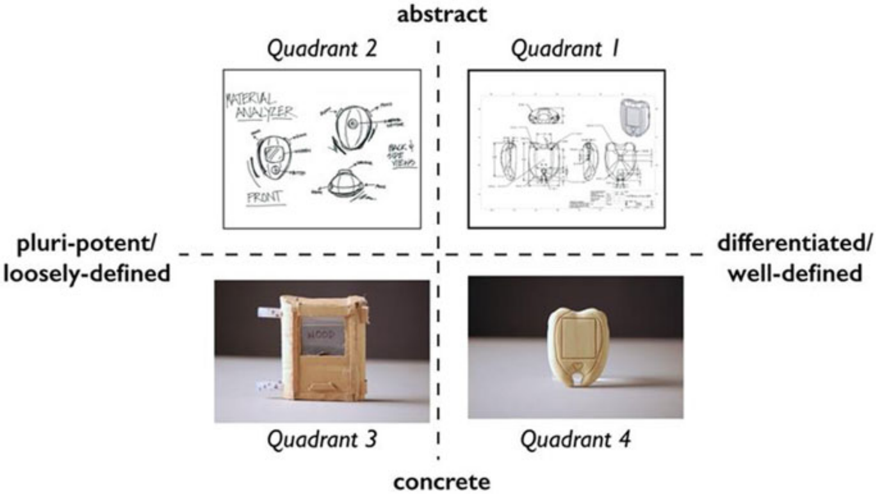


**Fig. 2** Media Models framework

Generative Cognition. Additionally, Quadrants 1 and 2 are associated with a low level of physical expression or enactment, whereas Quadrants 3 and 4 are associated with a higher level of physical expression or enactment (Fig. 2).

In both research and training scenarios, we have observed how the media itself makes an impact on the discussion and interactions. Confusion and oblique communication frequently are accompanied by mis-matched representations. For example, a carefully rendered drawing (Quadrant 1, affording analytic cognition/engagement) is brought to a generative design session (with the expectation of generative cognition/engagement), only to be ignored or worse, players on design teams get caught in a cycle of asking Analytic Questions ('how big is that?' 'can you fit your hand in there?'). Generative cognition is, by definition more appropriate to move the exploration to new ground, and thus media from Quadrants 2 and 3 would support and afford effective team engagement.

## 5 Iterative Development and Evaluation

While much of the Designing-as-Performance curriculum content was realized before and during the 2017–2018 research period from work done in the Research to Impact Group, we enlisted an iterative approach of test-reflect-improve in cultivating that content for classroom and workshop use. There were several domains that we tested and consequently improved the content: the Digital Health Design Lab, a full-semester course at the Digital Health Center at the Hasso Plattner Institute, a Master Class called Advanced Coaching Strategies for Teams conducted at the HPI Academy for industry professionals.

## *5.1 Preliminary Evaluation*

### 5.1.1 Faculty and Staff European University Workshop

A preliminary opportunity to test our training packages happened in the context of a several days DT training of faculty staff from a Polish University. The group, who had previously experienced Design Thinking, was introduced to the theoretical background of the packages followed by practical experience in the form of warm-ups, skills and drills. Specifically, the participants performed MEDGI (at the time a four-step process: MDGI), to practice distributed concept generation; and *Crumpled X* to work on to practice the media models framework. Feedback collected from the participants highlighted the effectiveness of concept generation when the process is distributed and that ownership of ideas gets dissolved among team members using MEDGI. On the improvements list, we noted that instructions needed to be more crisp and prescriptive for quick adoption. Since the group had an academic background, further preliminary testing was done in Industry and students.

The train-the-teachers workshop enlisted the following training materials:

1. Group Warm-up: One-word story (cultivates extended and distributed cognition)
2. Individual Skill: Crumpled X (Media Models)
3. Teams Drills: Disruption/Integration with objects like glasses, scissors, etc. (MEDGI)

### 5.1.2 Professional Workshop: Train the Trainer

Coaches from the Hasso Plattner Institute Academy led a workshop for corporate clients from the automotive industry. The context of the workshop was a creative confidence workshop. The HPI Academy coaches ran an hour-long prototype training session based on Designing-as-Performance and Performative Patterns training packages.

The Academy team consequently expanded the professional workshop session to become the Creative Confidence Bootcamp. The Bootcamp enlisted these training materials:

1. Group Warm-up: Human Machine (cultivates extended and distributed cognition)
2. Individual Skill: Crumpled House (Media Models)
3. In Pairs: What is/What if-questions on the Crumpled House media (Analytic and Generative Questions/Answers)
4. Teams Drills: Disruption/Integration with objects like glasses, scissors, etc. (MEDGI)

Valuable insight from this preliminary corporate testing was that despite the emphasis on Cognitive and Skills-based learning outcomes of D-a-P, it reinforces the effects on affective learning outcomes found in other traditional DT training formats. As an anecdote, after the crumpled house individual skill exercise, the participants—proud of what they had accomplished—mounted a “Crumpled House Exhibit” on one of the glass walls of the workshop venue to show their creative achievements.

#### 5.1.3 Legal Design Workshop: Redesigning Contracts

This is Legal Design GbR is a Berlin-based design consultancy that concentrates on the redesign of Law. In collaboration with This is Legal Design, our research group ran a 1-day workshop for a German Law school students that focused on contractual compliance terms. For this workshop, we enlisted MEDGI as a primary development tool. We led participants through several iterations of the MEDGI cycle, and the participants generated different concepts to improve the contract’s terms compliance.

The novelty of this workshop was the introduction of the Overlay individual skill to practice Media Models. Using a tracing paper sheet, the participants sketched out the contract to have a *pluripotent*—rough—version of the contract they had to redesign. The result was a sketch that enabled them to ask Generative Questions in an effective manner.

One crucial insight the research team gained was that in the context of a 1-day workshop, teaching MEDGI as an overarching D-a-P “play”, was sufficient to create engagement and favorable outcomes for the participants—law students—who had never been exposed to Design Thinking. The same workshop was successfully tested with different law students in Hamburg and Amsterdam.

The Contract redesign workshop enlisted these training materials:

1. Group Warm-up: One-word story (cultivates extended and distributed cognition)
2. Individual Skill: Contract Overlay for Mapping and Educing (Media Models, MEDGI)
3. In Pairs: What if-questions on the Contract sketch for disruption (Generative Questions/Answers, MEDGI)
4. Teams Drills: 3 × Gestalting and Integration (MEDGI as an overarching “D-a-P play”) (Fig. 3)

### *5.2 Evaluation of Designing-as-Performance and Performative Patterns*

After several iterations between the preliminary tests, we evaluated a more defined version of D-a-P and Performative Patterns in two venues and training scenarios—short-term coaches training and long-term student training. The short-term engagement took place at a professional Design Thinking coaches certification program. In this case, an evaluation was done with before and after questionnaires that


**Fig. 3** Contract overlay to apply media models. Using tracing paper, the participants made a sketch to map the different parts of the contracts and highlight the pain points and pleasure points

evaluated their knowledge in the context of coaching interventions based on affective, cognitive and skill-based outcomes (Kraiger et al. 1993). The long-term engagement was a semester-long design class for Masters students in Digital Health. The evaluation for the long-term engagement included assessments for affective, cognitive and skill-based learning outcomes.

### 5.2.1 Master Class 2019: Advanced Coaching Strategies for Teams (1-Day Workshop)

In the Master Class, the Designing-as-Performance and Performative Patterns training-packages were tested in a short-term training format. The Hasso Plattner Institute Academy offers a Coaches Certification Program, which runs for 12 months and is divided into several training periods, including two three day Train the Trainer sessions. An additional 1 day Master Class is also offered to participants. The Certification Program lead team offered our research team an opportunity to run a master class for coaches based on Designing-as-Performance and Performative Patterns. This led to ‘Advanced Coaching Strategies for Teams’, a 1-day master class in which participants learned research-based techniques for coaching design teams.

The coaches in training learned new theory and robust methods for improving team performance through performative patterns. They were also introduced to the concepts of Affective, Cognitive and Skill-based learning outcomes, and shown examples of how these modalities are taught in sports and music. Coaches were exposed to design theory and practiced associated warm-ups, individual skills and team drills. They learned to identify high and low function team behaviors and were introduced to strategies to get teams back on track when they are performing poorly.

D-a-P and Performative Pattern materials included Warm-ups, Individual Skills, and Team Drills for each of these:

1. MEDGI (and the 4 Card Method, MDGI)
2. Dimensions of Engagement
3. Media Models
4. Analytic Questions/Answers and Generative Questions/Answers

### 5.2.2 Evaluation

Each semester about 25 coaches can participate in the Certification Program for Coaches at the HPI Potsdam. At our first assessment session, 25 persons were present and thus included in the study, 14 males, 9 females. Most participants reported a moderate to a high level of experience with design thinking, and most participants had prior coaching experience. 6 participants failed to fill the after questionnaire, and their data were discarded, resulting in 19 respondents. The participants filled in a short version of a questionnaire adapted from (Royalty et al. 2014) using a Likert Scale (Table 1).

In an open-reflection round, participant's responses to questions about what coaches did in the 'Before' questionnaire were characterized by descriptions of overwhelmingly *affective* activities such as encouraging teams and ironing out interpersonal issues on the teams. Responses to the identical 'After' questionnaire included accounts of more technical interventions that reflected *cognitive* and *skill-based* material that was covered in the workshop. Furthermore, the workshop

**Table 1** Questions and Results from the adapted Creative Agency Assessment during the short-term evaluation venue "train-the-trainers" with DT coaches

| Questions adapted from Creative Agency Assessment (Royalty et al. 2014) Based on your experience as a coach, how confident are you to provide the team with resources to | Before | After |
|---|---|---|
| Find sources of creative inspiration that are unusual or not obviously related to a given problem or task | 3.2 | 3.6 |
| Effectively ask different kinds of questions, depending on what they are working on | 3.5 | 3.8 |
| Building on each other's idea by disrupting and integrating concepts that appear, at first glance to be unconnected | 3 | 3.7 |
| Shape or change their external environment to help yourself be more creative | 2.8 | 3.5 |
| Distribute team roles based on individual skills, depending on what they are working on | 2.8 | 3.5 |

evaluation demonstrated an overall increase of creative confidence of 2.8 points (an average of 0.56 points per question), or 18.3%.

### 5.2.3 Digital Health Design Lab, Summer Semester (15 Weekly Sessions)

In the Digital Health Design Lab course, the Designing-as-Performance and Performative Patterns training packages were tested in a long-term training format. In the Digital Health Design Lab course, Masters students Performative patterns such as the MEDGI design framework to develop and investigate their research questions throughout the semester. Supported by the Research to Impact Group as well as senior digital health scientists from diverse backgrounds, students used human-centered and design-driven approaches to explore plan, conduct, analyze and report a psychological or medical study using a digital solution. For example, behavior tracking via smartphone.

The Digital Health Design Lab teaching format was built around weekly theoretical and hands-on sessions that included warm-ups, individual skill building, and team drills. The curriculum consisted of extensive warm-ups, individual skill practice, and team drills in each of MEDGI, Dimensions of Engagement, Analytic and Generative Questions/Answers, and the Media Models Framework, as well as theoretical instruction and readings.

### 5.2.4 Evaluation

To evaluate the impact of the training packages in the class, three learning outcomes were assessed: cognitive, skill-based and affective outcomes (Kraiger et al. 1993). We evaluated individuals and groups for their affective development, theoretical knowledge, and skills through a questionnaire, a multiple-choice test, and a hands-on exam in which they were put into teams and given a redesign challenge (Table 2).

Before the design training with D-a-P materials, students at the Digital Health Design Lab scored, on average, 26 out 50 in a cognitive evaluation. After training with D-a-P materials, the same students scored 46 points out of 50 in the cognitive evaluation, as shown in Fig. 4. This represents an overall improvement of 20 points or 40%.

To evaluate the effects of D-a-P training on skill-based learning outcomes, we ran hands-on testing. In groups of four participants, the students were evaluated on skill composition—the ability to perform different trained skills—as well as speed and fluency of performance of those skills. The evaluation methods employed were targeted behavior observation—e.g., adequacy of reaction to interventions from other team members and evaluators—by three jury experts using a five item assessment with Likert Scale. All students performed in a range from adequate performance to fluent performance. While we did not do a preliminary assessment of the class and thus can make no detailed assessment of the improvement of skill,

**Table 2** Evaluation focus and methods of the effect of D-a-P on affective, cognitive and skill-based learning outcomes

| Learning outcome | Focus (Kraiger et al. 1993) | Evaluation method |
|---|---|---|
| Affective | Attitude<br>Confidence<br>Motivation | Self-report using Creative Agency Assessment (Royalty et al. 2014), Creative Growth Mindset Questionnaire (Dweck 2008) and Innovation Self-Efficacy Questionnaire adapted from (Schar et al. 2017) |
| Cognitive | Verbal knowledge<br>Amount of knowledge<br>Speed and accuracy of knowledge recall | 50 items test with multiple choice answers, fill the blank, reorder information based on hierarchy and match concepts |
| Skill-based | Composition<br>Speed and fluency of performance<br>Adequacy of reaction to interventions from other team members and evaluators | Hands-on testing and targeted behavioral observation by three expert juries. The student's skill-based performance was assessed using an original five-item assessment employing a Likert Scale |

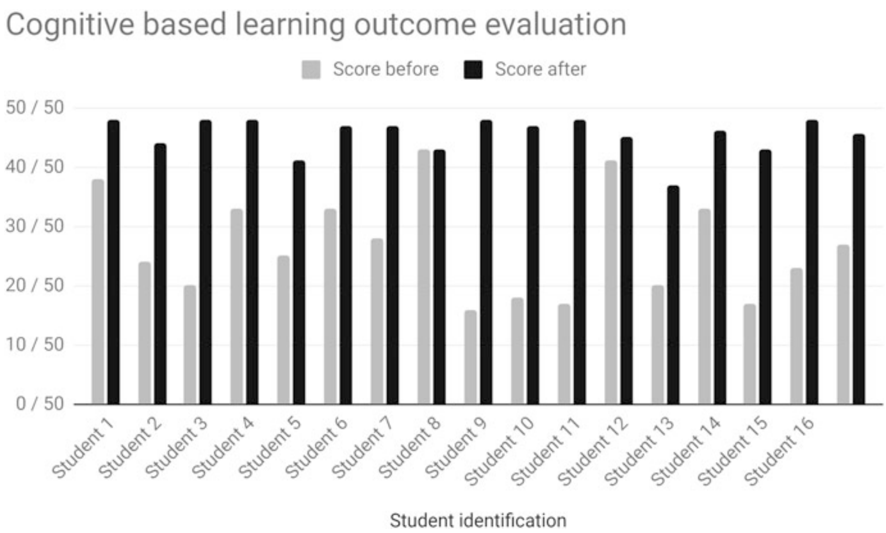


**Fig. 4** Results of the cognitive learning outcome evaluation from 16 students taking part in the Digital Health Design Lab at the HPI. Score before corresponds to the test done at the beginning of the semester; and after refers to the test taken at the end of it

we note that there was a palpable and positive development of skills throughout the term. In many instances, team members could automatically perform micro-interactions in sequences, such as Mapping and Disrupting. However, Gestalting

**Fig. 5** (**a**, **b**) Team 3 and 4 during D-a-P Final Exam, Skill Based Learning Outcome. Here we look at the proceduralization and the students' ability to perform D-a-P tasks without continuous monitoring

proved to be more difficult for some students. Disrupting seems to be easy, Gestalting more difficult (Fig. 5).

To assess affective outcomes, we employed the Self-report as an evaluation method using the Creative Agency Assessment (Royalty et al. 2014), Creative Growth Mindset Questionnaire adapted (Dweck 2008), and Innovation Self-Efficacy Questionnaire adapted from (Schar et al. 2017). The students completed the self-report at the start of the semester and at the end of the semester. The results show an increase between before training and after training affective outcome assessments. In detail, the students' reported creative agency average score increased from 3.5 to 4.2, or 0.7 points, which is an improvement of 20%. The average self-efficacy score


**Fig. 6** Results of the effect of D-a-P training on affective learning outcomes in Creative Agency Assessment, Innovation Efficacy, and Growth Mindset

increased from 3.4 to 4.2, or 0.8, which is an improvement of 23.5%. The growth mindset average score went from 2.7 to 3.5, or 0.8, which is an improvement of 29.6% (Fig. 6).

In comparison to previous research in creative confidence (Royalty et al. 2014), the impact of D-a-P on affective learning outcomes exceeds standard DT training by 4%. While our study engaged 16 student participants and Royalty's study engaged student 55 participants, both were semester long classes. The improvement rate in Royalty's study measuring the imact of Stanford d.school training for the Creative Agency Assessment was approximately 17% (Royalty's publication shows a graph or results, but does not supply numbers). The results for the Creative Agency Assessment study at the Digital Health Design Lab show an improvement of 21% (the pre-D-a-P assessment mean is 3.468 and the post-D-a-P assessment is 4.221, with a SD of 0.333 and 0.135 pre and post respectively). We find these results interesting, because we made no pretense of teaching to support affective outcomes. This suggests that focusing on Cognitive and Skill-Based outcomes have significant and complementary effect on Creative Agency Assessment that at least equal or exceed an approach that concentrates on creative confidence.

## 6 Discussion

The evaluation of a refined version of the D-a-P training packages provided us with three main takeaways regarding the issues proposed at the beginning of the chapter to overcome in order to bridge the gap between practice and research.

**Regarding issues concerning the dominance of affective outcomes over skill-based and cognitive outcomes in design thinking training contexts**
A stronger emphasis on skill-based and cognitive learning outcomes can contribute to bringing more clarity to what is the impact of Design Thinking training formats

beyond already well accepted affective outcomes. In this sense, by focusing on learning aspects such as the amount of knowledge, accuracy, and speed of knowledge recall, our study could enrich the measurement of the effects of DT training. We observed, throughout our evaluations, that the combination of theory and practice, presented in a well-crafted and structured package enhances the effect of DT training regarding cognitive and skill-based outcomes.

The evaluation of cognitive learning outcomes may seem familiar to the reader—or may even seem old-fashioned. This is not strange, because this evaluation method is widely used in traditional education. From the research results presented in this chapter, such evaluation proved to be beneficial to the ability of the participants to recall knowledge acquired during the training.

Limitations: in the present research project, we did not study the long term effects of the D-a-P training packages. In other words, it's not clear yet how reliable the transfer of the effects of *Designing-as-Performance* is after the training is over. Future assessment will need to be carried out to shed light on long term impact.

**Regarding difficulties experienced by academics in translating findings into tangible solutions in DT education and industry**
While the iterative process which we followed was not free of difficulties, we believe that the Research-Practice gap can be bridged through small iterations and intensive testing—failing included. As researchers, very often, we fell in the trap we were addressing. We found that academics often struggled to place the "practitioner-oriented" training materials into their academic concepts, models, and frameworks.

**Regarding the inability of design thinking practitioners and program managers in using research findings to improve their organization's performance**
The preliminary evaluations, train-the-teachers workshop, a corporate workshop for the automotive industry, and the contract redesign workshop for law students showed us that a critical factor for the success of the application of research findings by practitioners has to do with its versatility. A well-structured output with potential for versatile application regarding three aspects: content, context, and length. These insights were confirmed by the result in our evaluation venues, train-the-trainers workshop, and Digital Health Design Lab. As an anecdote, after a content-overloaded workshop, practitioner feedback was cold and sharp: "you have to kill your *academic* darlings".

**Content-Wise**
During our several iterations, we tested D-a-P for providing advanced DT content (e.g., train-the-trainers), as well as introductory DT content. D-a-P was successfully tested in different fields, such as education, DT methodologies, Law, and Health. We found that practitioners can "fill-in" the Performative Patterns with the relevant content depending on the context.

**Context**
Our pre-evaluation and post-evaluation were carried in diverse contexts ranging from corporate executives to students, from teachers to experienced DT coaches. It

has thus shown the suitability of D-a-P in professional education, academic settings, and industry.

**Length**
From a half-day workshop to a semester, the training packages allowed instructors to easily adjust the duration according to the needs of every project. This finding is especially relevant since one of the early expressions of resistance we received was “there’s no time for theory in Design Thinking, let’s get rid of it!”. In our different evaluation formats, a balance between theory and hands-on proved to be functional to the goal of increasing the effect of DT training on cognitive and skill-based learning outcomes.

## 7 Conclusion

Designing-as-Performance and Performative Patterns are a work in progress, a translational approach to bridging the research-practice gap. There is more work to do in translating team-based design research outcomes: identifying promising candidate studies, operationalizing these outcomes, and iteratively testing new teaching materials in academic and professional venues.

Nonetheless, Designing-as-Performance stands as a radical, relevant, and rigorous redesign of Design Thinking training. Based on 20 years of empirical studies in design, as well as grounding in contemporary cognitive science, D-a-P provides a robust foundation for the evolution and future development of team-based design. It is our hope that this training approach will make significant contributions to the education and training of designers in a wide array of fields, and that these designers will make a positive contribution to the world.

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## References

Bloom, B. S. (Ed.). (1987). *Taxonomy of educational objectives. The classification of educat. goals; handbook. 30th print*. London: Longman Group.

Brothers, T. D. (2014). *Louis Armstrong, master of modernism* (1st ed.). New York: W. W. Norton.

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis, 58*(1), 7–19. Retrieved from http://www.jstor.org/stable/3328150

Dweck, C. (2008). Mindset. The new psychology of success. In *Ballantine books trade paperback ed*. New York, NY: Ballantine Books (A Ballantine books trade paperback).

Edelman, J. (2011). *Understanding radical breaks: Media and behavior in small teams engaged in redesign scenarios*. Retrieved from https://purl.stanford.edu/ps394dy6131, updated on 1/29/2019, checked on 2/18/2019.

Edelman, J., & Currano, R. (2011). Re-representation: Affordances of shared models in team-based design. In H. Plattner, C. Meinel, & L. J. Leifer (Eds.), *Design thinking. Understand—Improve—Apply* (pp. 61–79). Heidelberg: Springer. https://doi.org/10.1007/978-3-642-13757-0_4.

Edelman, J., Agarwal, A., Paterson, C., Mark, S., & Leifer, L. (2012). Understanding radical breaks. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research. Studying co-creation in practice* (pp. 31–51). Heidelberg: Springer (Understanding innovation).

Edelman, J. A., Owoyele, B., Santuber, J., Talbot, A. V., Unger, K., & von Lewinski, K. (2020). Accessing highly effective performative patterns. In C. Meinel & L. Leifer (Eds.), *Design thinking research* (Vol. 25, pp. 15–33). Cham: Springer International (Understanding innovation).

Eris, O. (2003). *Asking generative design questions: A fundamental cognitive mechanism in design thinking*. Doctoral Dissertation. Stanford.

Gagné, R. M. (1984). Learning outcomes and their effects: Useful categories of human performance. *American Psychologist, 39*(4), 377–385. https://doi.org/10.1037/0003-066X.39.4.377.

Harnum, J. (2014). *The practice of practice*. [Online content edition]. Chicago, IL: Sol UT Press.

Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: MIT Press (A Bradford book).

Kirsh, D. (1996). Adapting the environment instead of oneself. *Adaptive Behavior, 4*(3–4), 415–452.

Kirsh, D. (2010). Thinking with external representations. *AI & Society, 25*(4), 441–454. https://doi.org/10.1007/s00146-010-0272-8.

Kirsh, D. (2011). *How marking in dance constitutes thinking with the body*. Retrieved from https://philpapers.org/archive/KIRHMI.pdf.

Kirsh, D. (2013). Embodied cognition and the magical future of interaction design. *ACM Transactions on Computer-Human Interaction, 20*(1), 1–30.

Kraiger, K., Ford, J. K., & Salas, E. (1993). Application of cognitive, skill-based, and affective theories of learning outcomes to new methods of training evaluation. *Journal of Applied Psychology, 78*(2), 311–328. https://doi.org/10.1037//0021-9010.78.2.311.

Lakiza, V., & Deschamps, I. (2019). How to develop an impactful action research program: Insights and lessons from a case study. *TIM Review, 9*(5), 34–43. https://doi.org/10.22215/timreview/1239.

Meinel, C., & Leifer, L. (2020). *Design thinking research. Investigating design team performance*. Cham: Springer.

Porter, P. (1974). *Judo from the beginning, volume 1: National coaching standards*. Zenbei.

Rousseau, D. M. (2006). Is there such a thing as "Evidence-Based Management"? *AMR, 31*(2), 256–269. https://doi.org/10.5465/amr.2006.20208679.

Royalty, A., Oishi, L. N., & Roth, B. (2014). Acting with creative confidence: Developing a creative agency assessment tool. In H. Plattner, C. Meinel, & L. J. Leifer (Eds.), *Design thinking research. Building innovation eco-systems* (Vol. 84, pp. 79–96). Cham: Springer (Understanding innovation).

Schar, M., Gilmartin, S., Harris, A., Rieken, B., & Sheppard, S. (2017). Innovation self-efficacy: A very brief measure for engineering students. In *2017 ASEE Annual Conference & Exposition Proceedings.* Columbus, Ohio, 6/24/2017–6/28/2017: ASEE Conferences.

Schmidt, R. A., & Lee, T. D. (2014). *Motor learning and performance. From principles to application* (5th ed.). Champaign, IL: Human Kinetics.

Taheri, M., Unterholzer, T., Hölzle, K., & Meinel, C. (2016). *An educational perspective on design thinking learning outcomes*. Retrieved from https://hpi.de/fileadmin/user_upload/fachgebiete/meinel/papers/Design_Thinking/2016_taheri_unterholzer_ispim.pdf, checked on 1/6/2019.

Tversky, B. G. (2019). *Mind in motion. How action shapes thought* (1st ed.). New York, NY: Basic Books.

Varela, F. J., Thompson, E., & Rosch, E. (1993). *Embodied mind. Cognitive science and human experience. 3. print*. Cambridge, MA: MIT Press.

# Developing a Tool to Measure the Transfer of Design Practice from Training Contexts to Applied Contexts

**Adam Royalty, Helen Chen, Bernard Roth, and Sheri Sheppard**

**Abstract** The goal of design thinking training is to prepare participants to transfer what they learn in the classroom to real world scenarios. Because context influences transfer, a crucial step towards developing a transfer measure is understanding differences between training contexts and applied contexts. This chapter presents a study that investigates the influence academic contexts have on design thinking. We found three general influences; Supports for Learning Design, Self-differentiation of Design, and Internal Responses. Additionally, we outline three pilot studies that explore influences a range of applied contexts have on design thinking.

## 1 Introduction

Design thinking is a methodology employed to creatively solve real world problems (Cross 2006; Kelley and Kelley 2013). People often learn design thinking through educational programs like courses or workshops (Royalty et al. 2015). In order for these programs to be successful, students must transfer what they learn in an educational environment and apply that learning in a real life environment. Transfer, generally speaking, is well a known aspect of learning (Bransford and Schwartz 1999; Perkins and Salomon 1992). How students transfer design thinking, however, is not well understood. This chapter examines the conditions influencing transfer of design thinking.

This work is important because the success of design thinking as a viable innovation methodology depends on how well training programs prepare people to solve real problems. Research that assesses the efficacy of these programs helps those designing training programs—in academia and industry—better communicate

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the potential benefits of design thinking and improves their own offerings. Although measures of design thinking exist, they tend to assess the individual (Dow et al. 2012; Royalty et al. 2014; Saggar et al. 2015) or the environment (Royalty and Sheppard 2018). This proposed work uses transfer as a mechanism to assess both together.

Transfer happens when learning in one context influences performance in another context (Perkins and Salomon 1992). The interaction between the learner, the contexts, and the learning content (knowledge) determines how transfer happens (Greeno et al. 1993). It is well documented that transfer is much more likely to occur when the learning context is similar to the application context—near versus far transfer (Detterman 1993; Woodworth and Thorndike 1901). It is also easier to transfer reflective, well practiced routines—known as low road transfer—then it is to transfer learning that requires deliberate abstraction in order to connect with the application context (Perkins and Salomon 1992). As Perkins and Solomon point out, most educational goals aim for the more difficult far and high road transfer.

Fortunately, there are ways to promote successful transfer. One approach is to teach a variety or “bundle” of concepts that work together (Luria 1976). Another is to focus on the underlying concepts rather than just the procedures (Chase et al. 2019; Chi et al. 1989; Wertheimer and Wertheimer 1959). Finally, dedicating time to metacognitive reflection can help students better identify and process underlying concepts and thus, increase transfer (Brown 1978; Flavell 1979).

As mentioned above, design thinking is a methodology typically learned in an academic environment and practiced in an applied environment. As more and more universities develop design thinking trainings it is crucial to understand what conditions lead to strong transfer—especially far and high road transfer. Although transfer is difficult, there is reason to believe that design thinking is up to the task. This is in part because design thinking fits this notion of bundling. There is not a single concept underlying the subject, but rather a web of interconnected practices (von Thienen et al. 2017). Moreover, the Reflective Design Practice (RDP) tool (Royalty et al. 2018) elicits metacognitive awareness of design thinking which we hypothesize will positively influence transfer.

However, before we can effectively measure transfer there are elements that we must better understand. In particular, we need to know to what extent the academic environment differs from the applied environment. Contextual variables play a significant role in teaching design thinking (Doorley and Witthoft 2011; Royalty 2018). The studies described in this chapter provide insight into how students perceive the environment as a driver of learning. What is not well known is how contextual variables influence design thinking in applied settings. In order to understand the full picture of transfer we need to understand how related academic environments are to applied environments. This leads to our primary research questions:

*How do academic and applied environments differentially influence design thinking?*

**Table 1** Studies run during the 2018–2019 academic year

| Study | Environment investigated | Data collection method | Goal |
|---|---|---|---|
| Study 1 | Academic environment | Reflective design practice | Develop a coding scheme to analyze RDP responses |
| Study 2 (Pilot) | Applied environment | Reflective design practice | Capture design practice in industry |
| Study 3 (Pilot) | Applied environment | Environmental variables | Capture how managers in industry manipulate environments |
| Study 4 (Pilot) | Initial transfer environment | Reflective design practice | Understand how student first apply design practice beyond the classroom |

To answer this question, we investigated both environments separately. Our primary study focused on the academic environment. It made sense to begin our work here because we had a great deal of access to an academic environment (the Stanford d.schools), and because most people begin their study of design thinking in an educational institution, complemented with two pilot studies examined the applied environments. We chose to run pilots instead of full studies because applied environments are generally more varied than academic environments (Royalty and Sheppard 2018), and we wanted to test our tools and methodologies before engaging in deeper study. Table 1 highlights the studies we ran.

While conducting our research, we discovered a third environment critical to transfer. The realization came while we studied Stanford d.school students through the RDP tool. Many students began to transfer what they learned in their d.school courses to their personal lives outside the context of d.school course work. We call this the *initial transfer environment*. It is important to study this environment too because this is an opportunity for students to practice transferring design thinking before encountering an (often more constrained) applied environment.

## *1.1 Reflective Design Practice*

Our primary data collection method was through the Reflective Design Practice (RDP) tool (Royalty et al. 2018). It is a digital reflection tool designed to capture subjects' *design practice*. We define design practice as the specific design thinking skills and mindsets an individual person internalizes. The tool asks subjects to photograph an artifact they created while using design thinking. The artifact could be tangible (e.g., a physical prototype) or it could be intangible (e.g., an interview protocol). Then subjects are given prompts to help them reflect on their creation (see Fig. 1). Reflecting once a week for 10 weeks, for example, produces a 10-page portfolio documenting aspects of a subject's design practice over time.

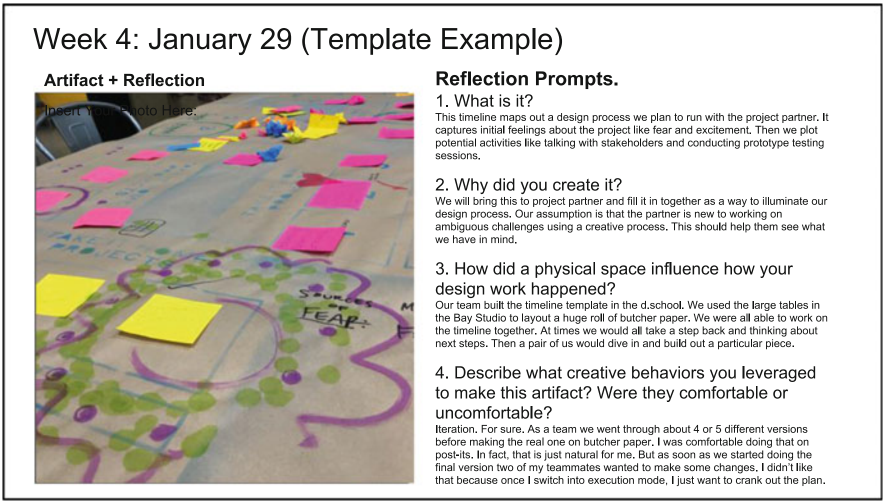



**Fig. 1** Reflective design practice tool

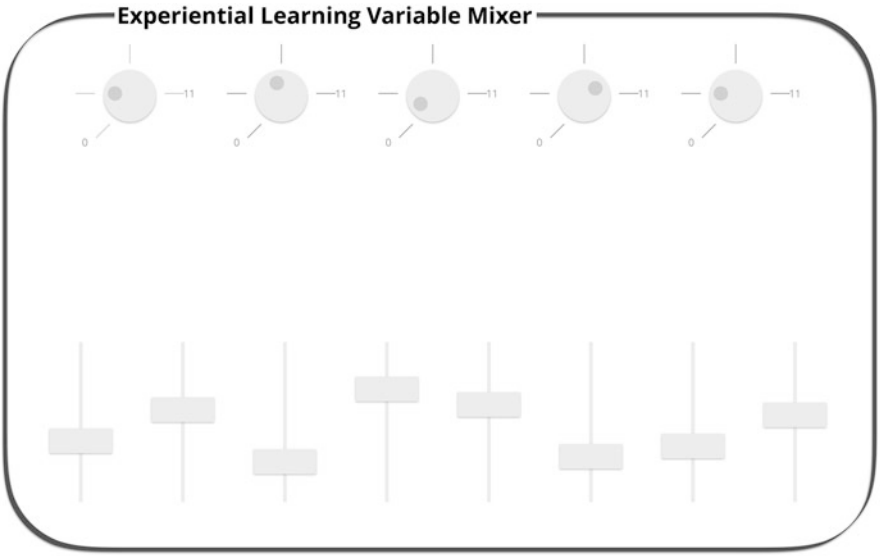



**Fig. 2** Environmental variables

## *1.2 Environmental Variables*

A second type of data we collected was what environmental variables instructors and managers use to support design thinking. The collection method we used was modified from a tool (Fig. 2) used in a previous study (Royalty 2018). In both cases we asked people responsible for facilitating design thinking to list all the variables of the environment they manipulate while facilitating design.

# 2 Study 1: Using Reflective Design Practice to Categorize and Measure Aspects of Student Learning

## *2.1 Background*

Our primary study examines how academic environments influence students' design practice. A complete understanding of the key features of an academic environment allows us to compare them to features of applied environments. There are two perspectives of the academic environment we want to account for: the instructor perspective and the student perspective. Previous research highlights the features of an academic environment experienced design thinking instructors build into their teaching (Royalty et al. 2015; Royalty 2018). Study 1 focuses on what features students respond to.

## *2.2 Participants*

The participants in this study were Stanford d.school students enrolled in the Reflective Design Practice course. We had a total of 33 unique participants. There were five engineering students, 13 business students, three medical students or fellows, four education students, and 8 students studying the humanities. There were 16 women and 17 men. The majority of students (30) were graduate students or fellows. Only three were undergraduates. This is not unexpected as most of the Stanford d.school student are in graduate school.

## *2.3 Methods*

Students in Reflective Design Practice enrolled in the course concurrently with other d.school courses. The primary assignment was to use the RDP tool to capture and reflect upon artifacts created in their other d.school courses. After 7 weeks researchers conducted a 45-min semi-structured interview with each student. Students were asked to respond to the interview questions by providing examples drawn from their seven reflections. This helped ground the responses in actual events.

Although we have a set of codes generated from previous studies investigating how instructors created academic environments, we recognized that these codes might not be appropriate to apply to the student responses captured in the RDP tool. Because we had no a priori hypothesis predicting what features students would respond to, we used grounded theory to establish a new set of codes. We open coded the transcribed interviews and RDP tool responses of six participants. We chose this subset of participants to generate the codes because they varied in discipline and d.school experience. Half the participants had taken at least one d.school course prior to the quarter in which they enrolled in Reflective Design Practice. The other half took their first d.school course the quarter they enrolled in Reflective Design Practice. We chose two students each from three general disciplines: engineering, business, and humanities. The experience level was split evenly across the discipline. For example, we had one engineering student who was new to the d.school and one engineering student who had taken a d.school course before. The same was true for the other two general disciplines. After the first round of open coding, we created over 100 unique codes. We narrowed those down to 24 independent codes across 3 categories.

## *2.4 Initial Results*

The three major categories of student responses found in academic environments are: supports for learning design, self-differentiation of design, and developing design practice.

Supports for learning design are the instructors, activities, and spaces students interact with while they are explicitly being taught design. Self-differentiation of design are the signals students receive that allow them to perceive the difference between design and other problem solving methodologies. In other words, students define and delineate design by contrasting it with more familiar ways of working. Finally, developing design practice are the internal cognitive and emotional responses to learning design.

Below are the codes for each major category. We will share the code, a brief description, and an example from the data. It is important to note that these codes may be reduced or rephrased as our work continues. The list below represents a snapshot of where we are now.

**Category: Supports for Learning Design**
These are aspects of the academic environment students identified that supported how they learned design. There are 11 codes (Table 2).

An example of the Flexibility code is, "[The] environment was a dynamic space equipped with all the materials we needed to create a low-res prototype."

Another example comes from the Care and Support code, "I walk into a class and I feel cared for as a person. That's really cool."

**Category: Self-differentiation of Design**
These are aspects of the academic environment that shape students' perspective of what design is and what design is not. Many of these realizations come from

**Table 2** Supports for learning codes

| Code | Description |
|---|---|
| Momentum | Continuing to move forward on a project without getting stuck |
| Pressure/Stress | The feeling of stress while working to complete a challenge or activity |
| Collaboration | Working with others |
| Instructor Demonstrations | Instructors demonstrating design techniques and behaviors in front of students |
| Flexibility | Working in a flexible space and having flexible deliverables |
| Access to Supplies | Always being able to locate an utilize tools to do design work |
| Space as a Manifestation of Activity | Physical space as a necessary integration into design work |
| Constraints | External constraints put in place by instructors or arising naturally during a challenge |
| Diversity of Team and Instructors | Teammates and instructors with diverse backgrounds, perspectives, and expertise |
| Care and Support | Teammates and instructors that care about students' wellbeing |
| Learning as a Primary Goal | An understanding that a primary motivation behind class work is to teach design (versus only solving a problem for a client) |

**Table 3** Self-differentiation of design codes

| Code | Description |
|---|---|
| Applied Work | Working on real world challenges using practical tools |
| Feedback | Receiving formative feedback from instructors and teammates |
| Visual Thinking | Communicating visually |
| Resistance to Fixation | Working to solve challenges that explicitly do not have a single correct solution |
| Ambiguity | Ambiguity of expectations and purpose of activities |

contrasting design work with work performed in other courses. There are five codes (Table 3).

An example of the Resistance to Fixation code is, "and the emphasis on ideas and things not having to be perfect, but it just being a constant process where you iterate, and there really is no end, but that's okay, that's a part of the process."

This student quote represents the Ambiguity code, "I think ambiguity has been also in my navigation at Stanford as a whole, but D-school has making it . . . If it's not more comfortable, it's less stressing."

**Category: Internal Responses**

These are the cognitive and emotional responses to design instruction that shape how students develop their own design practice. In our analysis they are still aspects

**Table 4** Internal responses codes

| Code | Description |
|---|---|
| Surprise | Student surprise in themselves for successfully applying a creative tool or behavior |
| Belonging | A sense of personal belonging in the class and general community |
| Shifting Perspectives | Seeing a problem in a new way—pivoting |
| Noticing Transfer Opportunities | Perceiving the ability to use design to do work that is not explicating framed as design work |
| Self-awareness | Students understanding what areas of design they excel at and what areas they need to work on |
| Stretching Beyond Comfort Zone | Thinking or working in a way that is new or different |
| Questioning Design Practice | Using past experiences with design to critique when and where to NOT implement certain methods |
| Affect | Named emotional responses to practicing design |

of the academic environment because they interact with the aspects listed above. In other words, even though these are all internal, they develop through working repeatedly within the academic environment. There are eight codes (Table 4).

This student quote is an example of the Surprise code is, "Brainstorming the ideas without any limitations was the most liberating and fun, and it surprised me how many interesting ideas we were able to come up with. I was initially constrained to practical ideas; but when I saw my team-mates come up with completely wacky ideas, it released the gate in my mind and more ideas started flowing."

Another example is the Self-awareness code, "I'm still struggling with identifying what's an appropriate "level" to anchor my design challenge and how to craft it that it's broad enough yet narrow enough. I did notice however that I was more aware of not embedding solutions in my POV, and could even identify that in my design ally's POV statement. I also find that having my design ally push me by asking questions is immensely helpful to my distillation process in the why/how."

The final example comes from the Stretching Beyond Comfort Zone code, "I literally felt my brain stretching as I tried to change the paradigm of problem solving that I was so accustomed to."

The codes listed above describe and categorize how students make sense of design as they learn it. Immediately it is clear that students are learning so much more than a design process. Visual thinking and flexibility are two aspects linked closely with creatively. Belonging is a massively important psychological construct with profound impact on success (Walton and Cohen 2007). It is not too far fetched to connect the mental stretching students do with neural plasticity. In fact, the codes point to a range of phenomena studied across the social sciences—diversity, collaboration, etc. This study provides new insight into how students internalize design thinking. This is the first step in understanding how they apply it in the world.

The next steps are to use this scheme to code all students' interview transcripts and RDP tool responses. We will look for the most common codes and any temporal patterns. The coding categories and frequencies will serve as the baseline for comparison. The amount of overlap between academic and applied environments can then be measured.

Because the academic environment has two parts—instructor perspective and student perspective—we will compare these student perspective codes to codes generated from the instructor perspective (Royalty et al. 2015). We will look for overlapping categories and compare frequency of mentions in each category.

## 3 Study 2 (Pilot): Using Reflective Design Practice to Capture Applied Design Practice

### *3.1 Background*

This pilot study examined how effective the RDP tool was at capturing artifacts and associated reflections in an applied environment. Based on the data we have been able to collect from Stanford d.school students, we were optimistic that similar data could be collected from participants practicing design in industry. If we are able to effectively capture design practice—and what supports it—using the same tool in multiple settings, that allows us to do direct comparisons.

### *3.2 Participants*

The RDP tools was piloted with two distinct groups. The first group consisted of six undergraduate engineering interns working at a large American automotive company. The interns were all part of a summer internship program within the company's engineering division. The second group we piloted with were attendees of a conference for design thinking managers and a total of 25 participants completed the RDP tool.

### *3.3 Methods*

The interns were asked to complete three reflection activities (Fig. 3) each week for 4 weeks. The first activity focused on the physical space in which they worked. The second activity centered on how they collaborated. The final reflection prompted the interns to articulate the culture of the workplace. On the fifth week, the interns completed a final reflection (Fig. 4) where they were asked to use their weekly reflections to summarize what they learned during the previous 4 weeks. Due to

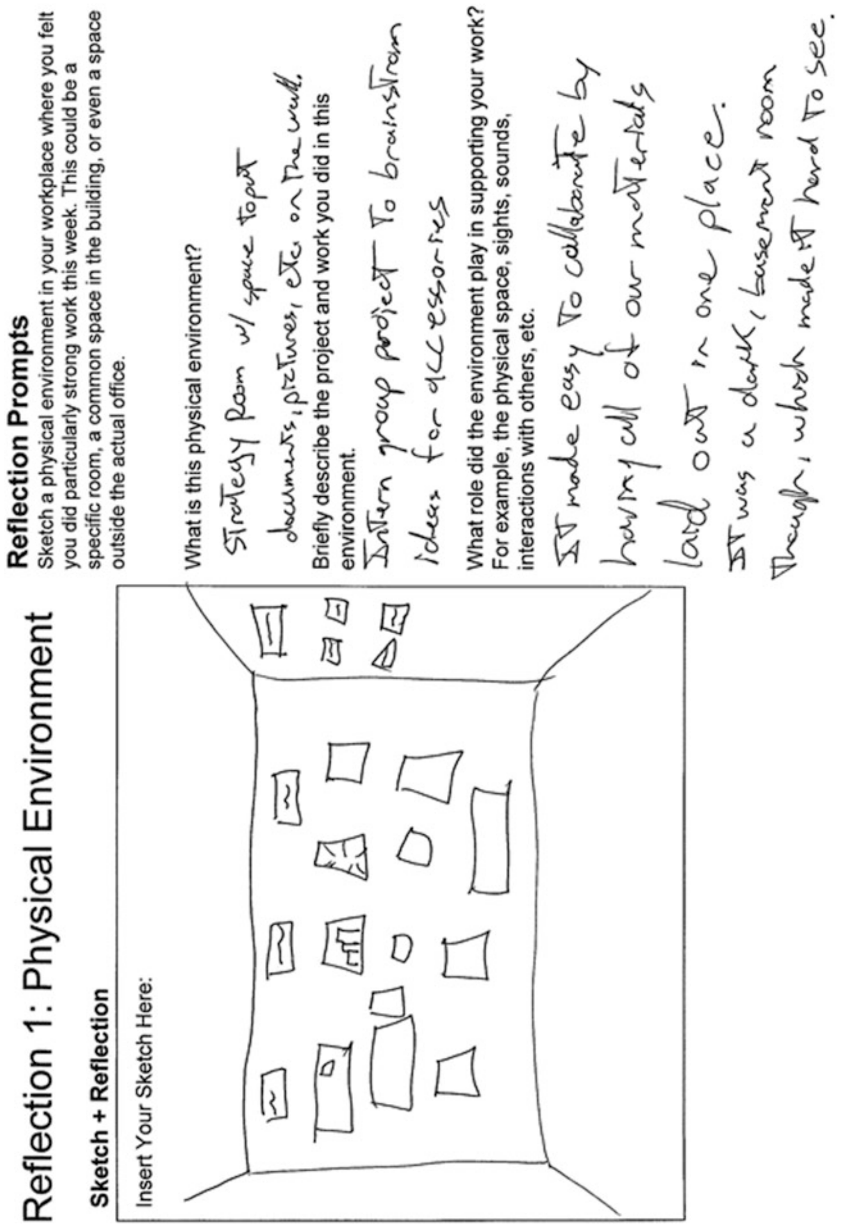



**Fig. 3** Weekly reflection activity

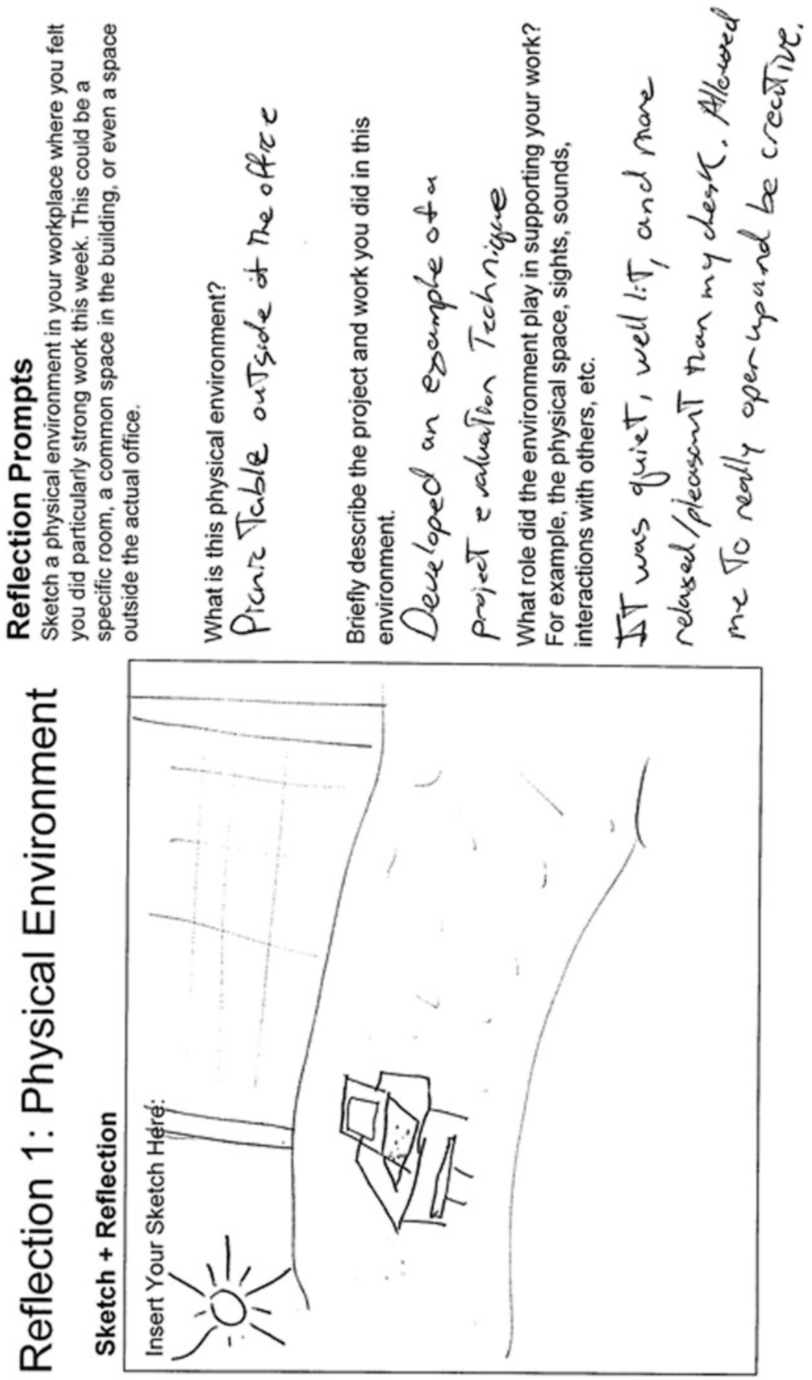



**Fig. 4** Final space reflection

organizational concern about product privacy, the interns were not permitted to photograph their work. However, they were permitted to sketch artifacts. Because the vast majority of RDP data we analyze comes from the written reflections associated with the image, we did not feel this constraint presented too great a confound.

Our pilot with design thinking managers included subjects who facilitated design thinking work in a range of industries. The managers were primarily at the director level, having between 5 and 15 years of experience managing teams. We gave the participants the option to complete the RDP tool digitally or on paper. If the participants chose the paper option, they were asked to sketch the artifact. Some of the participants chose to submit a digital photograph and write the reflection on paper (see Fig. 5).

### 3.4 Future Analysis

We will use the coding scheme developed in study 1 to analyze these data throughout the summer. Our focus will be on identifying environmental features that are similar and different to an academic environment.

Interestingly, preliminary results reveal that interns articulate culture in a very nuanced way. For example, one intern identified the desks of two coworkers stationed next to each other. One desk was completely open and often saw other employees coming over to work with the desk's occupant. The adjacent desk had cardboard boxes piled up on the edges of the desk. No other employees dared collaborate with that person. The intern perceived this as a cultural microcosm where about half the organization feel like the open desk, and the other half felt like the boxes in desk.

## 4 Study 3: Capturing Environmental Variables in Applied Contexts

### 4.1 Background

In this study we used the Environmental Variables tool to understand what managers manipulate when they support innovation work. We collected the Environmental Variables managers who support design thinking in applied environments manipulate through surveys distributed at the 2017 d.confestival. There is existing research showing what instructors teaching design thinking in academic environments manipulate (Royalty 2018). This study serves as a third comparison group—

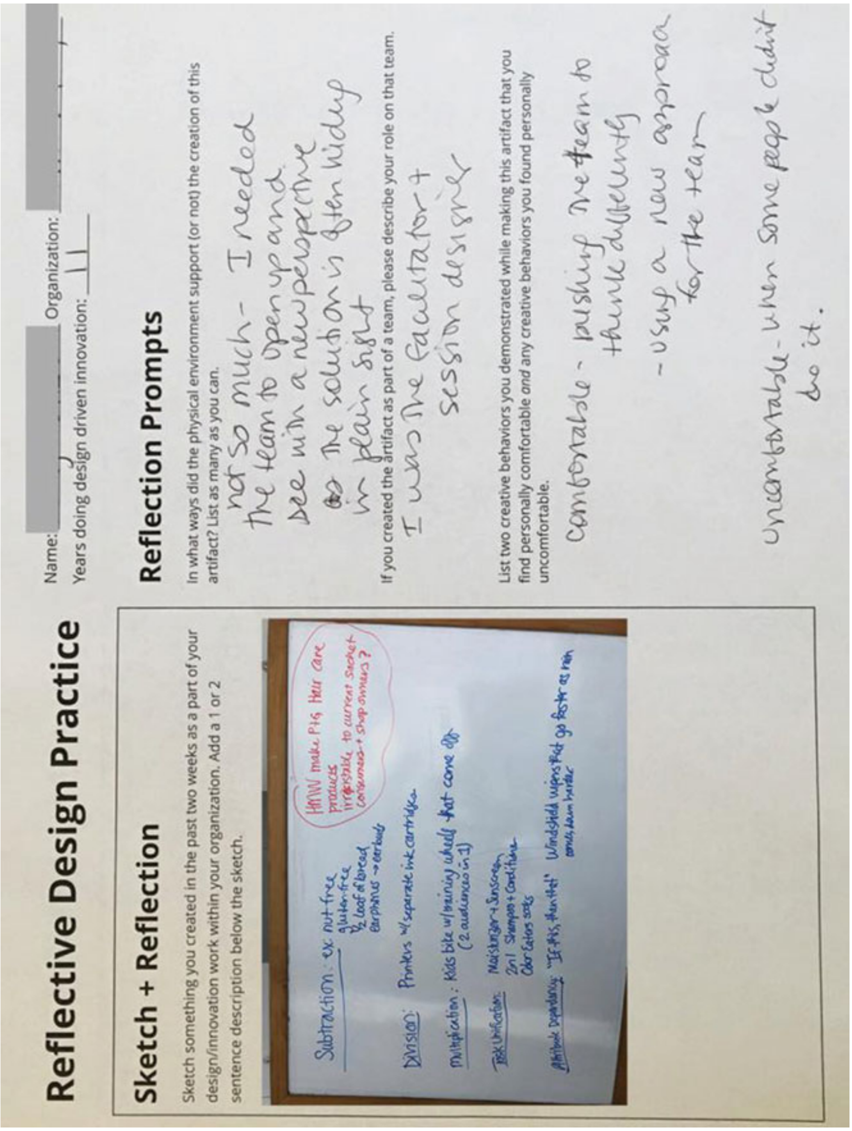



**Fig. 5** Reflective design practice tool given to design thinking managers

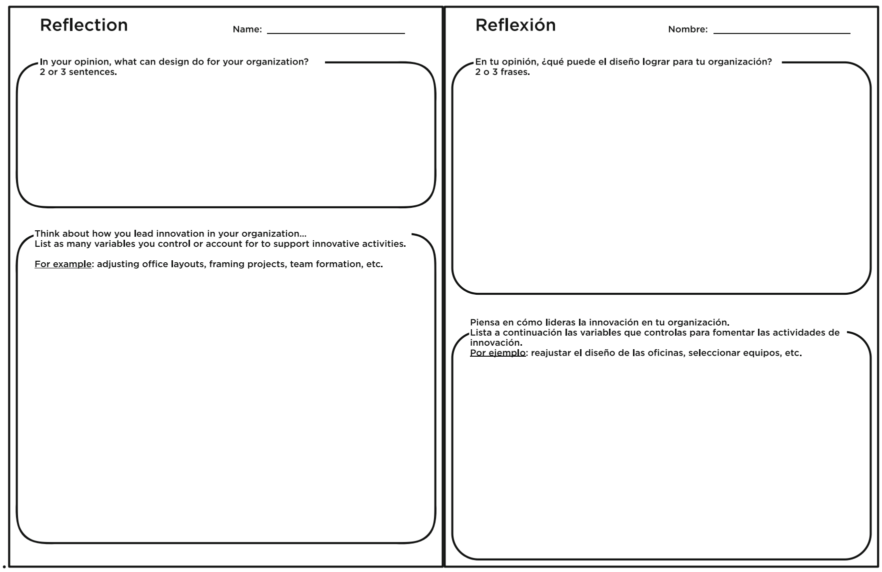
another in an applied environment which acts as a control for the data collected at the d.convestival. These data are essential because we can compare both applied environment groups with the educational environment group.

### 4.2 Participants

The participants were 110 Chief Technical Officers (CTOs) and Chief Information Officers (CIOs) from companies spanning 10 Latin American countries. The participants were all part of an innovation training program centered around design thinking.

### 4.3 Methods

Prior to the design thinking training we gave each participant a paper worksheet instructing them to list the environmental variables they control or account for while leading innovative work (see Fig. 6).



Reflection
Name:
In your opinion, what can design do for your organization?
2 or 3 sentences.
Think about how you lead innovation in your organization...
List as many variables you control or account for to support innovative activities.
For example: adjusting office layouts, framing projects, team formation, etc.

Reflexión
Nombre:
En tu opinión, ¿qué puede el diseño lograr para tu organización?
2 o 3 frases.
Piensa en cómo lideras la innovación en tu organización.
Lista a continuación las variables que controlas para fomentar las actividades de innovación.
Por ejemplo: reajustar el diseño de las oficinas, seleccionar equipos, etc.

**Fig. 6** Environmental variable tool for CTOs and CIOs in English and Spanish

### 4.4 Future Analysis

Once we have the responses translated from Spanish and Portuguese to English. We will compare the responses with our other data sets. We will measure the percentage of features in common and compare the most frequent categories in each environment.

One clear issue is that participants in this study work in different cultures than the subjects in our comparison groups. This may end up being a limitation we cannot overcome. If that is the case, we would need to seek out another comparison group. However, these data could still prove useful if we are able to use this tool to collect data from managers from even more cultures. That would setup a study where we could look at cultural influences on manipulated environmental variables.

## 5 Study 4 (Pilot): Using Reflective Design Practice to Measure Initial Transfer

### 5.1 Background

This pilot study emerged as we taught our RDP course. We noticed that students reported instances of applying their emerging design practice to challenges beyond the bounds of a class while still enrolled in d.school courses. This suggests a more nuanced model of transfer then just learning design in a course and then applying it when you start a job. Students do not wait to enter a work environment before applying their design practice. So, we created a new set of prompts to capture this initial transfer.

### 5.2 Participants

We collected transfer prompts from 12 students who enrolled in the Reflective Design Practice course during the 2018–2019 academic year. Eleven were graduate students and one was an undergraduate. Two students were engineers, two were in medicine, four were in business, and four were in the humanities.

### 5.3 Methods

Students completed the transfer prompts in week 8 of the quarter—1 week after the semi-structured interviews. There were two prompts. The first instructed students to modify a space outside of the d.school to make it more conducive to creative work (see Fig. 7). The second prompt asked students to identify a creative behavior they found personally uncomfortable and use it to address a challenge outside their d.school course (see Fig. 8).

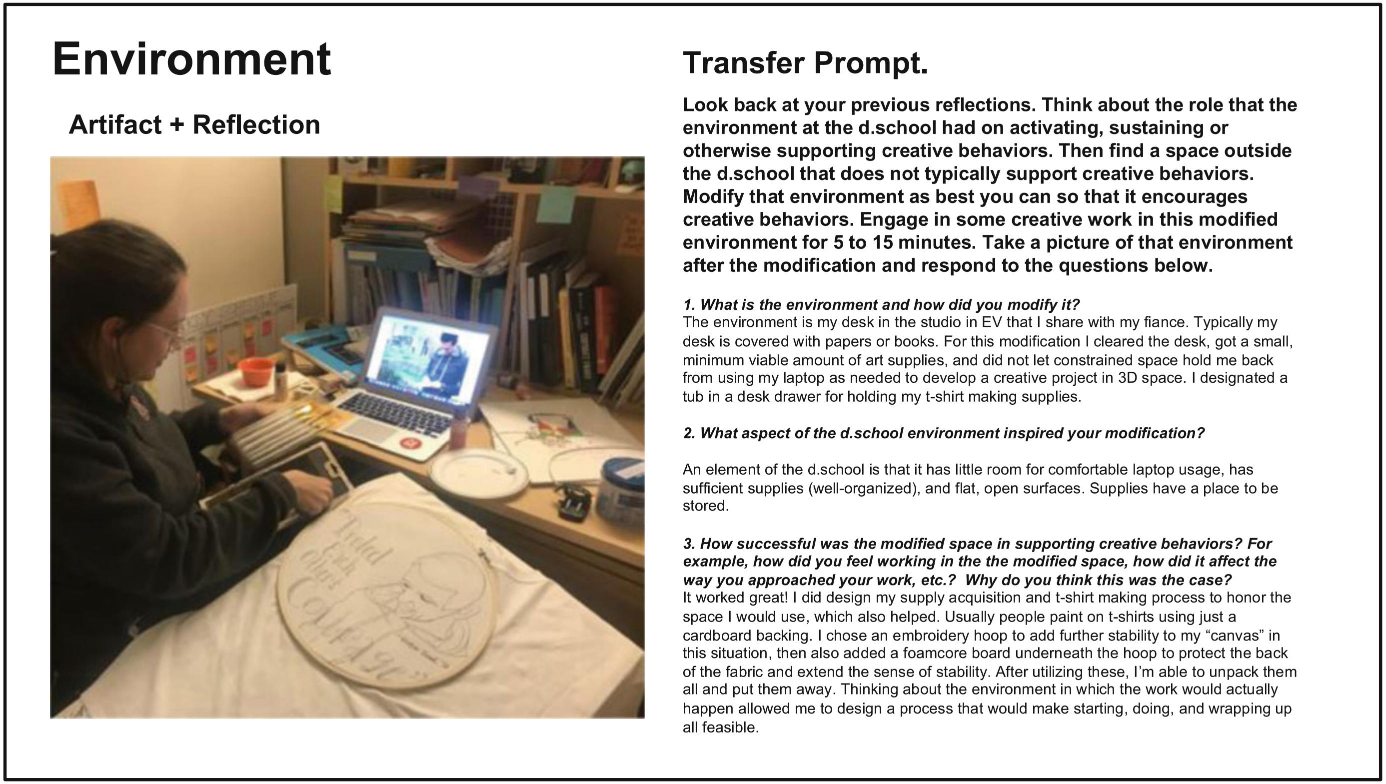
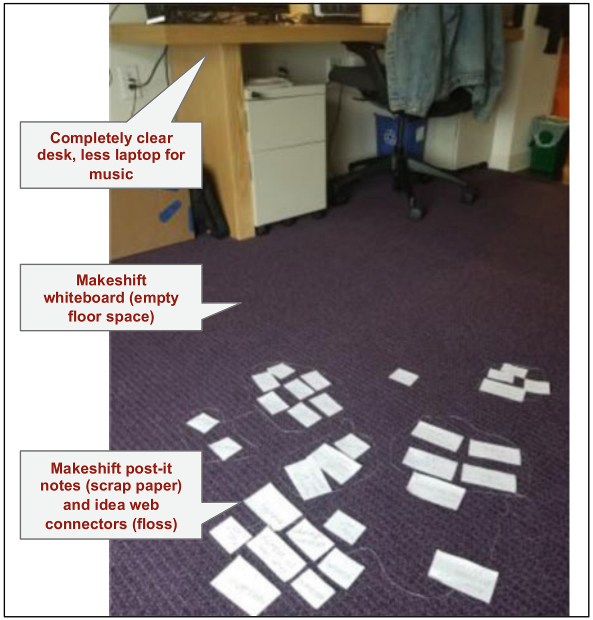



**Fig. 7** Physical space transfer prompt

# Environment

## Artifact + Reflection




**Transfer Prompt.**

**Look back at your previous reflections. Think about the role that the environment at the d.school had on activating, sustaining or otherwise supporting creative behaviors. Then find a space outside the d.school that does not typically support creative behaviors. Modify that environment as best you can so that it encourages creative behaviors. Engage in some creative work in this modified environment for 5 to 15 minutes. Take a picture of that environment after the modification and respond to the questions below.**

1. What is the environment and how did you modify it?

**I selected my bedroom as the environment. I modified it by:**

a. **Removing all objects from the top of my often cluttered desk**
b. **Making my desk a ‘no go zone’ during the work process**
c. **Using a bunch of scrap paper and floss as materials rather than my laptop**

2. What aspect of the d.school environment inspired your modification?

**Each of these modifications were based on a d.school environmental consideration or lesson(s):**

a. **Creating a ‘clean’ space that is entirely open**
**A**
c. **Forcing a change in my behavior to spark a change in my thinking; using informal materials to reinforce creative approaches, reduce formality, and be a bit silly**

3. How successful was the modified space in supporting creative behaviors? For example, how did you feel working in the the modified space, how did it affect the way you approached your work, etc.? Why do you think this was the case?

**I completed this prompt as I worked on a grant application. I hoped to inspire creativity but also give life to flurry of underdeveloped ideas. I found that working in the modified environment helped me brainstorm more quickly and exhaustedly. I fleshed out the logical and emotional components of my grant application much more effectively than when I tried to just sit down at my computer and write things out (akin to the post-it notes and idea map in class). I could also physically move ideas to create a storyline and show connections (akin to the cluster maps in class). Overall, things just felt lower risk and less output-oriented in this environment and work style, which I think let me idea dump without hesitation or too much thought.**

**Fig. 8** Discomfort transfer prompt

### 5.4 Future Analysis

We will use the coding scheme developed in study 1 to analyze these data. Our focus will be on identifying environmental features that are similar and different to the academic environment described in each student's prior RDP entries.

## 6 Conclusion

In response to strong, positive student feedback we will continue to iterate the RDP tool. The next step is to enhance the visual and interactive aspects of the tool. This will increase the usability and make it easier for educator and managers to implement the tool. Once that is complete, the RDP tool will become much more scalable. We will make the tool open to practitioners and researchers who want to use reflection to enhance student experiences and more deeply understand design thinking.

The data we collected this past year give us tremendous insight into both the academic environment and the applied environment. Study 1 provides a novel, rich description of the academic environment through the student lens. Studies 2 and 3 demonstrated that tools previously used to collect data on academic environments can be used to collect comparable data on applied environments. Study 4 uncovered a crucial insight—students begin to transfer their design practice beyond the classroom well before they apply it in a job setting.

Based on these initial findings, the development of a measure that compares how environments support design thinking relies on understanding the complete arc students go through: learning in an academic context, initially transferring design practice into a non-academic context, then applying design practice in an organizational context.

Once complete, our measure will not only guide academic pedagogy—it will also inform organizations of how best to create environments that support employees who learned design thinking in an academic setting transferring and putting that learning into action into applied settings.

## References

Bransford, J. D., & Schwartz, D. L. (1999). Chapter 3: Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*(1), 61–100.

Brown, A. L. (1978). Knowing when, where, and how to remember; a problem of metacognition. *Advances in Instructional Psychology, 1*, 77–165.

Chase, C. C., Malkiewich, L., & Kumar, A. S. (2019). Learning to notice science concepts in engineering activities and transfer situations. *Science Education, 103*(2), 440–471.

Chi, M. T., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13*(2), 145–182.

Cross, N. (2006). Design as a discipline. In *Designerly ways of knowing* (pp. 95–103). London: Springer.

Detterman, D. K. (1993). *The case for the prosecution: Transfer as an epiphenomenon*.

Doorley, S., & Witthoft, S. (2011). *Make space: How to set the stage for creative collaboration*. Hoboken, NJ: Wiley.

Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., & Klemmer, S. R. (2012). Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. In *Design thinking research* (pp. 127–153). Berlin: Springer.

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry. *American Psychologist, 34*(10), 906.

Greeno, J. G., Smith, D. R., & Moore, J. L. (1993). *Transfer of situated learning*. In D. K. Detterman & R. J. Sternberg (Eds.), *Transfer on trial: Intelligence, cognition, and instruction*. Norwood, NJ: Ablex.

Kelley, T., & Kelley, D. (2013). *Creative confidence: Unleashing the creative potential within us all*. Currency. New York: Crown.

Luria, A. R. (1976). *Cognitive development: Its cultural and social foundations*. Cambridge, MA: Harvard University Press.

Perkins, D. N., & Salomon, G. (1992). Transfer of learning. *International Encyclopedia of Education, 2*, 6452–6457.

Royalty, A. (2018). Design-based Pedagogy: Investigating an emerging approach to teaching design to non-designers. *Mechanism and Machine Theory, 125*, 137–145.

Royalty, A., Oishi, L. N., & Roth, B. (2014). Acting with creative confidence: Developing a creative agency assessment tool. In *Design thinking research* (pp. 79–96). Cham: Springer.

Royalty, A., Ladenheim, K., & Roth, B. (2015). Assessing the development of design thinking: From training to organizational application. In *Design thinking research* (pp. 73–86). Cham: Springer.

Royalty, A., & Sheppard, S. (2018). Mapping and measuring design thinking in organizational environments. In *Design thinking research* (pp. 301–312). Heidelberg: Springer.

Royalty, A., Chen, H. L., & Sheppard, S. (2018). Reflective design practice: A novel assessment of the impact of design-based courses on students. In *Proceedings of the ASEE/IEEE Frontiers in Education Conference*, San Jose, CA.

Saggar, M., Quintin, E. M., Kienitz, E., Bott, N. T., Sun, Z., Hong, W. C., et al. (2015). Pictionary-based fMRI paradigm to study the neural correlates of spontaneous improvisation andfigural creativity. *Scientific Reports, 5*, 10894

von Thienen, J., Royalty, A., & Meinel, C. (2017). Design thinking in higher education: How students become dedicated creative problem solvers. In *Handbook of research on creative problem-solving skill development in higher education* (pp. 306–328). Hershey, PA: IGI Global.

Walton, G. M., & Cohen, G. L. (2007). A question of belonging: Race, social fit, and achievement. *Journal of Personality and Social Psychology, 92*(1), 82.

Wertheimer, M., & Wertheimer, M. (1959). *Productive thinking*. New York: Harper.

Woodworth, R. S., & Thorndike, E. L. (1901). The influence of improvement in one mental function upon the efficiency of other functions.(I). *Psychological Review, 8*(3), 247.

# Using 'Space' in Design Thinking: Concepts, Tools and Insights for Design Thinking Practitioners from Research

**Martin Schwemmle, Claudia Nicolai, and Ulrich Weinberg**

**Abstract** This chapter relies on an interactionist understanding of space, a shared leadership approach, and Design Thinking coaching to derive consequences for the use of space in Design Thinking workshops. It combines, on the one hand, concepts from theory with experience, insights, and tools from practice. On the other hand, it takes both the perspective of a Design Thinking coach and of workshop participants and it seeks to provide a broad perspective of how a space in Design Thinking can be prepared, used, and transformed to leverage its potential for teams. Deriving practical implications from theory will allow readers to better understand, reflect, and teach space in a Design Thinking context and further support them in developing their own interventions or variations of the tools presented.

## 1 Introduction

Design Thinking, as taught and practiced at the HPI School of Design Thinking is understood as comprising three Ps—people, place, and process. The Design Thinking process with its division into problem and solution space and its iterative nature builds the structure and backbone of most Design Thinking workshops and has been discussed in several research- and practitioner-oriented publications (Brown 2008; Liedtka 2015; Micheli et al. 2018). In a similar vein, the role of interdisciplinary collaboration is one core component of Design Thinking and, hence, new concepts of leadership, such as shared leadership, the team-of-teams approach, or coaching as a leadership style are intensely discussed in both Design Thinking and management research (Hackman and Wageman 2005; Carson et al. 2007; McChrsytal et al. 2015). However, the third P, "place", is still underleveraged as a crucial component in Design Thinking. We assume, this lack of acknowledging

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and using space as an important component of both researching and doing Design Thinking stems from three reasons.

First, and as great philosopher Immanuel Kant mentioned, space and time are the given context factors of human behavior (i.e., they are always there), and so the awareness for them is, generally speaking, very low. In order to sense the impact of a current spatial situation or to actively make use of the potential of space, it is necessary to build a spatial awareness for both facilitators and participants of Design Thinking workshops.

Second, the use of space and elements in spaces, such as material and furniture, is trained. For instance, the educational system teaches pupils how and where to sit (teacher at the front, pupils facing the teacher), and meeting rooms have a classical setup, which is unusual to change. Even the position of people around a table reflects trained habits and implicitly reveals who the boss is based on the place at the table (Zweigenhaft 1976; Becker et al. 1983; Marx et al. 1999). Hence, some of these trained behaviors need to be overcome and participants need to be encouraged to take charge of their spatial environment.

Third, many people involved in Design Thinking consider space an architectural topic and refer to "planning and constructing a space." They therefore hand over the responsibility of their environment to other people and overlook the possibilities (and power) they themselves have as users of the space. Or, they overtrivialize the topic of space by acknowledging its flexibility, for example, by having furniture on wheels, without making use of it. In a similar vein, research in the area of space needs to combine sources from architecture, business, phsychology, and sociology.

This chapter focuses on the active use of space as an element of doing Design Thinking—both from the perspectives of a coach preparing and facilitating a workshop and from the perspective of a Design Thinking team. To this end, we illustrate how concepts from the fields of architecture, management, psychology, and sociology can be turned into specific actions supporting the flow of a workshop and hence its results. We thereby contribute to the field of space in Design Thinking in three ways. First, we identify theoretical concepts and tools from different fields relevant for using space in Design Thinking and show how to apply them during a workshop. We thereby contribute to bridging the theory-practice gap in this area. Second, we distinguish between the preparation of a workshop space and the space use during a workshp as well as the roles of coaches and participants, and thereby provide a broad perspective of using space in Design Thinking workshops. Third, we illustrate our thoughts with specific examples from our own experience and reflect on them based on research.

The remainder of this chapter is structured as follows. We first provide the theoretical foundations for space and coaching in Design Thinking. Second, we focus on the the use of space in Design Thinking before a workshop (i.e., in the preparation phase). Third, we move the focus from before to during the workshop and emphasize the role of a coach using space and fourth, we regard the use of space during a workshop by teams. We close this chapter with a short discussion.

# 2 Theoretical Background

## *2.1 The Understanding of Space*

The understanding of space underlying this chapter builds on sociology and refers to an interactionist understanding. This understanding considers space not as a static entitiy with walls, but as the interaction of a user with a space. In line with Lefebvre and Löw, we follow the understanding that a space is only created by this interaction of elements of space with its users (Lefebvre 1991; Löw 2008). As illustrated in Fig. 1, such an interactionist space combines the (physical) elements that a space offers, such as its floorplan, distances, or atmospheric cues as perceived by the user (perceived constructed space) with the users' subjective elements, such as the individual's perception, its experiences and resulting behaviors (reflected constructed space).

This understanding has important conseqences for the use of space in Design Thinking. First, space is never solely the space of planners and architects, but can—or better—must be transformed by its users. This means that a participant in a workhop can no longer be considered the "victim" of the spatial planning by an architect or interior designer. She rather becomes co-creator of the space through her interaction with spatial elements. If people involved in Design Thinking realize this shift of power and the active role they can take, it allows them to move from accepting space as-is to changing or even preparing a space based on what best suits their requirements. Second, the interactionist understanding extends the notion of space from a purely physical to a behavioral level. If space is created by the interaction with a user, the perception and behavior of this user determine the space. Hence, changing a space is not tied to changing its physical components, such as moving walls or even moving furniture. Instead, if users behave differently in a space, this changed behaviors also transforms the space. Third, since Design

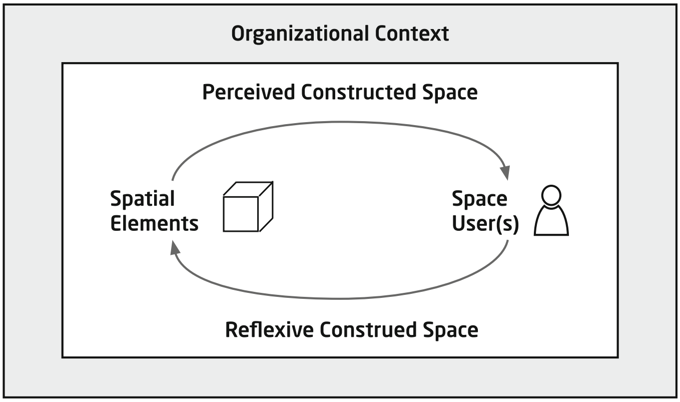


**Fig. 1** Interactionist understanding of space [based on Lefebvre (1991) and Löw (2008)]

Thinking builds on working in collaborative teams, the creation of a space not only happens by the interaction of one person with spatial elements, but by several interactions by several team members. As a consequence, the behavior of other people in the space will be a further determinant of one's own perception and behavior in that very space. Hence, using space in a workshop requires taking into consideration not only singular participants, but the whole team and even the surrounding teams.

### *2.2 Design Thinking Coaching*

The work of Design Thinking teams is often compared to improvisation in music or theater. Similar to jazz players who let themselves be inspired by the patterns and chords of the other players as they take turns playing solo passages, participants in a Design Thinking workshop also organize themselves (Hatch 1999). This implies that there is not one determined leader who tells the team what to do next or how to proceed, and that the leadership roles emerge during the process. Hence, and following the concept of shared leadership, participants distribute the leadership, depending on the expertise of each team member (Zhu et al. 2018). This might imply that depending on the Design Thinking phase a team is in, different people drive the process. Or, that some roles emerge, where one person is responsible for timing, and another one for documention, etc.

Research has acknowledged the effectiveness of shared leadership, but at the same time stresses the "critical role of external team leaders in the development of team members' motivation and capabilities to lead" (Carson et al. 2007). Similar to sports, these external leaders take the role of team coach, which is defined as "direct interaction with a team intended to help members make coordinated and task-appropriate use of their collective resources in accomplishing the team's work" (Hackman and Wageman 2005). Operating both on a substantive level—linking the team's behavior to the overall goal—and at the same time on an internal level—better understanding the team processes—a coach observes a team and, if needed, gives guiding interventions.

These concepts of shared leadership and coaching have implications for the topic of space in Design Thinking in two different ways. The absence of a dedicated leader in a shared leadership team heightens the relevance of other elements that can support the team with structure and further strengthen its shared leadership skills and behaviors. One of these elements is a coach supporting the team. With his responsibility to support a team in using available resources adequately, a Design Thinking coach is also in charge of the adequate use of the space where a team operates. A second component is the process a Design Thinking team follows. If there are doubts of how to proceed, the Design Thinking process suggests a next step and further gives orientation by helping a team to situate itself in a certain Design Thinking phase within the problem or solution space. A third element that encourages a team to engage in shared leadership is the space where the team is operating. On the one hand, the space can stimulate the flexibility needed for taking turns in leading the team. On the other hand it can create a shared environment where all paticipants have equal access to material, for instance by gathering around a whiteboard instead of working around a table, where some team members who stand on the opposite side would have to read upside down.

# 3 Preparing the Workshop Space

An effective use of space during a Design Thinking workshop requires the proper preparation of the space. Following the Jobs-to-be-Done Framework, the job of a workshop space is not only functional, but also emotional and social (Christensen et al. 2016). To this end, we next discuss the preparation on a more functional level—assuring that the space provides all elements necessary for an adequate working environment—and the preparation on the emotional and social level—setting the right atmosphere for the workshop.

## *3.1 Elements and Zones of a Design Thinking Space (Functional Jobs of the Space)*

The different work modes of the diverging and converging phases of a Design Thinking workshop, as well as the focus on intense collaboration, require different zones in a Design Thinking space. We refer to these different zones as team space, share/presentation space, protoyping space, and social space.

### 3.1.1 Team Space

The team space denotes the central space of a Design Thinking team. It is the "home zone," where the team will work the most of the time. Given the self-organized method of team work (see Sect. 2.2), the team space should allow and foster intense collaboration in a shared leadership style. It will accordingly provide a physical space for knowledge sharing and visualization. To this end, a team space in particular must allow a team to collaborate and work together on the same task. Hence, vertical surfaces such as whiteboards, which all team members can see and interact with at the same time, are crucial. In addition, moveable whiteboards help to partition a space and allow an easy separation from other surrounding team spaces. Compared to tables, such as in a meeting room set-up, a whiteboard where the team gathers creates a "democratic" spatial set-up where everybody has the same distance from the board, a setting which invites every team member to step in. Futher, writing at a table usually means that half the team can't see what's actually being written (since it's upside down), thereby hindering member contribution. Too keep energy and dynamism high, we encourage Design Thinking teams to work in a standing

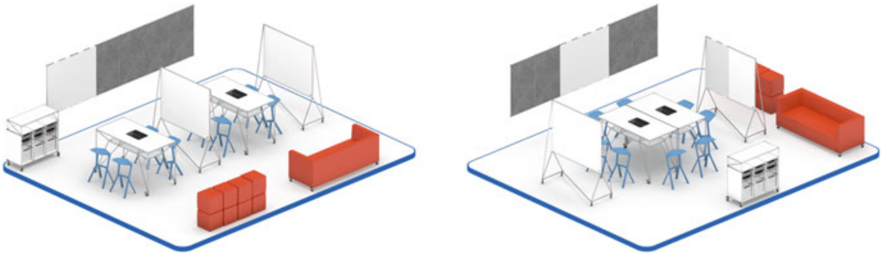

**Fig. 2** Team space for two teams or one larger team (Source: System 180)

position and use stools that are high enough to keep a position between sitting and standing. Depending on the length of a workshop and the age of participants the use of regular chairs might be also be suitable.

In preparing a team space, the Design Thinking coach can underline the different working modes of Design Thinking by actively generating affordances that communicate a certain behavior. Affordances are elements in the environment that encourage a certain behavior (Gibson 1979). For instance, the affordance of a button is that it can be pushed, just as the affordance of a handle is that it can be used to open something. Similarly, chairs in rows, as in a theater, are affordances that indicate looking to the front and being silent, whereas chaires in a circle invite communication. Hence, a coach can set up an initial configuration, where the table is moved to the side and high stools are arranged around a whiteboard. Without further comment, participants recognize this setup as a contrast to the normal meeting room. It prevents them from sitting down around a table and mentally shutting down. If the coach further positions himself as part of the circle (and not in the teacher-like position next to the board), or even behind it, this positioning already indicates the role of a coach and symbolizes handing over responsibility to the team.

In a similar vein, distributing certain kinds of material in the team space can already indicate that the team shall work in a self-organized manner. It is not the coach who will handle material, but, rather, everyone in the team is asked to contribute. Affordances might also work in negatives ways. For instance, if they are created unintentionally and then encourage behaviors that should not be fostered. An example could be traditional chairs around a table in a team space that could encourage participants to sit down, although the coach would like to start energizing the team and have them remain standing. A coach should therefore try to look at the spaces she has prepared from a fresh perspective to avoid such unintended behaviors. An example for a team space is shown in Fig. 2.

### 3.1.2 Share Space

Following a team-of-teams perspective (McChrsytal et al. 2015), we see that Design Thinking teams not only rely on the expertise and diverse background of their

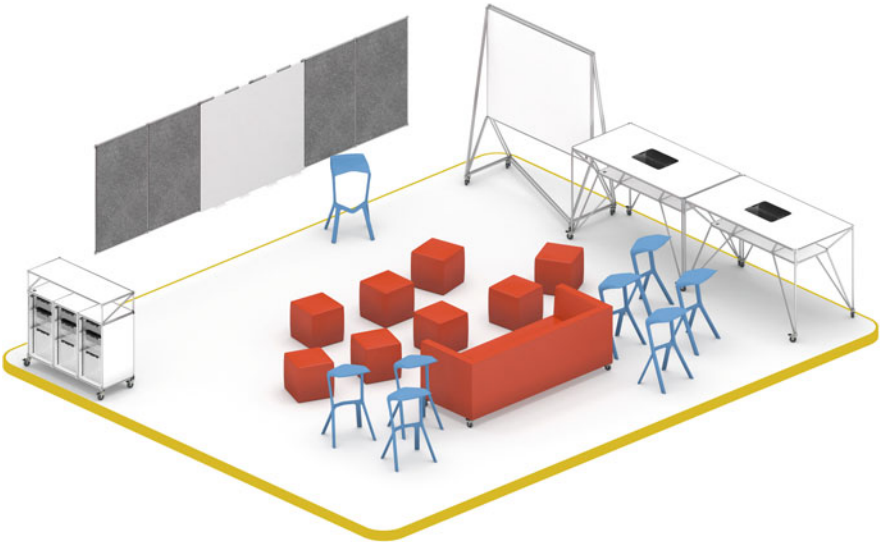

**Fig. 3** Share space (Source: System 180)

members. In addition, all teams participating in a workshop are seen as a large team so that each team can benefit from other teams’ knowledge and experience. To this end, sharing with other teams and getting feedback is important. In addition, there are several moments during a workshop when information has to be shared among all participants—for instance, during the welcome phase of a workshop, introducing the challenge or giving interim inputs, and, finally, to present results to all participants and maybe even to an external audience.

With these requirements, a share space resembles the classical auditoriums in organizations or lecture halls in universities. Therefore, such a space should provide seating opportunities for all participants and a stage area for presenations. However, there is one important difference. While conferences and lectures typically take place in such a space from start to finish, this permanence is not required during Design Thinking workshops. Teams either gather in the presentation space or work in their team spaces. Hence, the presentation space can be considered a temporary space and teams can extend their team spaces into the share/presentation space if it not needed. Thus, again, flexibility through furniture that can be easily moved is key for such a space.

Since most workshops don’t begin in a team space but in the share space, coaches should ensure that this space is setup in a welcoming way before the workshop. Setting up the audience in a way other than the typical cinema-style rows, while experimenting with other seating arrangements, can already indicate that the upcoming workshop might be a bit different. An illustration of a share space is shown in Fig. 3.

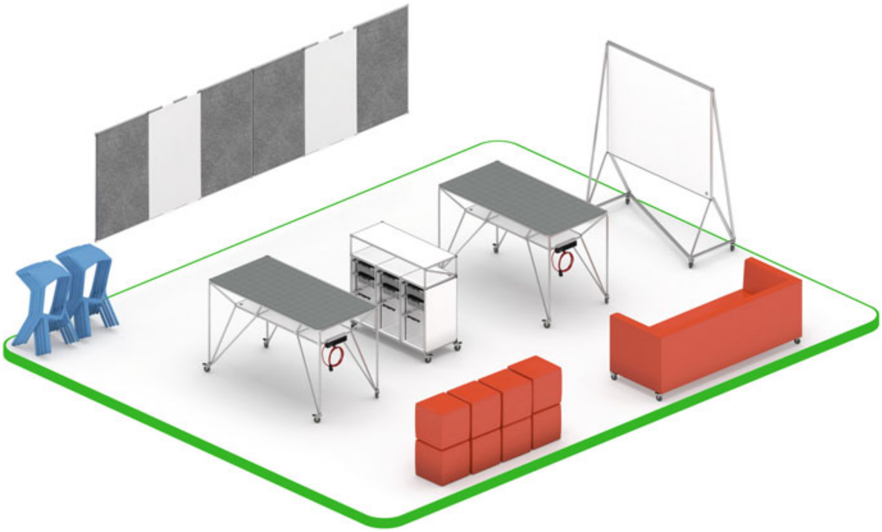

**Fig. 4** Prototyping space; the material is contained in the trolley between the tables (Source: System 180)

### 3.1.3 Prototyping Space

Design Thinking not only focuses on a better problem understanding but also on the creation of solutions including tangible artifacts. For the creation of such prototypes, the availability of a prototyping space can be helpful. Such a space not only offers materials that inspire teams to prototype, but it also allows building and tinkering. Depending on the length and focus of a workshop, prototyping might use tools that range from paper and scissors to roleplays with props, audio and video pieces including technology and software, or "real" building with cardboard or wood, hammer, nails, and saws.

From a coach's perspective, a prototyping space should fulfill three functions. First, it should bring the team from thinking into doing. An empty (wooden) table and some tools can support this notion. Second, it should inspire teams by showing them the material that is available. Third, it should allow the team to physically build things. To this end, having enough space and tables—where things can also be cut—are necessary. Thus, even if teams remain in their team spaces to build the actual prototype, a coach should make use of some prototyping space to inspire teams and make a clear trasition into doing, for instance by moving away material from previous working phases, by turning the table, or by moving whiteboards away. An example for a prototyping space is given in Fig. 4.

### 3.1.4 Social Space

Other than the other three spaces, the social space is not used for the "actual" team work. In this space, participants can arrive, have something to drink, do warm-ups,

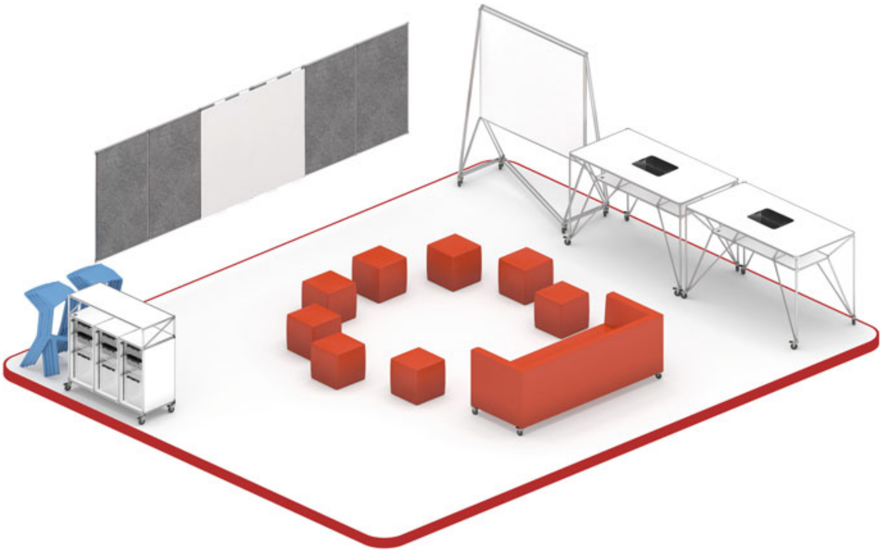

**Fig. 5** Social space (Source: System 180)

conduct networking, have a team check-out or take some time off in breaks. Since innovation heavily relies on social connections and informal enounters between people, the social space is absolutely crucial. In addition, the collaborative work mode of workshops can be really intense, which is why the provision of a more relaxing space is important for participants. Thus, a physical separation from the other spaces might be advantageous. Depending on the room situation, the social space might also be outside of the actual workshop space (e.g., be a lobby our lounge, or even be outside the building, like a terrace). As a coach, the most important task during preparation is not to forget to create a social space since it is an integral part of the workshop. Because it is usually the first space participants encounter, creating a positive atmosphere will make people feel welcome and spur motivation and curiosity. A social space is illustrated in Fig. 5.

### 3.1.5 Four Spaces vs. All In One

As the descriptions of the four Design Thinking Spaces have indicated, these four spaces do not necessarily have to be four different rooms or dedicated zones of a space. Instead, and depending on the built-in flexibility, one single room can be transformed into these different spaces by rearranging furniture and creating an adequate atmosphere (e.g., music and light). If the coach asks the participants to support making the spatial transitions, this engagement might even help participants to mentally follow the different set-ups. It is, however, important not just to fulfill the functional needs of each zone but also to use the different setups to trigger different

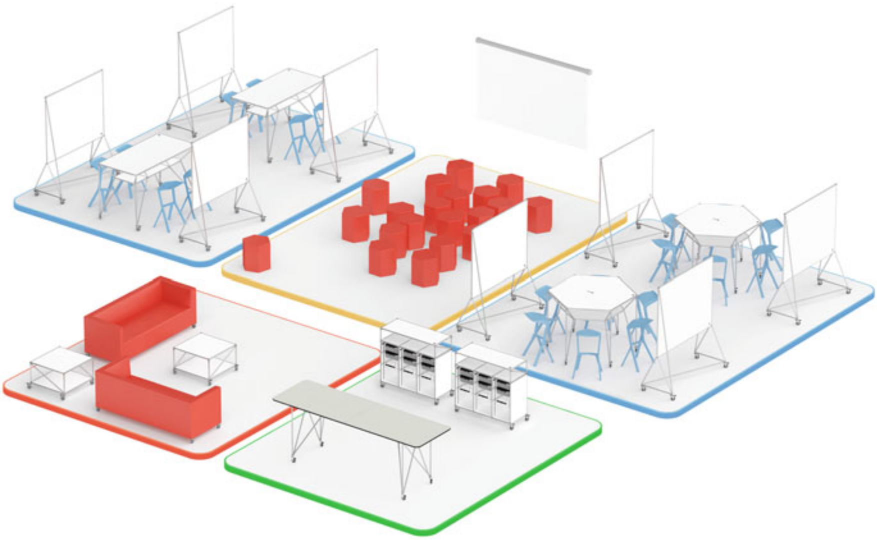

**Fig. 6** Different design thinking spaces in different physical areas (Source: System 180)

modes depending on the phase of the workshop. To this end, one might focus on different areas of the space (‘check-in corner’, ‘prototyping corner’, etc.).

Figures 2, 3, 4, and 5 illustrate that different Design Thinking spaces can be created within the very same physical space. Figure 6 illustrates a larger space with different physical areas for each space.

## *3.2 Creating the Right Atmosphere in a Design Thinking Space (Emotional and Social Jobs of the Space)*

In addition to setting a space for the different working modes during a workshop, there are some aspects of the atmosphere that a coach can use to support the emotional and social jobs of the space. We will introduce three theoretical concepts underlying these jobs.

### 3.2.1 Creating Ownership

An important job of a space is to provide a home for a team. This goal fosters the creation of a physical anchor that, particularly in contrast to a fast-paced and quickly-changing Design Thinking workshop, allows participants to develop a sense of belonging (Schmidt and Brinks 2017). Having a “home” thereby helps to create a safe space for participants, which provides a basis for tapping into one’s creative potential and to experiment and fail as a part of the Design Thinking mindset (Micheli et al. 2018).

Such a creation of home is strongly linked to the concept of psychological ownership. This concept follows the understanding that people can feel as owners of something even though they are not the legal owners (Dawkins et al. 2017). For instance, a Design Thinking team might work in "their" space and write on "their" whiteboards, despite not literally owning them. Feeling like a psychological owner creates safety for a team, allows identification and fosters well-being.

From a coach's perspective, it is crucial to allow a team to create such feelings of ownership. The possibility to bring personal items to the space, decorate it or change it to make it suit the teams' needs are crucial components. A coach can actively encourage a team to take ownership. As a consequence of ownership, teams also might develop feelings of territoriality (Brown et al. 2005). Therefore, people who do not belong to the team but who enter a team's space might be considered as "invaders.". This is why participants should respect other teams' spaces and avoid taking other's spaces or walking through them.

### 3.2.2 Inspiration from Within and Without

Inspiration is an important aspect of creative work, however, and similar to waiting for "the Muse's kiss" inspiration cannot be forced. Literature differentiates between inspiration from within and from without (Thrash and Elliot 2003). Inspiration from within stems from one's unconsciousness and thoughts that emerge without being "forced to appear" at will. Inspiration from without relies on cues in the environment, such as on other people or nature.

A space can support both forms of inspiration. To support inspiration from within, the creation of an atmosphere where participants feel well and can let their minds wander is supportive. In this regard, inspiration from within strongly relates to the creation of a safe home, as described previously. To support inspiration from without, a coach can bring in inspiring elements (objects, pictures, . . .) that are connected to the topic the team is working on or that are totally distinct from it to trigger new connections. Materials in a space that teams can use might become sources of inspiration. Further ways to foster inspiration from within are to change spaces, such as by going outside or taking a walk or by consciously observing other teams in their spaces and consequently gaining inspiration from them.

## 4 Using the Workshop Space from a Coach's Perspective

Besides preparing the space for Design Thinking as described in the previous section, a coach can (and should) actively make use of the space during a workshop. We introduce two different options in the following—creating spatial awareness and reflection.

## 4.1 Creating Spatial Awareness

To allow a team to better unlock the potential of a space, it needs to realize that space is not just there, but that it can be actively used and adapted, according to the team's needs. In other words, the perception of space needs to change from latent to explicit. A first and important prerequite for realizing the potential of space is the creation of a team's spatial awareness.

Awareness refers to "the background 'radar' of consciousness, continually monitoring the inner and outer environment" (Brown and Ryan 2003). We propose three approaches for a coach who seeks to increase the spatial awareness of teams—knowledge, experience, and intervention.

The first approach focuses on creating awareness through providing knowledge. To this end, a coach can share his knowledge about the use of space with the team, for instance during a short input or by sharing a model or structure. He might refer to the understanding of space, as outlined at the beginning of this chapter, or also elaborate on the necessity of creating awareness and what that implies. A further option is to walk a team though different working phases and illustrate by use of simple figures of table, boards, and chairs how the very same team space can be changed by rearranging furniture (table in the middle for prototyping, gathering around a board for unpacking, splitting a team during shared work phases, etc.). Having these different options in mind gives participants an overview of spatial setups and helps them to better detect in which setup they are currently working in, and hence increases their awareness.

While the first approach was targeted at increasing knowledge, the the second approach to increase spatial awareness—experience—targets the bodily experience of space. According to the concept of embodied cognition, humans not only think with their brain, but with their whole body and, thus, experiencing space can contribute to a better awareness and understanding (Shapiro 2014). Experience exercises can be easily introduced as warm-ups, followed by a short reflection. An experience exercise that makes the conceptual framework of the interactionist understanding of space experienceable could work as follows: The coach plays music and asks participants to walk in the space as inspired by the music. Without changing the physical elements of the space, different genres of music (classical, ambience, rock, pop) instantly change how people behave. Following the interactionist understanding, space is defined by the interaction of users with spatial elements, hence, if this interaction changes the space changes as well. Another experience exercise relies on the different phases of a Design Thinking process.[1] Participants form circles of five people and the coach guides them through the phases of a Design Thinking process. The small circles are asked to represent this phase on a more abstract level or with pantomime without speaking, for instance to look outside during the observe phase or to huddle and illustrate inwards orientation

[1] We kindly thank Carmen Luippold and Sabine de Schutter for developing this warm-up.

during the synthesis phase. Participants can thereby feel the spatial mode of a particular phase and understand that their own needs might change depending on the process phase. They further realize in which phases interacting with other teams might help or annoy them.

The third approach to create spatial awareness—intervention—implies that the coach actively sets the focus on space during the workshops and thereby creates attention for space. For instance, he may do this by asking the team to “freeze” and then follows this up by asking all the members if they feel comfortable in the position they find themselves in. In a similar vein, he could also take a picture of the team allowing the team members to observe themselves from an outside point of view. Being provided with such external cues allows participants to complement their own experiences with an outward perspective and link the two. What sounds easy, has proven to be an effective tool for teams in better realizing their current situation.

## *4.2 Reflection*

According to Schön’s Reflecive Practitioner, the process of learning is deeply linked with the activity of reflection (Schön 1983). Schön describes two different modes of reflection. While “reflection of action” means that the action is over or stopped and then, afterwards, reflected on, “reflection in action” means that the reflection takes place as part of the activity. An example of reflection of action could be reflecting at the end of a project or workday on how the project or day went. Based on the reflection, changes can be pursued the next time the activity is done. Reflection in action would imply that a participant realizes in situ what is going on and can apply the learning of the reflection directly by requesting (an) immediate change. The general idea is that by practicing the reflection of action, participants become better in detecting situation and move towards reflecting in action. Hence, in particular for longer projects, we propose that coaches trigger reflections with their teams to allow this learning process. At the HPI School of Design Thinking, we have run different space reflections during the course of a semester. Using a reflection template,[2] as shown in Fig. 7, we asked participants to reflect on their use of space and formulate the lessons they had learned. By linking their reflection findings with lessons learned, we ensured that the reflection was directly transferred into a specific action. We will report some outcomes of these reflections in the next section of this chapter.

While such longer reflections generate many insightful learnings, at the same time they can be time consuming both in doing and analyzing. Of course, coaches can also encourage reflection by discussing one question at the end of the day or by

[2]We kindly thank Adam Royalty for providing us with some of his reflection questions, which we used on the second page of the template.

## Personal Space Reflection BT

TEAM NAME

ARE YOU … ❑ Student ❑ Coach

### A – Space Usage in General *(about 5 min)*

Space is one of the three pillars of Design Thinking. **To what extent have you actively used the space as part of your Design Thinking journey?** Just give your personal guess between 0 % and 100 %, where 100 % means: We used the potential of space, completely. And 0 % means: We did not use the potential of space at all.

................ %

At the beginning of the semester, you have prepared your team spaces after a space building activity. **Has your interaction with and the usage of the space changed during the course of the semester?** If yes, how and why?

**How often did you change the spatial setting during a project? How was this change triggered—and by whom?**

### B – Space And the Design Thinking Process *(about 10 min)*

Think of the phases of the Design Thinking process across the different projects. **For each phase, give one "good" and "bad" example for your usage of / interaction with the space.** This can refer to either you personally or to you as the team. If necessary, give some background information about the specific situation.

For instance, a bad example could be that you felt super stuck during POV, but were all standing around the table. Nobody had changed the position, moved, or changed the space in any other way to gain a new perspective.

| DT PHASE | GOOD EXAMPLE | BAD EXAMPLE |
|---|---|---|
| Understand | | |
| Observe | | |
| POV | | |
| Ideate | | |
| Protoype | | |
| Test | | |
| Other / Misc | | |

PLEASE TURN THE PAGE ➔

### C – Lessons Learned *(about 10 min)*

**1. Express a meaningful lesson you learned through your D-School work about using space (one sentence, try 10 words or less).** This can refer to either space and Design Thinking or to the usage of space in a more general way. Please write it both on this sheet and on a Post It.

(POST IT HERE)

**2. Describe a moment or situation that exemplifies this lesson.**

**3. Why is this lesson meaningful to you?**

**4. How might you ensure that this lesson sticks?** In other words, if something about you changed, how do you make sure that this change persists? (Maybe, even after your time at the D-School.)

**5. How could you teach your lesson to other D-School students and teams?** (Exercise, Story, Material, Card Deck, …)

**Any further comments and ideas?**



**Fig. 7** A reflection prompt

doing an instant reflection session when they sense a learning opportunity for teams during a workshop.

## 5 Using and Transforming the Workshop Space from a Participant’s Perspective

To complement the perspective of using space as a Design Thinking coach with the perspective of a participant, we report some insights from students at the HPI School of Design on the topic of on a space reflection. We asked students in the Basic and Advanced Track, at the end of the semester in summer 2018, to reflect on their space use using the reflection prompts shown in Fig. 7. The reflection sheets were transcribed for further analysis. In total, we received 44 individual reflection sheets from Basic Track students and 23 from Advanced Track students. The following insights are meant to illustrate the topics we have discussed in this chapter so far, mostly theoretically. They are not meant to represent a thorough qualitative analysis. Based on these insights, we further developed two tools that can help teams to make better use of space during their Design Thinking projects. After introducing the main insights from the data, we will also introduce these tools.

### *5.1 The Use of Space: Evidence from Reflections*

In the following, we present some insights into the reflection results. We grouped these findings in the three areas of space usage and awareness, triggers for spatial change, and inhibitors of space change.

#### 5.1.1 Space Use and Awareness

A set of questions we asked referred to the general use of space. More particularly, we started by asking the students how much of the potential that their space offered had been used by them during the past semester. Basic Track students reported an average of 66%, Advanced Track students reported an average of 70%. These numbers indicate that, in general, teams and coaches already leverage a lot of the space potential; however, they realize that one third of the potential is still unused.

The second question referred to the interaction of students with the space over time. Here, interestingly, two opposing patterns emerged which we will introduce and discuss along two quotes representing these two patterns. The first pattern is expressed in the following quote: “I became more conscious about how different space setups can help or hinder certain situations and over time actively shape the space/how specific space is used for my (team’s) purpose.” This student felt it was important to internalize the topic of space and, during the course of the semester, intuitively manage to include space in her team's Design Thinking project. She even took ownership of shaping the space for her teammates. In essence, working with the space and reflecting on it had supported students in learning and internalizing learnings so that using space felt natural.

Contrary to this, the second pattern reads as follows: "As we were made aware about space in the beginning and the possibilities to redefine it, there was more thinking and acting/changing involved. Now it's less." This quote indicates that spatial awareness was based on on external triggers for many participants. If coaches reminded the teams about using space, teams worked on it, but if the focus of coaches turned to interventions on the content of the project and the process, some teams forgot about it. As a consequence, we conceptualized three short space talks for the next semester so that students would continuously be reminded of the topic. We further developed the 60 s for space tool, which we show in Sect. 5.2.

Since our data is descriptive, we can only speculate on why students participating in the very same program show two opposite patterns of using space. We offer three possible reasons. First, there are interindividual differences with regard to the importance of space. Research has shown, for instance, that different people react with a different emphasis on the relevance of product design (Bloch et al. 2003) or on their need to deal with cognitively challenging tasks (Cacioppo and Petty 1982). Hence, we can also assume that some teams might consist of people who feel a stronger need to create a suitable environment for themselves or for their team, or who are just more sensitive towards their spatial environment. Second, the same holds true for the coaches working with the teams. While some might encourage teams to make use of spaces, others might set a stronger focus on the process and—as one student reported—even ask the teams not to focus on space but on another issue during their work. Third, and as we will show in the remainder of this chapter, in many cases, external factors initiated or inhibited spatial changes. For instance, the position of a team situated near to a door or the behavior of the surrounding teams might have forced the team to change their space more often and thus increased the awareness for the topic since such a factor was a regular pain point.

### 5.1.2 Triggers for Space Chance

To better understand who had initiated changes in the spatial set-up and what these changes were aimed at, we asked students to report on these triggers for space change. Based on the responses, we want to highlight three potential patterns of changing space. The three patterns can be seen along a continuum between reactive and proactive behavior.

First, teams changed a space when external triggers forced them to do so: "Only when others moved the objects due to activities." This means, that the space change was not proactive or driven by the own needs or goals of team, but rather that it was reactive in that a team had to cope with a new situation. In addition to other physical external factors, many students reported that noise forced them to move elsewhere. Ideally, these reactive behaviors provide a basis for reflection so that teams learn about the high noise level of specific phases and can proactively plan to go somewhere else or change their setup even before the external triggers occur.

Second, students reported that the Design Thinking process helped to initiate a change of space, as illustrated by this quote: “[We c]hanged space around 3 times a day, triggered by transitions from one phase/method to another.” Hence, the spatial setup was tied to the phase and the methods the teams were operating in. According to literature on behavior change, tying an activity (change space) to a trigger (new phase or method) is very supportive in changing behavior (Fogg 2009). Hence, linking the question of what a team does next (method) with where it does it or what the optimal spatial setup is can be an extremely helpful guide. If teams get used to continuously thinking about the adequate space for their activities, they might have to rely less on external triggers as a scaffolding, but can move to an even more proactive planning.

Third, students’ answers showed that a team’s or individuals’ needs lead to a change of space. One example would be that sensing the energy level of the team initiated a space change: “We, as a team, decided to change the space when we felt that our train of thought[s] got stuck.” Another example illustrates that one person felt responsible for making changes. “The changes in space were usually triggered by our teammate [*name*].” Hence, an individual’s need for proper spatial surrounding initiated changes and, with a growing spatial awareness, teams or individuals within a team made the connection between the current situation and a potential space change, which they then initiated. This nicely illustrates the transition from a reflection of action to a reflection in action.

Besides these three patterns of changing space, many students also reported that they did not change the space very often or regularly. In addition, (in line with the general patterns introduced previously) some teams just forgot about space in the course of the project or, despite noticing problems, did not take any actions. We therefore also looked for inhibitors of space change in the data.

### 5.1.3 Inhibitors of Space Change

As literature of behavior change emphasizes, an intention to change a behavior does not necessarily lead to a behavior change (Madden et al. 1992). Thus, also students reported different factors that they perceive to inhibit activities to change space. We present three different inhibitors in the following.

A first inhibitor is to find time for changing space. Students mentioned “being caught in the complexity of the challenge” or “routine and time constraints”. While, on the one hand, time is always a scarce resource in Design Thinking workshops, two counterarguments also appear. First, in many instances, no time can also be seen as no priority, since, teams working with shared leadership can decide on the use and allocation of their time. Second, in many cases also small and seemingly insignificant changes to a space—cleaning up, moving to another corner, moving or rearranging tables and boards—already harbor the potential for having a huge impact. As one answer to this inhibitor, the semester schedule provides time for a space set-up when new projects begin. Further, the 60 s for space check-in (see Sect. 5.2.2) might be a helpful approach.

A second inhibitor is knowledge of existing options. This is illustrated by a positive example: "We know now the pros and cons of the different places in and around d-school." Hence, knowing and having experimented with different spatial set-ups allows teams to more easily initiate change, since they know what they can do. In other words: if you know what you can do, chances are high that you will actually do it. While the quote already implies that time and experience can support this learning process, we also came up with a tool that provides teams with a structured overview of the options they have (see Sect. 5.2.2). In a similar vein, teams can start to explore by forcing themselves to experiment with different work environments, every day. Or coaches can encourage teams to try out different set-ups in order to experience them and hence learn about their benefits.

A third inhibitor refers to the confidence in making change and the belief that it can make a difference, as the following quote demonstrates: "I thought it is just me having a problem with the space." This student was aware enough to sense issues, but did not take action, because she felt that others didn't have this impression. While it might be true and nobody else would have had a problem, also the opposite could hold true: Her awareness might have been much better than that of other team members and thus others didn't sense spatial issues, not because they are not there but because the other team members lack awareness for them. To sum it up, it could have been beneficial for the team if she had shared her impression.

Together with our coaching team, we discussed different ways to tackle this inhibitor. One idea was to provide a tool to indicate when somebody feels the need to change space. For instance, a person would put a sign on a wall. If others had the same impression, they would add a sign too. It was thus possible to non-verbally find out a status and then take action. In addition, the provision of knowledge about space and positive shared experiences of a space change can encourage team members to initate a change with more confidence in the future.

## 5.2 *Learnings and Tools Based on Students' Reflection*

We drew learnings from students' reflections in two different ways. On the one hand, we asked them at the end of their reflection to formulate a learning ("a meaningful lesson"), on the other hand, we developed two tools based on what students shared with us.

### 5.2.1 Lessons Learned from Students

The lessons learned from students were mainly about becoming active and thus underlined the thoughts we shared earlier. One student, for instance, shared her lesson of “own the space and adapt it”Another shared that “a change of perspective changes the perspective.”While a third example is that “standing helps to get into action faster than sitting.” Therefore, most of the lessons could generally be summarized as an encouragement to make use of space and support the importance of creating awareness for the topic. Using these quotes as a coach might help to encourage other teams to behave in the same way, since these recommendations are not based on theory but come directly come from fellow students and are thus perceived as having greater credibility.

The way students suggested teach their lessons include constant reminders (e.g., “Keep it up! Repetition!” or “Remember how little effort the change in perspective took compared to its result.”). Other ideas refer to exercises to experience different set-ups and spaces to allow a better understanding of what is possible. These suggestions also referred to a more emotional approach relying on mindfulness or medititation exercises. Some suggestions also included creating an irration in the form of external triggers forcing students to act. This could include a directive such as: “Rearrange tables and whiteboards randomly every morning, so students must think about space every morning when they come in.” To sum it up, the lessons students shared and the ways of teaching them to particular groups reflects the assumptions we mentioned earlier in this chapter.

Finally. we asked for general ideas. These touched very specific aspects, such as noise and light, but also raised the topic of “the digital layer” of work. One idea also asked for a stronger support by coaches to “help the teams to work with the whiteboard, as it is a new mode of working for many.”

### 5.2.2 60 s for Space (Check-In and Check-Out)

To put the idea of a constant reminder as a trigger and move a proactive planning into doing, we developed a tool guiding the check-in and check-out of a team. The idea is that teams use 60 s during their daily check-in and 60 s during their check-out to turn their awareness to space. Linking the topic of space to an existing routine ensures that it does not get lost and creates a regular awareness and reflection opportunity. The guiding questions as illustrated in Fig. 8 support the teams. The headline mentions 60 s and thus seeks to avoid overlong discussions and also to reduce the fear of wasting time.

During check-in, the questions refer to an assessment of the status quo and seek to ensure a feeling of well-being in the space. For instance, teams might recognize that a clean-up or rearrangement might be required. Articulating this questions also supports more insecure team members to share their concerns. The last question then asks for direct planning: linking the agenda for the day ahead with specific ideas for spatial requirements. Since these ideas are connected to the person responsible for making the changes, the check-in assures that they are turned into action, later on.

The check-out mirrors the questions of the check-in and in particular seeks to create reflection and learning opportunities. Starting with preparing the space for the next day, a connection is made to the ongoing project. The subsequent questions

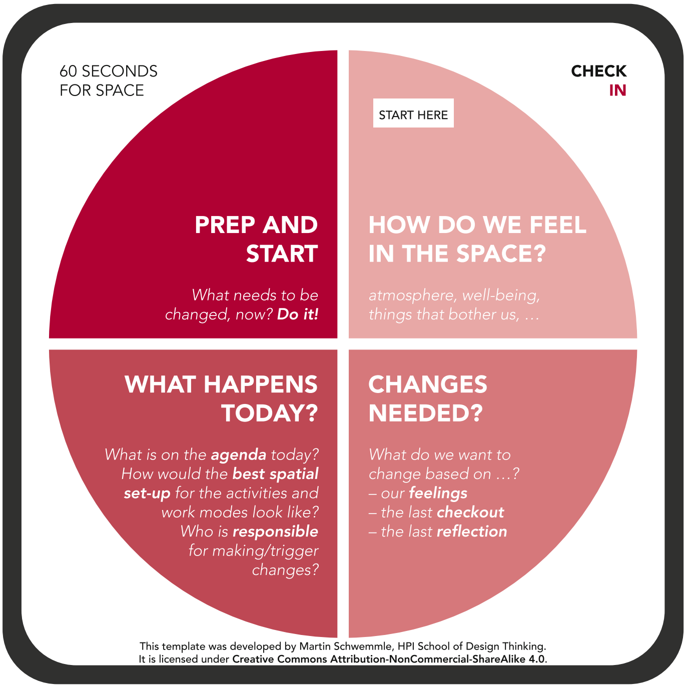


**Fig. 8** 60 s for space

allow teams to then identify positive and negative points of spatial usage during the day that are turned into lessons learned and, again, tied to responsibilities.

### 5.2.3 Space Configurator

To inspire students to explore different spatial set-ups, but also to help them structure their decision-making process when identifying an adequate spatial set-up, we developed the space configurator, as illustrated in Fig. 9. It distinguishes between four basic questions of where, how, what, and who. The Where? refers to the different physical spaces students might use inside and outside the D-School. We often recognize that despite knowing a building quite well, workshop participants regularly oversee potential work spaces. We further overcome trained patterns of the mindset of "you are only allowed to work in your classroom" and encourage experimentation with different spaces. The second question How? refers to the aim participants want to achieve and the atmosphere they need to create. Being clear as a team about the intent is crucial to direct the proper actions to transform the space (Moultrie et al. 2007). These different forms of atmosphere might directly stem from the work mode the team seeks to achieve and hence rely on the process phase they are in at the time.

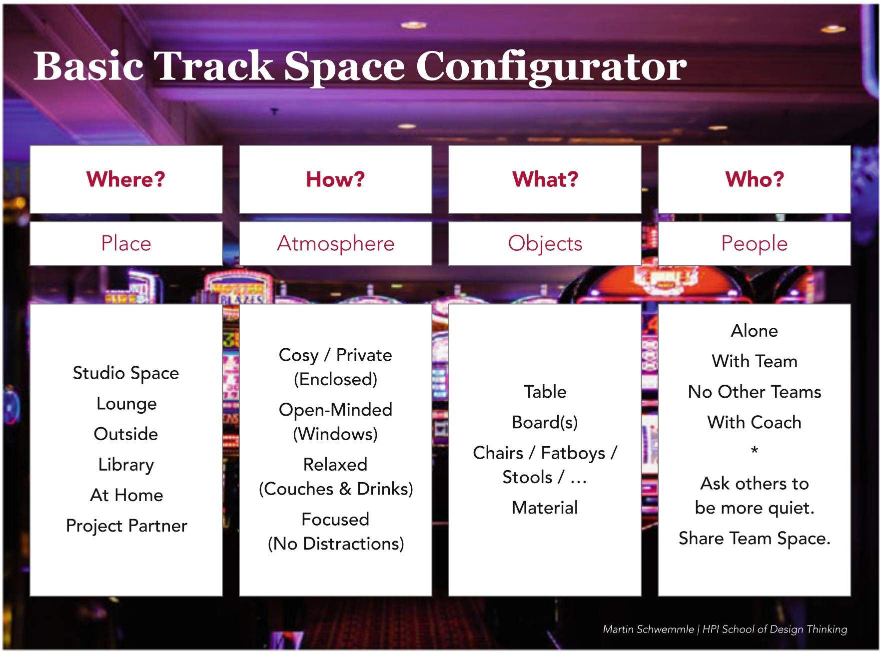


**Fig. 9** Space configurator

The third and fourth questions reflect the interactionist understanding of space and focus on the objects or elements of/in the space (What) and the people (Who). Creating different atmospheres often needs only slight changes of furniture. For instance, moving to bright areas with a view of other teams or the outside, and removing partitions to other teams (such as whiteboards) creates an open atmosphere. Similarly, moving into a corner with a focus on the team through chairs in a circle and visual partitions around, will help a team to feel more private and focused.

The Who? question reminds teams of mainly two things. On the one hand, teams realize that a space can be transformed by changing its users, for instance through moving positions or lying on the floor. On the other hand, it extends this perspective to people outside the team. Hence, if a team suffers from noise, it can either use earplugs or move somewhere else, or ask the team next to them to be a bit quieter.

In essence, these four categories and the examples given for each category, provide a useful tool in providing teams with both structure and inspiration for adapting their team space to situations and needs.

## 6 Discussion

This chapter has introduced the theoretical foundations of an interactionist understanding of space and the role of a coach in Design Thinking. Relying on these theoretical foundations, it first takes a coach's perspective and illustrates how a Design Thinking coach can prepare and make use of space for a team before and during a workshop. Second, relying on a space reflection with students, it takes a participants' perspective and reflects space use during a workshop. Specific takeaways by students and tools provided by the authors give clear directions on how to apply the learnings in an actual workshop setting.

From a research perspective, this chapter bridges findings in the field of work and innovation spaces with the leadership literature of coaching and shared leadership. It shows how theoretical findings can be turned into practice and thereby inspires questions for future research, such as effective ways of teaching and measuring how a team best interacts with a space. Design Thinking practitioners receive specific tools and insights on how to implement research findings in workshop facilitation.

We hope, this chapter has, on one hand, shown that the use of space in Design Thinking relies on a rich theoretical background that goes beyond furniture on wheels. On the other hand, we hope to have illustrated that details matter and that directed actions, no matter how small, make it possible to transform a space and support teamwork in the space created.

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## References

Becker, F. D., Gield, B., & Froggatt, C. C. (1983). Seating position and impression formation in an office setting. *Journal of Environmental Psychology, 3*, 253–261. https://doi.org/10.1016/S0272-4944(83)80004-8.

Bloch, P. H. H., Brunel, F. F. F., & Arnold, T. J. J. (2003). Individual differences in the centrality of visual product aesthetics: Concept and measurement. *Journal of Consumer Research, 29*, 551–565. https://doi.org/10.1086/346250.

Brown, T. (2008). *Design thinking*. Harvard Business Review, June, 84–92.

Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology, 84*, 822–848. https://doi.org/10.1037/0022-3514.84.4.822.

Brown, G., Lawrence, T. B., & Robinson, S. L. (2005). Territoriality in organizations. *The Academy of Management Review, 30*, 577–594.

Cacioppo, J. T., & Petty, R. E. (1982). The need for cognition. *Journal of Personality and Social Psychology, 42*, 116–131. https://doi.org/10.1037/0022-3514.42.1.116.

Carson, J. B., Tesluk, P. E., & Marrone, J. A. (2007). Shared leadership in teams: An investigation of antecedent conditions and performance. *The Academy of Management Journal, 50*, 1217–1234. https://doi.org/10.2307/20159921.

Christensen, C. M., Hall, T., Dillon, K., & Duncan, D. S. (2016). Know your customers' "jobs to be done". *Harvard Business Review, 17*, 1–19.
Dawkins, S., Tian, A. W., Newman, A., & Martin, A. (2017). Psychological ownership: A review and research agenda. *Journal of Organizational Behavior, 38*, 163–183. https://doi.org/10.1002/job.2057.
Fogg, B. J. (2009). Fogg-persuasive behavior. *A Behavior Model for Persuasive Design*. https://doi.org/10.1145/1541948.1541999.
Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
Hackman, J. R., & Wageman, R. (2005). A theory coaching of team. *The Academy of Management Review, 30*, 269–287. https://doi.org/10.2307/20159119.
Hatch, M. J. (1999). Exploring the empty spaces of organizing: How improvisational jazz helps redescribe organizational structure. *Organization Studies, 20*, 75–100. https://doi.org/10.1177/0170840699201004.
Lefebvre, H. (1991). *The production of space*. Oxford: Basil Blackwell.
Liedtka, J. (2015). Perspective: Linking design thinking with innovation outcomes through cognitive bias reduction. *Journal of Product Innovation Management, 32*, 925–938.
Löw, M. (2008). The constitution of space: The structuration of spaces through the simultaneity of effect and perception. *European Journal of Social Theory, 11*, 25–49. https://doi.org/10.1177/1368431007085286.
Madden, T. J., Ellen, P. S., & Ajzen, I. (1992). A comparison of the theory of planned behavior and the theory of reasoned action. *Personality and Social Psychology Bulletin, 18*, 3–9. https://doi.org/10.1177/0146167292181001.
Marx, A., Fuhrer, U., & Hartig, T. (1999). Effects of classroom seating arrangements on children's question-asking. *Learning Environments Research, 2*, 249–263. https://doi.org/10.1023/A:1009901922191.
McChrsytal, S., Collins, T., Silverman, D., & Fussell, C. (2015). *Team of teams: New rules of engagement for a complex world*. London: Penguin.
Micheli, P., Wilner, S. J. S., Bhatti, S. H., Mura, M., & Beverland, M. B. (2018). Doing design thinking: Conceptual review, synthesis, and research agenda. *The Journal of Product Innovation Management, 23*(2), 124–148. https://doi.org/10.1111/jpim.12466.
Moultrie, J., Nilsson, M., Dissel, M., Haner, U.-E., Janssen, S., & Van der Lugt, R. (2007). Innovation spaces: Towards a framework for understanding the role of the physical environment in innovation. *Creativity and Innovation Management, 16*, 53–65. https://doi.org/10.1111/j.1467-8691.2007.00419.x.
Schmidt, S., & Brinks, V. (2017). Open creative labs: Spatial settings at the intersection of communities and organizations. *Creativity and Innovation Management, 26*, 1–9. https://doi.org/10.1111/caim.12220.
Schön, D. A. (1983). *The reflective practitioner*. New York: Basic Books.
Shapiro, L. (Ed.). (2014). *The Routledge handbook of embodied cognition*. Milton Park: Routledge.
Thrash, T. M., & Elliot, A. J. (2003). Inspiration as a psychological construct. *Journal of Personality and Social Psychology, 84*, 871–889. https://doi.org/10.1037/0022-3514.84.4.871.
Zhu, J., Liao, Z., Yam, K. C., & Johnson, R. E. (2018). Shared leadership: A state-of-the-art review and future research agenda. *Journal of Organizational Behavior, 39*, 834–852. https://doi.org/10.1002/job.2296.
Zweigenhaft, R. L. (1976). Personal space in the faculty office: Desk placement and the student-faculty interaction. *The Journal of Applied Psychology, 61*, 529–532. https://doi.org/10.1037/0021-9010.61.4.529.

# Video Capture Interface Prototype for Design Knowledge Capture and Pedagogical Implications

**Lawrence Domingo, David Sirkin, and Larry Leifer**

**Abstract** Design engineers and teams have found value in recording (in analog or digital form) the details of their process—including meeting notes, sketches, physical prototypes, enactments, and so on—so that they can revisit, or even reuse, these details at a later time, or multiple later times, even on another project years later to build upon the ideas of others. Design knowledge capture and reuse is an underutilized practice for professional, as well as student, design teams We studied students enrolled in a graduate level academic-year-long course in design practice at Stanford, which focuses on developing students' skills in design process, project management, physical prototyping, and global team dynamics. Experienced designers value design knowledge capture and reuse highly but are challenged to communicate and facilitate their value to students through graded activities alone. This chapter describes our own design process to address the teaching team's challenge by quickly prototyping a "critical experience prototype" to help students learn, use, and reuse a video-based design archiving system. We built and tested a (relatively) large, table-top, electronic pushbutton that design team members could press whenever they encountered a moment, or insight, that they considered potentially important for their team's prospects. A press on the "recording engineering design" (or RED) button initiates the recording and storage of video of the surrounding several minutes of team activity. We found during testing that (1) the button was fraught with novelty effects during usage, and (2) it would occasionally break the flow of thought and progress during meetings. We also find that while the prototype might effectively capture salient design moments, it still does not address the needs of design knowledge reuse, as it does not assist team members with the subsequent consumption of that documented knowledge, or emphasize the value of design knowledge reuse.

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# 1 Background

## *1.1 Project Context*

Failure is an important part of the design learning process for novice designers to experience. Learning from the failures of others is a key characteristic of expert designers. We first set out to study temporal design communication. That is, how might we increase design knowledge reuse amongst novice design students? The purpose of this research direction was to develop activities that could improve efficient use of time by students to avoid "reinventing the wheel" (Davenport 2015). Design knowledge includes sketches, drawings, prototypes, and meeting notes that help contextualize and document a design process.

Bowker and Star describe archiving information as a non-trivial task. Designing an archive involves designing for future users and recording information that might have a possibility of being relevant. The decision to not record information might be a more difficult question since not all information can be recorded due to technological constraints and acquisition for reuse. Storing and organizing data in an archive requires metadata for filtering in which search algorithms can assist with filing through a dictionary of data (Bowker and Star 2000). Archived documents are filtered forms of information, but the story in design documents and the reality of the design project process inherently tells two different stories (O'Leary 2016; Sole and Wilson 2002).

We found, anecdotally, that documents are often not properly contextualized and only provide a chunk of the design process experienced by the design team. This is a natural and unavoidable problem with design capture (Grierson 2006). We are often unaware of the hidden assumptions that exist in our current time and space within our culture that are only made obvious in hindsight (Yang 2000). Therefore, knowledge recall transmitted through story via interviews of the document's authors can reveal a richer design process that is typically unclear in the moment (Sole and Wilson 2002). As a metaphor, we framed past design team members as the "book carriers" found in Ray Bradbury's *Fahrenheit 451* (Bradbury 1953). These "book carriers" were thought of as individuals with masses of knowledge, whether factual or exponential, that are prepared to share that knowledge.

Design documents serve as a textual storage of knowledge, prototypes serves as a physical storage of knowledge. Prototypes reveal the manufactured reality of what design teams accomplished in addition to the hidden workarounds that were not documented. While not the focus of this report, prototypes serve as excellent mediums for communication as boundary objects (Bowker and Star 2000) amongst team members in a same present time. Prototypes or even tooling for manufacturing can be stored and passed down to future design teams, however, the storage cost is high for holding onto prototypes for the present time being (Bardzell et al. 2012). Housing past prototypes is an excellent practice for future teams to benchmark against but the benchmarking team must first recognize the value of product teardowns. Furthermore, while physical prototypes are rich in information,

**Fig. 1** The RED Button was designed to be noticeable in a cluttered workspace and seamlessly easy to use. An IR sensor breakout board was "mounted" as a Wizard-of-Oz aesthetic and communicated as a wireless transmitter for recording time stamps

they are far less easily transported across space and time. A textual document serving as a design communication medium is far more easily distributed across co-located teams and stored for future teams to consume.

Video data is a desirable middle-ground between verbal archiving and prototype storage since video captures the context of design meetings and prototype interactions. Video data captures more candid interactions amongst team members and can reveal other design behaviors for design researchers to study. Advances in data storage enables video storage and sharing where the cost for storage has significantly decreased in the past decade alone.

In this report we document the development of the Recording Engineering Design (RED) Button prototype. The RED Button is a critical experience prototype that is visually noticeable and seamless for design teams to use for video data recording (Fig. 1). We anticipate for future work in design knowledge management to explore the theme of design knowledge reuse.

## *1.2 Course Context*

ME310 is a year-long project based learning (PBL) graduate-level course with projects sponsored by industry partners (Dym et al. 2005). Project prompts can vary from developing or applying a novel technology to designing for open-ended wicked problems (Buchanan 1992; Rittel and Webber 1973) across a wide range of domains, from cosmetics, to wearable interactive devices, to satellite construction processes. Students use design thinking to explore an open-ended design space, develop numerous prototypes, and create a final concept that is presented to industry sponsors and the broader design community through presentations and a trade show. Student teams comprise Stanford students partnered with a similar number of students from a global university partner (Wodehouse 2010). ME310's primary objective is to teach students design methodology. In this process, students develop new engineering skills, strengthen their creative confidence, and participate in an extended community of designers to develop a tangible, polished, final prototype. ME310 challenges students to determine project requirements and specifications, rather than just building a system specified by the teaching team or their industry partner. This openness is often challenging for engineering students who need to learn to dance with ambiguity (Jung et al. 2007). Students are also expected to complete a final report to document the project's problem exploration through to its eventual final design development process for other teams and industry partners to share in the lessons learned (Grierson 2006).

Students are complemented by a teaching team that is responsible for providing students with allocentric perspective and feedback. Teaching teams are responsible for facilitating design critique sessions, where they provide coaching and technical support that guides teams throughout the school year.

## 2 Users and Stakeholders

### *2.1 Current Students*

The primary users of the video capture archive interface are students currently working on an ME310 design project. Current students would ideally avoid reinventing the wheel and prototyping ideas that have already been explored so that the organization of ME310 can learn as a whole. The most limited resource in any design project is time and every design team has a daily choice of how to utilize their time in the most efficient and effective manner. Historically, the design archive is an underutilized resource by current students that can aid with utilizing team member's time efficiently. Our goal is to design a tool that would promote the use of the design archive by current students and understand the obstacles students experience towards design knowledge capture and reuse.

### *2.2 Future Students*

Relevant beneficiaries of a design archive and design knowledge reuse are future students. The digital archive itself should be designed in a way that is easy to navigate. Future students are difficult to design for because there is no way of knowing what information is relevant to them. Design thinking methods would suggest designing for extreme users who utilize the design archive as a tool. However, that group is so small that relevant findings cannot be scaled beyond the individual. Collected design knowledge would ideally be broad enough that it can be reapplied and detailed enough to communicate the nuances of a past team's design process.

## 2.3 Course Assistants

Course assistants (CAs) make up half of the teaching team, complementing the Teaching Faculty. The course assistants are responsible for organizing lectures and students activities. At a more hands-on level, CA's provide weekly feedback to student teams on their design project progress such as detailed design and team dynamics. Communicating ideas effectively across time is the responsibility of current students and enforcing effective communication across time is the responsibility of the teaching team. By referencing the archive, CA's are better able to direct students towards subject matter experts that can help compliment the courses curriculum according to each individual project's need.

## 2.4 Coaches

Coaches are individuals recruited for their expertise and are assigned to a specific team for mentorship. Coaches meet with students periodically according to the specific team's needs. Coaches are often long standing collaborators of ME310 and carry institutional knowledge of past projects. However, the details of past projects are often forgotten. Coaches can recommend to current students to read the documentation of past projects in order to fill the knowledge gaps.

## 2.5 Teaching Faculty

The teaching faculty are the most persistent stakeholder of the ME310 course. These stakeholders can be thought of as the seasoned engineers of a company that have worked at the same company for decades, housing encyclopedic tacit knowledge. Teaching faculty can be thought of as design experts that store experiential, tacit knowledge from observing and coaching the progress of past design projects or engineering challenges. Like coaches, Teaching Faculty can forget the details of projects and recommend past project documents for students to review that are relevant to the current students' projects.

# 3 Benchmarking

## *3.1 Tang and Leifer*

Tang and Leifer recommended the development of tools that supported design work for shared workspace activity. Tang noted that these workspace tools should:

- Convey gestures while maintaining the relationship of gestures to the workspace
- Minimize the overhead with information storage
- Convey the process of creating artifacts to express ideas
- Enable participants to share a common view of the workspace
- Facilitate the participant's ability to coordinate their collaboration

While Tang's work was completed in a different technological era, many of the human problems in communication still persists to this day as communication and information technology evolves (Tang 1989).

## *3.2 Yang and Cutkosky*

Yang and Cutkosky developed a design knowledge archiving thesaurus that could facilitate communication among co-located design team members by recommending projects that explored similar design concepts. Yang recognized the importance of informal information and the evolution of design ideas, vocabulary, and terminology that leads to design retrieval challenges. Yang found that a manually stored design knowledge archive was more effective than a machine-generated design knowledge archive. However, Yang noted that there is a high overhead for manual development of a design knowledge archive. Yang also discussed the development of search engines and the Internet (Yang 2000).

## *3.3 WorkSpace Navigator*

Ju et al. developed WorkSpace Navigator to explore how knowledge capture and access tools could enhance the physical workplace. Ju noted several design requirements relevant for the development of knowledge capture such as: multiple media inputs, implicit and explicit capture, and refined system integration. Ju also noted design requirements for knowledge recall needs such as: discrete level of detail, contextual organization, visual organization that can be navigated intuitively, and multiple views. Ju and Yang both stress the importance of a well-designed, intuitive design archive interface. Technological advancements such as the ubiquity of the laptop and cloud storage have changed the technological environment and warrant a re-exploration of many of the design challenges explored by Ju (Ju et al. 2004).

### 3.4 ActiveNavigator

Moore et al. sought to build on Ju's WorkSpace Navigator and leverage advances in technology that could streamline the video capturing process. Moore implemented a similar video camera system as Ju and leverage emerging technologies that would assist with team analysis. Moore implemented audio transcription and text analysis, implemented speaker identification technology, updated the navigability of the design archive, and utilized a listing software that would digitally note action items. ActiveNavigator found that future design knowledge capture technology needed a degree of seamless integration with the physical design workspace (Moore et al. 2018).

## 4 Design Vision

We imagine a design knowledge archive that stores not just verbal text documents, but also video meeting clips. Video meeting clips capture the design project context through meeting, prototype demonstrations, and manufacturing iterations. We wanted to take advantage of advances in data storage and video capture in our design and chose to passively capture design review meetings with actively marked time stamps. We provided an explicit interface through the RED Button that would suggest for students to reflect on their engineering workstream and design process. Advances in data storage and video recording enables us to record copious amounts of video data passively. The major difficulty is parsing out the data that is relevant for design knowledge reuse (Bowker and Star 2000).

We used two total video cameras for each design team. Cameras were mounted with one top-down, allocentric perspective and one student facial angle to collect user interactions with the RED Button in situ. Student teams and teaching teams were instructed to press the button when something was communicated that was (1) relevant to look back on, (2) to communicate to their global partner team, or (3) to communicate to future design teams. We then coded the videos for RED Button prototype interaction.

### 4.1 Critical Experience Prototype

We imagine a system prototype that utilizes various camera recording angles, an interface switch that aids with flagging salient design moments (Fig. 2), and

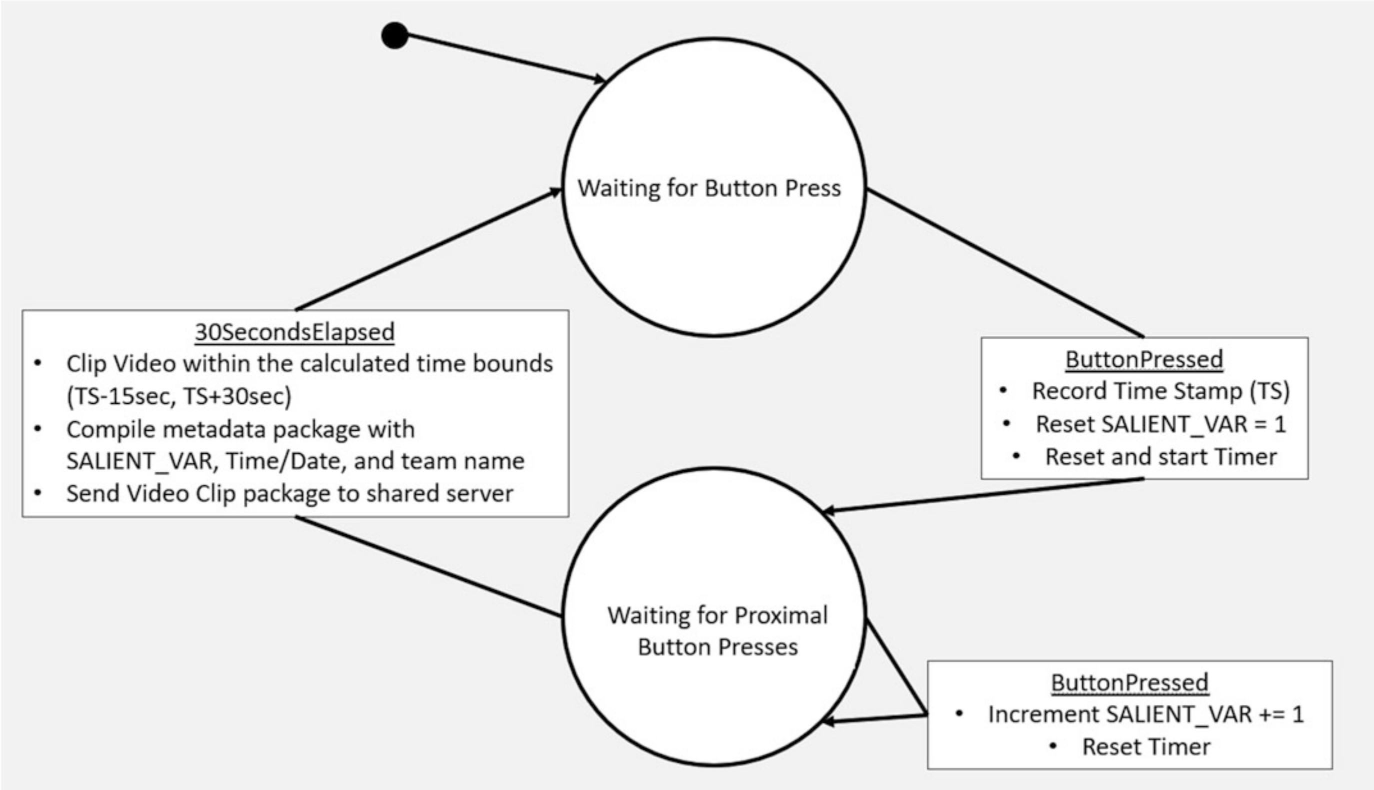


**Fig. 2** The RED Button state diagram depicts a broad overview of the anticipated software execution. This enables users to assess salience of an event. That is, if an event is important to multiple meeting attendees, then video clip packages can record that salience through metadata

a cloud based server for video storage and sharing. Past projects (WorkSpace Navigator and ActiveNavigator) explored the use of cameras and cloud based data storage. Furthermore, advances in hardware through GoPros, cloud servers, and telecommunication (e.g. Skype, FaceTime) have made use of these technologies less ambiguous (Moore et al. 2018; Ju et al. 2004). We, instead, chose to focus on testing the Recording Engineering Design (RED) button as a critical experience prototype (CEP). RED was designed to have a quick user interface with a satisfying haptic and audio feedback. The prototype was quickly hacked together using a Staples red "That was Easy" button and an IR sensor. The original exterior of the Staples button was masked while maintaining a visually noticeable bright red exterior. An IR sensor was mounted into place to placehold what a wireless communication board would look like and was communicated to students to be a wireless transmitter of time stamps as a part of the Wizard-of-Oz prototype (Fig. 2).

## 5 Testing

### *5.1 Video Capture*

Seven student design teams were recorded throughout a 10 week period during small group meetings (SGMs) with both the student team and teaching team present. SGMs, in essence, are feedback sessions for students to present their ideas and teaching team members to provide feedback for pivoting or development. A front facial perspective (Fig. 3) was captured, using GoPro4 cameras, of the students in order to capture various shared communication media as suggested by Ju et al. Common shared media included verbal and non-verbal communication of the students, prototyped parts displayed on the desk space, and the projected models and diagrams on the computer monitor. Videos of meetings were also captured with a top-down, allocentric perspective and a front facial, desk angle (Fig. 4). We focused on student teams since we were interested in creating video clips that would feel like an extension of the meeting space for other viewers such as future students and remotely co-located team members. A top-down, allocentric perspective was captured in order to capture the teaching team's verbal and non-verbal communication. RED Button presses were recorded and clipped for coding manually.

### *5.2 Video Coding and Analysis*

A longitudinal sample of the videos were coded for button presses for two time points. We found that not many teams utilized the button and use was fraught with novelty effects. The act of pressing the button was one of reflection and would


**Fig. 3** Front face camera angle of the student team to capture non-verbal communication, physical prototypes on the desk space, and images projected on the computer monitor such as simulations of computer generated images. The RED Button can be seen in the center of the student team's table for students to reach


**Fig. 4** A top-view allocentric camera angle of the student team captured non-verbal communication and physical prototypes in the floor workspace of both the student and teaching team. The RED Button can be seen in the right-hand corner of the student team's table for students to reach. The allocentric perspective is useful for design researchers

cognitively pull and individual out of the meeting. Occasionally, button presses for salient activities would cascade to additional button presses from the student team members.

Most of the salient activity button presses were for advice from the CAs (see Appendix). The RED Button was primarily used as a note taker to review important parts of a meeting for the recorded student team. Furthermore, many of these clips would be relevant to share with the partnering university and possibly future design teams by happenstance. Time stamps and descriptions based on parallel verbal content for button presses were coded.

## 6 Findings and Future Directions: Design Methodology Learning Goals

### *6.1 Benchmarking*

Benchmarking activities should include researching past projects with similar project themes. Benchmarking techniques need a pedagogical revamping and an activity that can promote the use of the design archive. Designing something innovative for the future often, if not always, involves studying the past and where past designs came from, then projecting out into the future.

Furthermore, we ponder the design development effects of poor benchmarking on developing radically divergent prototypes and suggest future studies that can map the relationship between Benchmarking quality and prototype divergence.

While we and past projects have looked at technologies to enable design knowledge capture, the design knowledge reuse by students remains a major problem. In a typical Academic setting, students are often told not to look at past assignments as it can be seen as an act of plagiarism. However, in a design context, students should be encouraged to look at past projects for inspiration and lessons learned in order to more effectively utilize time. This can be confusing when juxtaposed to the plagiarism philosophy communicated to students the previous 10 years of academic education. In academic contexts, there is value in exploring ways to communicate the economic cost of rework.

### *6.2 Reflection*

Our prototype testing was riddled with novelty effects throughout the entire longitudinal study. Future work should focus on improving the communication of the value of knowledge capture. Students are a part of the ME310 course typically for a single year. Students should be incentivized to consider long-term goals relative to the time-scale a learning organization operates.

Reflection, given a finite project schedule, is frequently crowded out by the in-process engineering design work. ME310 appears to both want it's cake and eat it too, suffering from severe feature creep in it's 50 year development.

The act of pressing the RED Button was one that took a participant out of the meeting cognitively to reflect on the design process. In a design project with a finite schedule, time utilization is traded-off.

As a meeting facilitating tool, the RED Button served as a group reflection check-in in-the-moment. For some teams, the RED Button served a design methodology process reflection tool.

We implemented the prototype in design team meetings and found that usage was generally minimal or forced. The challenge instead, for future work, is to develop skills or activities that facilitates in the appreciation of past design knowledge for current students and future students. Such an activity would involve developing empathy for future consumers of the time capsule design archive.

### *6.3 Contextualization*

In congruence with Tang and Leifer, Yang and Cutkosky, Ju et al., and Moore et al., we recognize that design knowledge capture does not reach its fullest potential without design knowledge reuse. Future work should investigate methods to promote design knowledge reuse whether it is information coded thorough story or cookbook circuits to build up into a system. Conducting Needfinding in settings where effective design knowledge reuse practices are used can offer insight into the cultural mores that can be adopted by design courses.

Design course students should develop practice in contextualizing all gathered knowledge and information. All design projects are different in some way where lessons learned from past projects do not always transfer exactly into current projects. We believe there is pedagogical value in introducing more qualitative methods such as explaining the differences between substantive and formal theory (Glaser and Strauss 2017) to enable students to conceptualize the generality and applicability of knowledge. Perhaps, as a learning organization, ME310 needs to develop the skill in communicating case studies of how past teams successfully transfered learnings from past projects into future projects. For example, engineers in industry communicate through story past experiences working with past clients. The Teaching Team can encourage alumni to revisit ME310 and share stories of working with past partnering schools as a form of knowledge transfer through story.

## A.1 Appendix

| Button press context description | Salience (# of meeting participants who thought the event was relevant) |
|---|---|
| TA suggestion for user interaction | 1 |
| User interface concerns for refilling the water cooler | 1 |
| Advice for designing device signifiers for use<br>Including a "Help" option for how to use a device | 3 |
| How to manufacture fiberglass | 1 |
| How to prototype using paper mache | 1 |
| Algae to process and treat water | 2 |
| TA advice for contacting authors for water research paper | 3 |
| Manufacturability concerns from the TA's | 3 |
| Designing advertising | 1 |
| Advice from the TA's for hardware debugging | 1 |
| Siloing | 1 |
| Four-wheel versus three-wheel scooter modification | 1 |
| Folding mechanism of the trailer | 1 |
| Location of the ratchet strap for mounting the trailer | 1 |
| Teaching team advice for visioning and creating solutions for unmet needs | 1 |
| Teaching team request to print out prototype interaction script | 1 |
| Passive loading of wheels to prevent downhill rolling | 1 |
| CA question for the team to develop a high fidelity prototype that is unvalidated or a validated lower fidelity prototype | 1 |
| Advice for how to collaborate with global partnering team | 1 |
| TA advice to address the driver's blind spot for a vehicle prototype | 1 |

## References

Bardzell, S., et al. (2012). Critical design and critical theory: The challenge of designing for provocation. In: *Proceedings of the Designing Interactive Systems Conference*. ACM.

Bowker, G. C., & Star, S. L. (2000). *Sorting things out: Classification and its consequences*. Cambridge, MA: MIT Press.

Bradbury, R. (1953). *Fahrenheit 451: A novel* (Vol. 41). New York: Simon and Schuster.

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues, 8*(2), 5–21.

Davenport, T. H. (2015). Whatever happened to knowledge management. *The Wall Street Journal*.

Dym, C. L., et al. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education, 94*(1), 103–120.

Glaser, B. G., & Strauss, A. L. (2017). *Discovery of grounded theory: Strategies for qualitative research*. London: Routledge.

Grierson, H., Ion, W., & Juster, N. (2006, September 7–8). Project memories: Documentation and much more for global team design. In *DS 38: Proceedings of E&DPE 2006, the 8th International Conference on Engineering and Product Design Education*, Salzburg.

Ju, W., et al. (2004). Where the wild things work: Capturing shared physical design workspaces. In *Proceedings of the 2004 ACM conference on computer supported cooperative work*. ACM.

Jung, M. F., et al. (2007, July 28–31). Design knowledge coaching—A conceptual framework to guide practise and research. In *DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design*, Paris.

Moore, D., et al. (2018). ActiveNavigator: Toward real-time knowledge capture and feedback in design workspaces. *International Journal of Engineering Education, 34*(2), 723–733.

O'Leary, D. E. (2016). Is knowledge management dead (or dying)? *Journal of Decision Systems, 25*(sup 1), 512–526.

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences, 4*(2), 155–169.

Sole, D., & Wilson, D. G. (2002). *Storytelling in organizations: The power and traps of using stories to share knowledge in organizations* (pp. 1–12). LILA, Harvard, Graduate School of Education.

Tang, J. C. (1989). *Toward an understanding of the use of shared workspaces by design teams*. Print.

Wodehouse, A. J., et al. (2010). A framework for design engineering education in a global context. *AI EDAM, 24*(3), 367–378.

Yang, M. C.-Y. (2000). *Retrieval of informal information from design: A thesaurus based approach*. Print.

# Razors for Arctic VIP Travelers: Using Warm-Up Games in MOOCs

**Karen von Schmieden, Lena Mayer, Mana Taheri, Hanadi Traifeh, and Christoph Meinel**

**Abstract** Massive Open Online Course (MOOC) instructors often use written discussion forum posts to initiate the course and to onboard their learners. To improve and expand on this practice, we adapted "warm-up games" from the context of design thinking and improvisational theatre to the discussion forum format of three MOOCs. In this chapter we describe how we set up these visual, interactive and purposeful games and explain or aims in implementing them. We conclude that warm-up games help to boost discussion forum usage and warm-up game activity may be used as an indicator for high assignment performance.

## 1 Introduction

In every Massive Open Online Course (MOOC), course instructors need to introduce and onboard participants to the elearning platform, community, and course content. They often use introduction posts in the discussion forum to accomplish this. In this book chapter, we describe how we adapted typical "warm-up games" from the context of design thinking[1] and improvisational theatre to the context of three MOOC discussion forums. In this way, we aimed to facilitate the use of discussion forums and offer participants a playful entry point to the content.

We explain our research goals regarding course content introduction, course onboarding, discussion forums, and warm-up game adaptations in physical classrooms and digital contexts. We report on our experiences with the two discussion

[1]Design thinking is a user-centered approach for problem solving and idea development. Stanford University initially extended and developed Design Thinking education programs. The approach has been implemented in organizations internationally.

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forum warm-up games. Subsequently, we discuss how the warm-up games succeeded in wooing learners into the discussion forum, and that learners who successfully participated in the course assignments were mostly active in the warm-up games as well. Participation in a warm-up game may be an indication for assignment participation. We close by encouraging fellow course designers to adopt warm-up games in MOOCs with different teaching topics.

## 2 Context of Discussion Forum Warm-Ups Games

### *2.1 Onboarding*

Research about the onboarding experience for MOOC platform users revealed that consistent, sophisticated techniques are mostly missing (Renz et al. 2014). Going past the registration and platform onboarding features, this chapter deals with the onboarding to the course environment and content. As instructors, we have experienced courses with large numbers of first-time MOOC participants who need to understand the platform, the role of the community and the course structure before they can actively explore and enjoy the learning content. We conduct MOOCs on design thinking skills, which is a novel topic to many participants (Mayer et al. 2020) and may furthermore differ from the teaching style of other courses. Additionally, many participants enroll early on, for example at the release of the course landing page, and may need to rediscover the topic at the course start several months later.

**Instructor Aim 1: As course instructors, we aim to introduce participants to the course content and community in a playful way**.

### *2.2 Discussion Forums*

Discussion forums have become an indispensable platform for interaction and communication in MOOCs (Wong et al. 2015). Critics emphasize that forum discussions often only involve a minority of course members, and a small number of vocal students dominate the threads (Onah et al. 2014). The number of active forum participants have been reported as low as 3% (Breslow et al. 2013). Posters are often young, Western professionals (Gillani and Eynon 2014). These so-called superposters are statistically more influential (Wong et al. 2015). Mustafaraj and Bu have underlined that studies on forum activity do not monitor "invisible activity", namely reading or searching the forum. According to their research, only 3.3% of forum actions are visible activity (Mustafaraj and Bu 2015).

Research suggests that learners who participate in the discussion forum are more likely to complete a course, and that superposters show higher learner performances than other participants (Wong et al. 2015; Onah et al. 2014). Kizilcec, Piech and Schneider hypothesize that participation in discussion forums creates a positive feedback loop for some learners, because they receive social and informational input (Kizilcec et al. 2013).

For clarity, we refer to the interactions in our platform's discussion forum as three types: Every new discussion starts with a *topic*, and a *reply* is a message in this topic. A *comment* is a message that answers to a reply.

**Instructor Aim 2: As course instructors, we strive to introduce learners to the discussion forum, which might have a positive impact on participants' performance**.

## 2.3 Warm-Up Games in Design Thinking and Improvisational Theatre

In our MOOCs, we teach design thinking skills. A common facet of physical design thinking trainings are warm-up games. Warm-ups are short, playful exercises preceding work or learning sessions. They are often used in design thinking sessions to transition participants into certain work modes and to support team dynamics (Tschepe 2018; Osann et al. 2018; Thoring and Müller 2011). Warm-ups are derived from the context of improvisational theatre which is typically viewed as an alternative to scripted theatre (Berk and Trieber 2009) and has been defined as "intuition guiding action in a spontaneous way" (Crossan and Sorrenti 1997). Here, warm-ups are games with little content and structure, allowing players to explore, develop trust, and transition into an improvisational mode in a safe environment. Warm-up activities allow participants to improvise verbally and physically, use their sense of humour, listen to one another, and open up to spontaneity (Koppett 2013; Berk and Trieber 2009). In design thinking, practitioners and theorists describe the goals of warm-up games as

1. Helping participants to get familiar with their teams and creating a positive group atmosphere
2. Generating a safe environment with few social barriers
3. Preparing teams for different working modes or mindsets
4. Generating creative energy and confidence in participants
5. Helping participants to get rid of the concern of "feeling foolish" when exploring new methods or mindsets
6. Energizing and reducing pressure[2]

Warm-ups ideally suit the group that facilitators are working with. The goals of the game should be communicated and demonstrated clearly. Practitioners often conclude a warm-up game with a reflection round (Osann et al. 2018).

[2]Adapted from Tschepe (2018) and Thoring and Müller (2011).

### 2.4 Warm-Ups and Improvisational Techniques in Physical Classrooms

Improvisational techniques have been added to existing teaching strategies in classrooms with medical students (Hoffman et al. 2008), designers (Gerber 2009), in various business and management contexts (Berk and Trieber 2009; Moshavi 2001) and in work trainings ranging from technical engineering to state probation officers (Huffaker and West 2005).

Several studies describe the goals and experiences of higher education teachers with improvisational techniques. Huffaker and West (2005, p. 854) describe their objectives of including improvisational techniques into a business curriculum as creating "an environment conducive to learning", facilitating experiential learning, and facilitating creative, nonlinear idea exchange and co-learning. As a result, instructors have experienced high levels of engagement with the course content (Moshavi 2001; Huffaker and West 2005) and more genuine classroom discussions, with learners embracing their own creativity. Some learners reported feeling uncomfortable with the improvisational techniques. They faced psychological risk in participating, but eventually overcame their fear of failure (Moshavi 2001). This created an open, trusting relationship between students (Huffaker and West 2005). Theatrical improvisation helped to support group dynamics which enhanced the effectiveness of brainstorming in classes with design students (Gerber 2009).

**Instructor Aim 3: Warm-ups and improvisational techniques have been successfully used in design thinking workshops by practitioners and a variety of physical classroom sessions. We aim to adapt specific aspects of warm-up games for a MOOC context, achieving some of the positive results that instructors experienced in physical environments**.

## 3 Warm-Up Games in Three Design Thinking MOOCs

The authors conceptualized and ran three consecutive MOOCs on different design thinking skills from 2017 to 2019 on the free learning platform openHPI,[3] which is hosted by the Hasso Plattner Institute in Potsdam HPI since 2012. The platform came to life through tele-TASK, an advanced lecture recording system and an online portal_ for the distribution of lecture videos (Totschnig et al. 2013). Our first MOOC, subsequently referred to as the *Empathy MOOC*, focused on the design research skills of identifying striking user behavior and conducting qualitative interviews. 5491 learners enrolled, 3040 learners participated actively.[4]

[3]https://open.hpi.de

[4]We define enrolled learners as all learners that enrolled until the end of the active MOOC. We define active learners as enrolled participants who showed up in the course at least once.

The second MOOC, subsequently referred to as the *Synthesis MOOC*, targeted the skills of synthesizing research data and facilitating idea generation sessions. 3641 learners enrolled, 1604 learners participated actively.

The third MOOC, subsequently referred to as the *Prototyping MOOC*, conveyed skills for basic prototyping and validating solutions with users. 3533 learners enrolled and 1583 learners participated actively. For all three MOOCs, we adapted design thinking warm-up games.

Our instructor aims were to introduce learners to the community and course content in a playful way, encourage learners to use the discussion forum, and adapt specific aspects of warm-up games to reap their positive impact on learners. Based on these overarching instructor aims, **we defined the goals for utilizing warm-up games in the discussion forum as follows**:

1. motivate learners to use the discussion forum in a playful way and help them get familiar with different features of the learning platform
2. create a sense of community among the learners
3. set a playful and joyful tone for the course and among the learning community
4. reducing barriers between learners and creating a space where they would feel comfortable to share stories and artefacts from their own lives
5. induce creative energy within the course
6. offer an easy entry point to the learning content by introducing the topic in a playful way

We faced several challenges in adapting design thinking warm-up games to the structure of a MOOC discussion forum. In this context, games had to be open for all course participants and take place within discussion forum posts consisting of text and images.

For the Empathy MOOC, we adapted a warm-up game called "My Object". In physical design thinking classes, participants bring a personal object with them to play this game. They pair up and swap their objects. Next, each person tries to introduce their partner, inspired by their object, and creates a story about the meaning of that object in their partner's life, e.g., "*This is Maya, and she wears this colorful scarf whenever she starts a new adventure, because this scarf brings her a lot of luck.*"

This warm-up is a fun and creative way for participants to get to know each other, sets a playful tone and encourages participants to be creative. Inspired by this warm-up, we created a game for our discussion forum called "My Three Objects" (see Fig. 1). In this game, we asked learners to introduce themselves by posting a picture of three artefacts from their lives: one artefact that is very practical and useful for them, one that has room for improvement, and one that is valuable to them. We asked learners to arrange or visualize these objects as they wish using three icons (star, sad face, heart) to demonstrate them to others and to contextualize their picture with an explanatory sentence.

The course instructors demonstrated their objects in an introductory video and shared a picture using those three icons in a discussion topic. In this way, we encouraged others to join the warm-up as well.

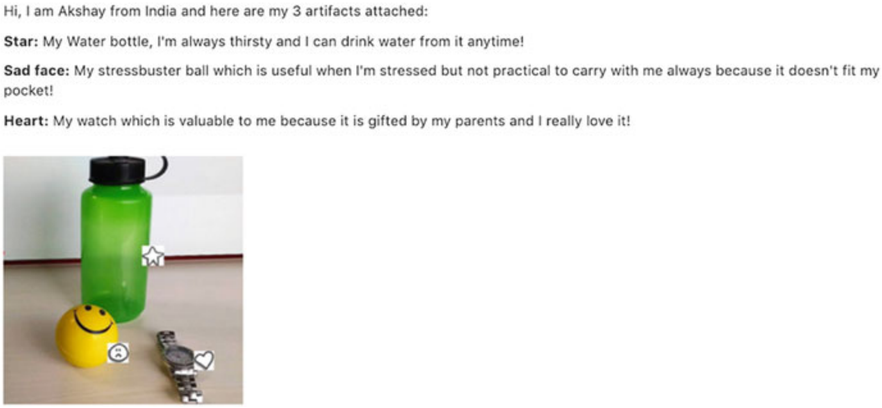


**Fig. 1** Example of a forum post in the “My Three Objects” game

With this game, we hoped to achieve our goals for using warm-ups through

- offering an introduction to the topic of observation in a playful way by encouraging learners to pay careful attention to the daily objects around them and their relationship with them
- encouraging learners to express their thoughts through visualization by asking them to show their objects using drawing or photography
- creating a sense of community by emphasizing similarities among learners from all around the world

For the Synthesis MOOC, we adapted the “Bingo” warm-up which is often used in physical workshops as a playful way for participants to get to know each other. In this game, facilitators provide Bingo templates with number of different categories regarding various experiences. Participants are supposed to wander around and find people who have been through those experiences or belong to those categories in a short time, and ask them to sign the related category on their template. When time is up, the person with the most signatures—the person who talked to most participants—wins the game.

In the adaptation of this warm-up for the Synthesis game we designed a template with nine categories related to physical activities, creativity and craftsmanship, pets, and learning a new skill (see Fig. 2). We discussed various categories within our team to make sure that all learners, regardless of their background, could relate to at least one of the nine categories. We introduced the game in a short video and shared which category we fit in and why. We posted the template with all nine categories on the top of the discussion topic. Learners picked a category that they identified with and posted a picture showing the respective activity or object. We asked them to include a hashtag with the title of their category, e.g. #marathon or #food (see Fig. 3). The goal of the game is to fill in all categories collectively with the learning

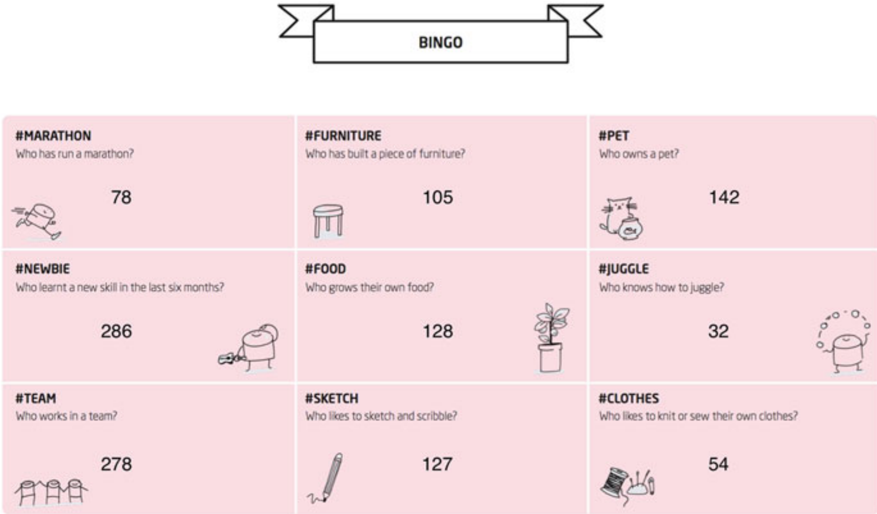


**Fig. 2** The filled-in Bingo template of the Synthesis MOOC at the end of the course. Many participants named several categories

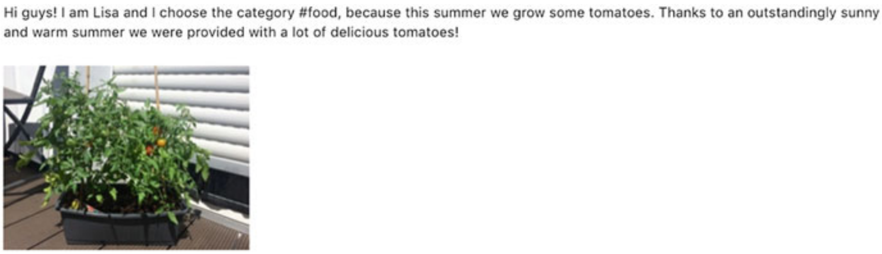


**Fig. 3** Example reply in the Bingo warm-up game

community. Therefore, we counted the replies for each category and updated the bingo template throughout the course.

Through this game, we hoped to achieve our goals for using warm-up exercises by

- offering Bingo categories that support participants to reflect on existing creative capabilities
- offering Bingo categories that support participants to acknowledge their drive towards learning new skills
- offering Bingo categories that represent components of the design thinking mindset and methodology, such as teamwork and visual expression
- offering accessible Bingo categories such as "who owns a pet" with the goal of encouraging every learner to participate, regardless of their previous skill level or (creative) context


**Fig. 4** Example reply in the Protobot warm-up game

- creating a sense of community by revealing similarities and common interests among users

Finally, for the Prototyping MOOC we introduced the "Protobot" game. Protobot is a website[5] that generates random service and product tasks, such as "Design a garbage truck that responds to voice commands" or "Design a knife that changes a little bit every day". It was designed by Molly Wilson as a warm-up game that encourages learners to prototype random ideas and get comfortable with making ideas tangible. In an introductory video, the teaching team played the Protobot to demonstrate the game. Each instructor received a random prototyping task. We gave ourselves a limited time frame of 3 min and showed the prototyping process in fast forward mode. After time was up, we showed our quick prototypes and encouraged our learners to do the same: giving themselves a limited time frame and trying to prototype the first task they receive, even if it seems silly or unrealistic. The time pressure should prevent learners from overthinking and trying to make their prototype look perfect. We asked learners to post the prototyping task they received and a picture of what they built in the forum (see Fig. 4).

Through this game, we hoped to achieve our goals for using warm-up exercises by

- offering a playful introduction to the course's topic of prototyping
- disassociating the term "prototype" from an understanding of a far-developed product by confronting learners with simple, fun and sometimes absurd prototyping tasks
- disassociating the term "prototype" from an understanding of a far-developed product by setting a constrained time limit
- creating a sense of community by encouraging discussion about different interpretations of building Protobot tasks

[5] http://www.protobot.org

By introducing these warm-up games to the discussion forums of our MOOCs, we were interested in answering two questions:

**Question A: Can we motivate learners to reply in the MOOCs' discussion forums through a warm-up game?**

**Question B: Were learners who received high points in the peer-reviewed course assignments active in the warm-up games of the three MOOCs?**

## 4 Results

Although the forum warm-up games were not mandatory and learners couldn't receive grades for the tasks, learners posted 900 replies in the Empathy MOOC, 669 replies in the Synthesis MOOC, and 544 replies in the Prototyping MOOC. From observing all three warm-up games, we identified overlapping learner behavior.

- Learners started to exchange with peers, e.g. they shared their likes, dislikes, and daily design problems or reacted if they found matching topics with others (e.g., hobbies in the Synthesis MOOC)
- Learners established a very open-minded atmosphere and friendly tone. They gave compliments to peers and suggested suitable further resources (e.g., books or podcasts) to each other (see Fig. 5)

Our MOOCs show that visual forum introduction posts can work out well to welcome learners and motivate peer interaction: Visual introduction posts helped learners connect in a more playful way and to detect interesting details about their co-learners.

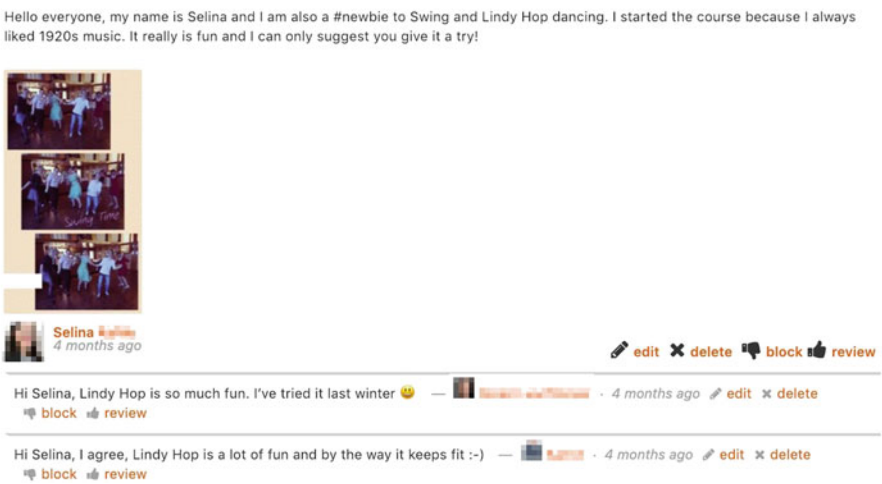


**Fig. 5** Participants in the Bingo warm-up game commenting on each other's replies

We found several overall advantages of using games to introduce learners in all three MOOCs. The Empathy MOOC game “Three Objects” helped learners to put on their observation glasses and report on product shortcomings, unsatisfied user habits, and to reflect on the emotional attachment they had with specific objects. These observation subtasks all triggered learners to acquire observation skills and thus take on a design thinking work mode early on. The large participation number in the Empathy warm-up game shows that the threshold to contribute to the introduction post was low and triggered learners to share their post.

We set a lower inhibition level for the Synthesis MOOC “Bingo” game. In line with the Instagram trend of highlighting photography over text, learners shared images from their personal lives fitting one of the nine Bingo categories. What stood out was that this game helped learners to easily connect with others through shared hobbies or achievements and compliment each other.

The “Protobot” Game in the Prototyping MOOC enabled learners to enter a “prototyping mindset” at great ease: they received a fun random task and started to build without overthinking their actions. Learners commenced to expand on their initial task, changing or adding to the primary idea, and explained the supplementary functions of their prototype. As a potential setback, learners shared less about their personal lives through the prototypes they built, but were happy to comment on and praise their fellow learners’ prototypes.

Instead of sharing personal details, this task showed the learners’ ways of thinking on different levels. Some learners built a mere representation of the terms in their prototyping task and “glued them together”. Others thought about the functionality of elements in the challenge and came up with a solution, and a third group thought about a new way of imagining the terms in the challenge alltogether. We believe this observation could be very valuable when it comes to teamwork: to recognize different cognitive styles and be mindful of them during projects.

With exceptionally large numbers of replies and attachements, the warm-up games caused some trouble: Participants and course instructors struggled with loading times, and, at some point, confusion: Some learners were unable to find their replies in the massive discussion forum topics. As a quick fix, we opened new topics to keep playing the games. In the long run, adding features that make the use of discussion forums more interactive and overseeable would facilitate the adaptation of warm-up games greatly.

Different scholars investigated how forum activity links to course completion or learners’ performance. For example, Onah et al. (2014) found that learners with course completion wrote more forum posts and reported higher levels of forum activity in contrast to those who only audited, disengaged, sampled, or quit the course (Kizilcec et al. 2013). Wong et al. (2015) found higher learning performance levels amongst superposters compared to the average forum participant.

In the **Empathy MOOC**, we provided learners with an Observation assignment and a Qualitative Interviewing assignment. In this chapter, we only focus on the Observation assignment. We received 932 submissions for this. In the next step learners reviewed their peers’ work and allocated points in given rubrics. Peers could also nominate particularly outstanding assignments. To answer the question

**Table 1** Number of active learners, warm-up game replies, and warm-up game views for all three MOOCs

| | Empathy MOOC | Synthesis MOOC | Prototype MOOC |
|---|---|---|---|
| Number of active learners | 3040 | 1604 | 1583 |
| Warm-up game replies | 900 | 669 | 544 |
| Warm-up game views | 1893 | 1252 | 1784 |

whether top performers are also active in warm up games, we ranked all assignments according to maximum points received and special nominations by peers. Our interest group then consisted of the top 5% learners of this list. The top 5% were 47 learners, of which 30 (63.83% of the top 5% learners) had replied in the warm-up game.

For the **Synthesis MOOC**, learners had to take one assignment task to receive points for course completion. The total number of submissions was 392. 20 learners represented the top 5% learners, of which only 7 (35%) had taken part in the Bingo warm-up game.

In the **Prototyping MOOC**, learners also uploaded one assignment task. 274 learners successfully finished the assignment. The top 5% consisted of 13 learners, of which 11 learners (85%) had participated in the course's warm-up game.

Overall, we can find similarities between previous research on this topic and our results. We will discuss our results in regards to the research questions in the following.

**Question A: Can we motivate learners to reply in the MOOCs' discussion forums through a warm-up game?**

With 900 replies and 1893 views in the Empathy MOOC (in comparison to 3040 active learners), 669 replies (1252 views) in the Synthesis MOOC (in comparison to 1604 active learners), and 544 replies (1784 views) in the Prototyping MOOC (in comparison to 1583 active learners), the warm-up games helped to guide considerable numbers of participants to the discussion forum (see Table 1).

Staubitz and Meinel (2018) examined the discussion forum data of 45 MOOCs on the openHPI and mooc.house elearning platforms with topics. 40 courses dealt with technical topics; 5 courses dealt with non-technical topics. Our 2017 Empathy MOOC is part of their sample. They report that the Empathy MOOC's forum participation coefficient (=forum participation divided by overall enrollment number) was remarkably higher than most other courses in the sample. Furthermore, their examination of discussion forum introduction games showed that traditional written introduction topics drew few replies but were among the most viewed topics in the course, and thus among the most popular ones. The total amount of replies in nine technical MOOCs ranged from 5 to 204. A 2018 MOOC on business development with a slightly more interactive introduction thread asked learners to post their survey results on being an intra- or entrepreneur, which drew 367 replies and 549 views in comparison to 1901 active learners.

Based on these numbers, we can hypothesize that warm-up games are more successful at guiding learners into the discussion forum than traditional introduction posts, and, more importantly, are more successful at triggering replies from learners.

**Question B: Were learners who received high points in the peer-reviewed course assignments active in the warm-up games of the three MOOCs?**

Learners who belonged to the top 5% of assignment participants were likely to have participated in the warm-up games: 63.83% in the Empathy MOOC, 35% in the Synthesis MOOC, and 85% in the Prototyping MOOC.

These non-uniform results from the three MOOCs are particularly interesting for us: In the Empathy MOOC, the top 5% learners contributed strongly to the warm up game, numbers dropped for the Synthesis MOOC game, and we noted the highest number for the Prototyping MOOC.

Further research could reveal why the games pulled different numbers of top learners. It is possible that top learners were more willing to participate in games that are clearly related to the content of the current course, which was obvious for the Empathy MOOC and Prototyping MOOC games, while the Synthesis MOOC game followed a more general structure.

Furthermore, the Prototyping MOOC game drew the highest number of top learner participation among the three games. A possible explanation might be a slightly competitive side to the game: Seeing the prototype pictures of other participants can motivate to build an even more absurd, funny, or smart prototype. Furthermore, the Protobot game revealed little personal information and thus easily accommodates learners who preferred to stay anonymous. Lastly, learners might have felt less inhibited to join the game: the task of creating seemingly purposeless prototypes does not put the pressure of presenting something smart or socially desirable on learners and rather welcomes them through the humorous context.

It might also be of interest to look further into the demographic background of the top assignment learners and check for participants with a design background compared to more analytical working contexts: It is possible that participants with more design-driven work experience were also more drawn to a voluntary prototyping game than others.

Overall, we hypothesize that warm-up game activity can be an indicator for successful activity in the course assignments.

## 5 Conclusion and Recommendations

In this chapter, we explained our approach and aims of adapting warm-up games for MOOC discussion forums. Warm-up games provided learners with a positive, interactive way of getting to know the learning community and share their enthusiasm in the games. In all three MOOCs, we perceived a very supportive, kind and open-minded atmosphere in the warm-up game topics.

In conclusion, our data supports the suggestion that warm-up games facilitated learner participation during the course introduction and into the discussion forum.

We found that high-scoring course learners also took part in the warm-up games in the Empathy and Prototype MOOC; results varied for the Synthesis MOOC (with only around one third of high performers participating in the Bingo game).

Based on our research in three consecutive MOOCs, our recommendation is to utilize warm-up games for MOOCs, and to move beyong conventional descriptive introduction posts (name, job, title). Warm-up games provide a playful, visually appealing and interactive approach to learner introductions in discussion forums.

To enhance our findings, larger sample sizes of successful course completers are desirable. Another future research direction could be to compare MOOCs with warm-up game introductions to MOOCs with conventional text-based introduction topics.

A limitation of our research could be that it is very sample-specific. Participants signing up to a design thinking course might be more tolerant and open-minded, thus finding an easier entry point for playful games, experiments and quests for being visual. Therefore, we especially welcome MOOC instructors with various backgrounds and course themes to adopt warm-up games for their courses, which could shed more light on this issue.

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## References

Berk, R. A., & Trieber, R. H. (2009). Whose classroom is it, anyway? Improvisation as a teaching tool. *Journal on Excellence in College Teaching, 20*(3), 29–60.

Breslow, L., Pritchard, D. E., DeBoer, J., Stump, G. S., Ho, A. D., & Seaton, D. (2013). Studying learning in the worldwide classroom: Research into edx's first MOOC. *Research and Practice in Assessment, 8*, 13–25.

Crossan, M., & Sorrenti, M. (1997). Making sense of improvisation. In J. P. Walsh & A. S. Huff (Eds.), *Advances in strategic management* (Vol. 14, pp. 155–180). Greenwich, CT: JAI Press.

Gerber, E. (2009). Using improvisation to enhance the effectiveness of brainstorming. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 97–104).

Gillani, N., & Eynon, R. (2014). Communication patterns in massively open online courses. *The Internet and Higher Education, 28*, 13–26.

Hoffman, A., Utley, B., & Ciccarone, D. (2008). Improving medical student communication skills through improvisational theatre. *Medical Education, 42*(5), 537.

Huffaker, J. S., & West, E. (2005). Enhancing learning in the business classroom: An adventure with improv theater techniques. *Journal of Management Education, 29*(6), 852–869.

Kizilcec, R. F., Piech, C., & Schneider, E. (2013). Deconstructing disengagement: Analyzing learner subpopulations in massive open online courses. In *Proceedings of the Third International Conference on Learning Analytics and Knowledge* (pp. 170–179).

Koppett, K. (2013). *Training to imagine: Practical improvisational theatre techniques for trainers and managers to enhance creativity, teamwork, leadership, and learning*. Sterling, VA: Stylus Publishing, LLC.

Mayer, L., von Schmieden, K., Taheri, M., & Meinel, C. (2020). Designing a Synthesis MOOC: Lessons from Frameworks, Experiments and Learner Paths. In *Design thinking research* (pp. 35–47). Cham: Springer

Moshavi, D. (2001). "Yes and . . . ": Introducing improvisational theatre techniques to the management classroom. *Journal of Management Education, 25*(4), 437–449.

Mustafaraj, E., & Bu, J. (2015). The visible and invisible in a MOOC discussion forum. In *Proceedings of the Second (2015) ACM Conference on Learning@ Scale* (pp. 351–354).

Onah, D. F., Sinclair, J. E., & Boyatt, R. (2014). Exploring the use of MOOC discussion forums. In *Proceedings of London International Conference on Education* (pp. 1–4).

Osann, I., Mayer, L., & Wiele, I. (2018). *Design Thinking Schnellstart: Kreative Workshops gestalten*. München: Carl Hanser Verlag GmbH Co KG.

Renz, J., Staubitz, T., Pollack, J., & Meinel, C. (2014). Improving the onboarding user experience in MOOCs. In *Proceedings EduLearn*.

Staubitz, T., & Meinel, C. (2018). Collaborative learning in MOOCs. Approaches and experiments. In *2018 IEEE Frontiers in Education Conference (FIE)* (pp. 1–9).

Thoring, K., & Müller, R. M. (2011). Understanding the creative mechanisms of design thinking: An evolutionary approach. In *Proceedings of the Second Conference on Creativity and Innovation in Design* (pp. 137–147).

Totschnig, M., Willems, C., & Meinel, C. (2013). openHPI: Evolution of a MOOC platform from LMS to SOA. In *CSEDU Proceedings* (pp. 593–598).

Tschepe, S. (2018). *Warm-ups in design thinking*. Retrieved from https://uxdesign.cc/warm-ups-in-design-thinking-more-than-just-a-game-7f755fcc8497, last accessed 2019/10/25.

Wong, J. S., Pursel, B., Divinsky, A., & Jansen, B. J. (2015). An analysis of MOOC discussion forum interactions from the most active users. In *International conference on social computing, behavioral-cultural modeling, and prediction* (pp. 452–457). Cham: Springer

# Part II
# Understanding Design Thinking Team Dynamics

# Design Team Performance: Context, Measurement, and the Prospective Impact of Social Virtual Reality

**Ade Mabogunje, Neeraj Sonalkar, Mark Miller, and Jeremy Bailenson**

**Abstract** Measuring design performance for effective support of team coaching and redesign efforts has been difficult to near impossible. This is because, design is context dependent and takes place in different environments. Virtual reality gives us as designers, the opportunity to construct and simulate different environments, as coaches, the opportunity to improve our effectiveness in different design scenarios, and as researchers, the possibility to measure design performance and factors that affect it. This possibility was investigated experimentally. Two environments were constructed—one corresponding to a garage in a rural setting, and the other, to a conference room on one of the floors of a skyscraper in the city. Teams of three designers were recruited for the experiment. They worked on two product concept generation tasks and two decision making tasks, while being situated in each of the spaces. Several types of data were collected including video records, screen records, participant questionnaires, and position data of the VR headset and the hand controllers. The position data was used to calculate the level of synchrony between the designers. To investigate the correlation between the synchrony scores and the environment, we used a Kruskal-Wallis ordinal test. The test showed that the teams in the conference room had significantly higher synchrony ($H(1) = 7.056$, $p = 0.0079$) than the teams in the garage. This data was surprising, unexpected, and difficult to explain. In the course of searching for an explanation, several earlier models of behavior and context from the literature were reviewed. This led to the development of a comprehensive model of human-environment interaction which we believe will help guide future experiments. Early prototypes of this model are presented and discussed.

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# 1 Introduction

## *1.1 Performance: Design Team Behavior*

High performance design teams are composed of autonomous learners, who can independently determine and pursue their learning goals and content. The nature of design activity requires them to act that way; designing is context dependent and open-ended, and therefore, does not revolve around a specific body of information or knowledge. This poses a problem for business administration and design education since managers and teachers cannot predict in advance what employees and students will decide to learn. Coaching, rather than managing or didactic teaching, has proved to be effective in addressing this problem. Expert coaches guide and facilitate rather than try to specify what information should be used, what task should be done, or who should talk to whom.

## *1.2 Context: Role of Environment*

Previous computer simulation studies have shown the effect of space design (interior design of architectural spaces) on design performance. Mabogunje et al. (1995) showed how the presence or absence of physical partitions in a design studio interacted with the strength or weakness of the hierarchy in the social organization—and affected project time and product quality.

More recently, Hwang and Horowitt (2012), argued that some of the unusual social behaviors experienced in the Silicon Valley was the result of the recency of its urban settlement. Building on Turner's frontier hypothesis (Ford 1993), they essentially suggested that the living conditions at a frontier of human migration made life less routine and led to more creative expressions. Indeed, some of their ideas can be borne by the fact that around 100 years ago, the American frontier was around Ohio. Inventors like Thomas Edison (light bulb), Henry Ford (mass automobile production), and Wilbur and Orville Wright (airplane) lived in that area.

Furthermore, we understand from the phenomenon of punctuated equilibrium, that the isolation of a specie from an original population and subsequent differences in environment can lead to the development of new features and behaviors in the isolated specie (Understanding Evolution: More on punctuated equilibrium, 2020) which may prove advantageous or disadvantageous or neutral when the populations are brought back together. This phenomenon is represented in Fig. 1.

Finally, there is a phenomenon described in the psychology literature called the bystander effect. Essentially the effect occurs when the presence of other people in a situation discourages an individual from taking action in an emergency situation. The theory is that people are more likely to take action in a crisis when there are few or no other people present. The greater the number of bystanders, the less likely it is for any one of them to provide help to a person in distress. A frontier

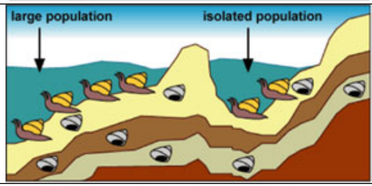
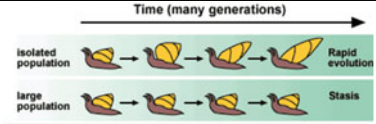
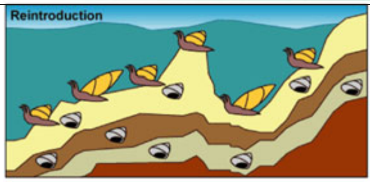
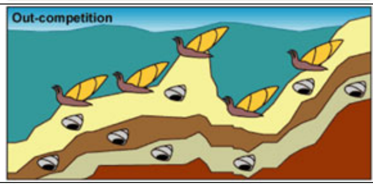
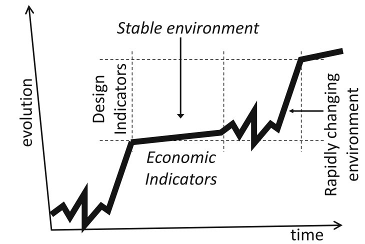
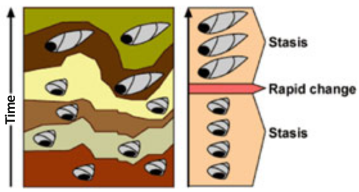
| | | |
|---|---|---|
| Mechanism | Stasis<br><br>A population of mollusks is experiencing stasis, living, dying, and getting fossilized every few hundred thousand years. Little observable evolution seems to be occurring judging from these fossils. |  |
| | Isolation<br><br>A drop in the sea-level leads to the formation of a lake and isolates a small number of mollusks from the rest of the population. |  |
| | Differential Evolution<br><br>The small, isolated population experiences strong selection and rapid change because of the novel environment and small population size |  |
| | Reintroduction<br><br>Sea levels rise, reuniting the isolated mollusks with their sister lineage |  |
| | Out-competition<br><br>The isolated population expands into its past range. The formerly isolated branch of the mollusk lineage may out-compete their ancestral population, causing it to go extinct. |  |
| Visual Representation | Punctuated Equilibrium | Fossil Record |
| |  |  |

**Fig. 1** Punctuated equilibrium. Source: Understanding Evolution: More on punctuated equilibrium, 2020). Economic indicators and interventions are often targeted to maintain equilibrium, order, and stability. Design interventions need to be developed to foster evolution, progress, and innovation; and design indicators need to capture the activity of designers, scientists, artists, entrepreneurs, engineers, marketers, venture capitalists, technologists, and futurists

region such as the state of Ohio, 150 years ago, or the Silicon Valley, 50 years ago is sparsely populated. As time goes on, people are attracted to these places, the population builds up, grand structures are built and soon responsibility becomes

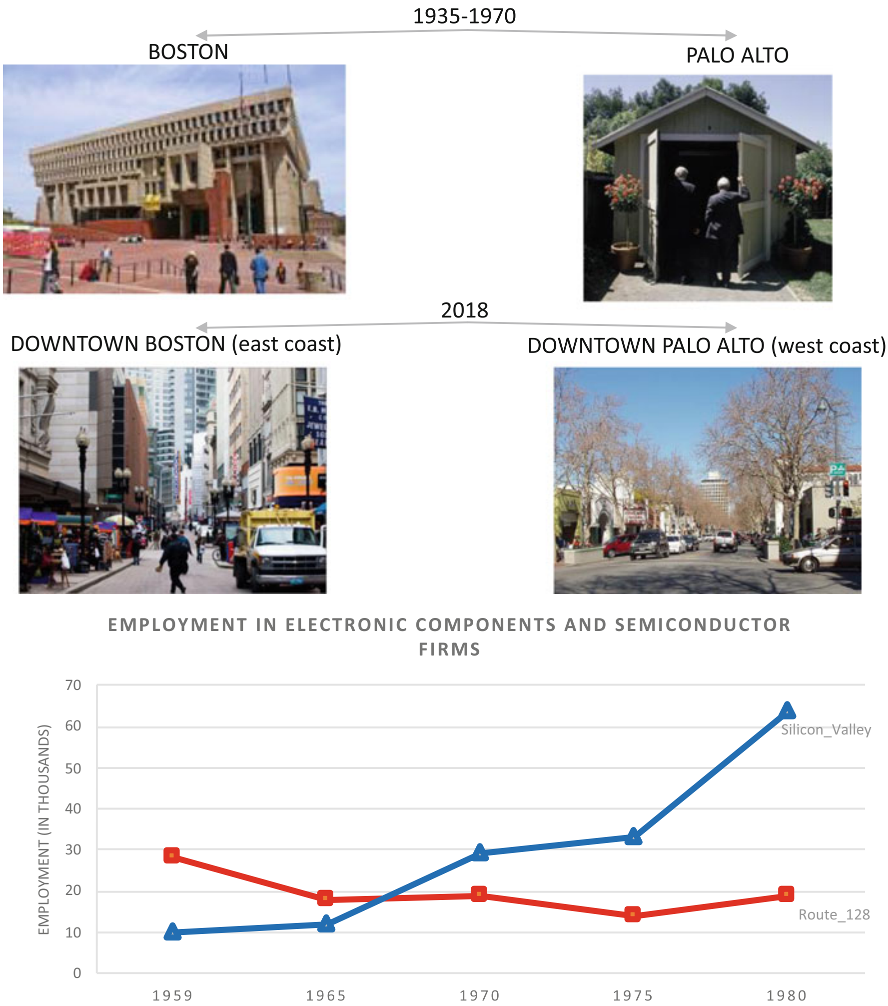



**Fig. 2** An exaggerated illustration of the potential effect of the environment on engineering design performance. Source: Saxenian (1994)

diffused. In Fig. 2, we have tried to illustrate this in an exaggerated manner by drawing comparisons between downtown Palo Alto on the west coast of the US and downtown Boston on the east coast. We used data from Annalee Saxenian's seminal comparative study of route 128 around Boston with the Silicon Valley around Palo Alto (Saxenian 1994).

These insights have led us to believe that the environment—physical, social, and psychological—is a critically important variable in design performance.

**Table 1** Comparison of conditions for research studies in industry and laboratory

| | Industry | Laboratory |
|---|---|---|
| Design task | Task has history and future | Task is self-contained |
| | Problem definition and requirements may change | Frozen assignment |
| | Internal and external factors emerge from data | Mainly functional problem solving |
| Design Research | Difficult to plan | Time and location can be set in advance |
| | Difficult to control | Control is easy |
| | Not repeatable | Several tests with same task is possible |

### *1.3 Measurement: Scientific Challenge*

Despite knowing the importance of the environment, it has been difficult to operationalize and vary environmental parameters for several reasons, chief amongst these being the difficulty in planning and controlling the environment in Industry, which makes it difficult to replicate and validate experimental studies. Table 1 shows a comparison made by Lucienne Blessing as far back as 1991 (Stomph-Blessing 1991). The net effect of these difficulties on the research community has been that most researchers have stuck to conducting small controlled experiments in laboratory settings or large surveys in industry settings, and a few have conducted semi-controlled studies in design classrooms, and computer simulation studies.

### *1.4 Promise: Social Virtual Reality*

There has been a growth in the field of design research since Lucienne Blessing first published the comparison table. More designers have been engaged in the use of video to study design behaviors and in particular we have learnt how to measure the moment to moment interaction behavior of designers (Sonalkar et al. 2013), how to measure the subjective experience of designers (Jung et al. 2012), and how the group affective balance (sum of positive and negative emotions across time) can be used to predict performance in the laboratory and classroom setting (Jung 2016). All told, and to the best of our knowledge, the research community has avoided any manipulation of the environment. In truth, we would love to see the work of others in this regard just because of the difficulty of carrying out such studies.

Concurrent with the growth in the number of studies focused on the subjective experience of designers, there has been a growth in the capacity and capability of virtual reality technology. This later growth has resulted in an ever-increasing comprehensiveness in the computational construction of external reality. The point we would like to underscore here is that Virtual Reality technology now gives us the capability to create and manipulate the variables of the environments, as well as the capability to record and measure the behavior of these variables in real time.

Now, this is not just the physical environment. Computational avatars can be created to simulate individuals and crowds. In addition, Virtual Reality stations can be networked to situate two or more designers who are physically in separate locations in the same virtual location. Last but not the least, given that the environment is computationally constructed, we can very easily go back in time. Specifically, we can attempt to recreate the frontier conditions and examine the corresponding subjective experience of the design team. Obviously, we will need a special caliber of designers for tasks that involve time travel—designers who are flexible and are comfortable and able to suspend their belief and tolerate the ambiguity of the situation. We will not be addressing this variable in the study described here. Our purpose in this section was simply to explore very concisely, the promise of virtual reality. In the next section, we will state our research question, and in the following section, we will describe the study we conducted.

## 2 Guiding Question

How does the environment affect team behavior?

## 3 Study Design and Experimental Setup

### *3.1 Experiment: Preparation*

The study design was initiated with the following requirements in mind.

Requirements for Social VR study:

1. The participants should be able to experience two variations of environment variable—core and periphery (Friedmann 1967).
2. The participants should be able to participate in two different design tasks—product concept generation (pc) and decision making (dm).
3. The participants should perform these tasks as a team.
4. The participants should be able to debrief after each task performance.

At the same time, given that the variation in environment was achieved in VR, the study design also faced a few constraints.

Constraints of the Social VR Study:

1. Participation in Social VR session must be limited to 20 min maximum at a time.
2. The overall study should preferably be no longer than 2 h. It is harder to recruit participants for studies longer than 2 h.

**Table 2** The 2 × 2 within-subjects design used in the study

| | | Task | |
|---|---|---|---|
| | | Product concept generation | Decision making |
| Environment | Core | Task 1 | Task 2 |
| | Periphery | Task 3 | Task 4 |

Given these requirements and constraints we chose a 2 × 2 within-subjects design for the study. This implies that each of the teams will perform all the four tasks as shown in Table 2.

The within-subjects design enabled us to account for variation in team performance with each team performing each of the four tasks. This stands in contrast to the between-subjects experimental paradigm in which the experiment group performs a certain task and the control group performs a control task and the effect of both the experiment and control task is tested on a dependent variable.

## *3.2 Experiment: Physical Setup*

The physical setup consists of three physical stations, each around 2 m by 3 m in area. Each station was equipped with a VR-ready laptop connected to an HTC Vive headset and a pair of Bose noise-cancelling headphones. The space also contained a table and chair for the participant to sit down when filling out the consent forms and questionnaires. Each space also had a video camera setup to capture the physical movements and verbal expressions of the participants. In addition, the laptop was running a screen-capture of the VR interactions of the participants and a body-tracking script that captured the physical movement of their head and their hands. The three stations used for the study are shown in Fig. 3.


**Fig. 3** The three stations used for the Social VR study

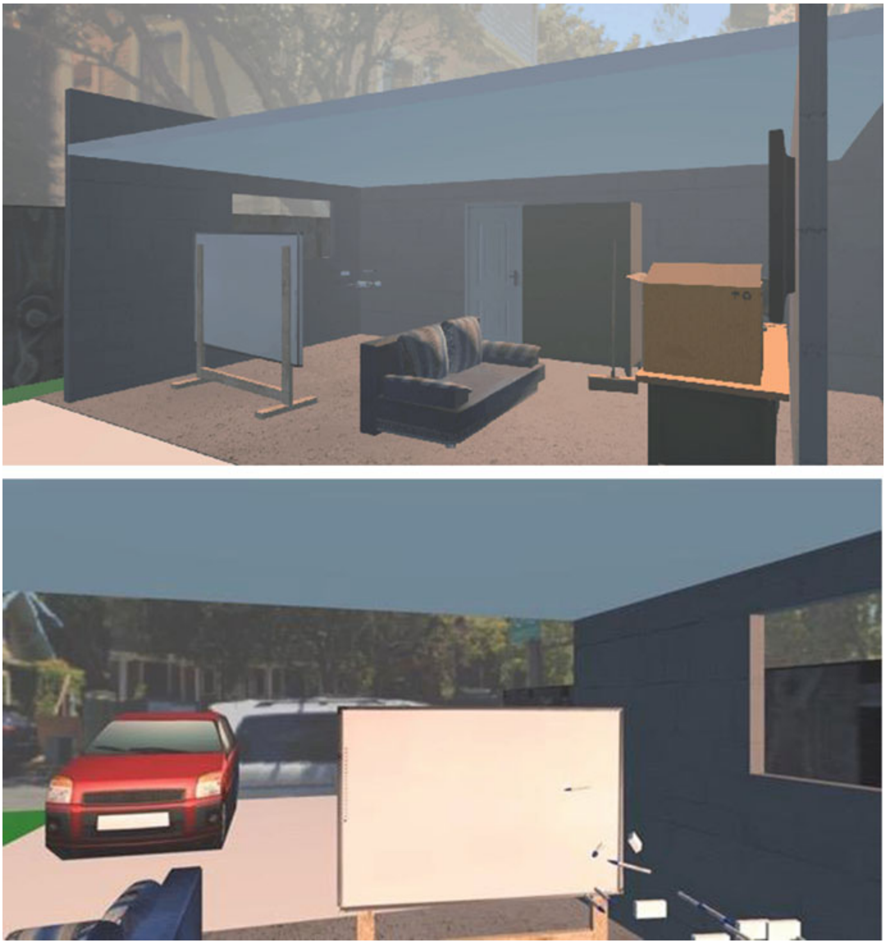


**Fig. 4** Environment designed to simulate a garage in a rural setting (periphery)

## *3.3 Experiment: Virtual Setup*

The two environments—core and periphery—that were needed in the VR space were created using a social VR platform called as High Fidelity. The following images show the two environments—garage for periphery environment, and conference room for core environment (Figs. 4 and 5).

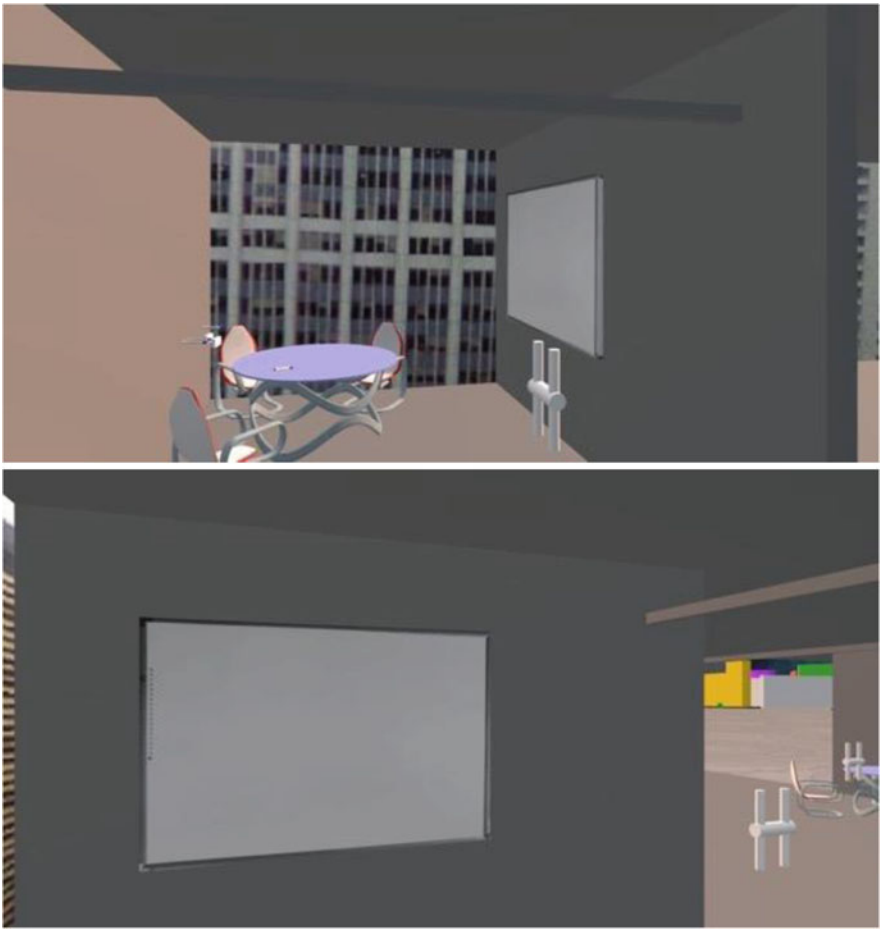


**Fig. 5** Environment designed to simulate a conference room in an urban setting (core)

### *3.4 Experiment: Participant Recruitment*

The participants were recruited from the pool of undergraduate and graduate students available at Stanford University. Two different recruitment systems were used to access the pool of experimental subjects already collected by Center for Design Research as well as the broader pool of student participants in Stanford. The participants were screened in terms of their design thinking experience and their susceptibility to motion-sickness. Only participants who had taken design thinking courses or had at least a 3-month internship experience in a design firm were eligible to participate. Since wearing a VR headset can induce motion-sickness in some participants, those who had a history of motion-sickness were asked not to participate in the study.

### 3.5 Experiment: Procedure

The study was conducted in the Spring quarter of 2019. A total of 24 teams participated in the study. However due to some of the participants not showing up after signing-up for the study, the total number of 3-person teams dropped to 17. Each study was conducted by a team of researchers who were available to guide the participants, perform the consenting and be on the look-out for their physical safety (so as not to bump into physical objects in the space) as the participants interacted in the virtual worlds.

After welcoming the participants, they were asked to fill out the consent form and the subject compensation forms. They were then assigned their VR stations and for those unfamiliar with VR they were shown how to use the buttons. There then followed a practice session, where the participants were allowed to explore, communicate, and play in the VR world which had a mirror and a few objects they could throw to each other and play a game of catch, for example.

Next the participants were taken out of the VR setup and given one of the four design tasks, and after reading it, they are then put back in the VR setup to work on the task together. While the participants were reading the task, one of the experimenters changed the parameters of the VR environment according to a prescribed order. This way each task was performed in either the garage in a "rural" environment or a conference room in a "city" environment.

## 4 Experiment: Data Collection

The following types of data were collected for each session.

1. Video record of each participant wearing the VR headset and interacting
2. Screen capture of the first-person view of each participant in VR interacting in the team.
3. Body tracking data obtained from sensors in hand controllers and headset.
4. Participant responses to the post-task reflection questionnaires.
5. Verbal debrief by the entire team at the end of the whole session, recorded on video.

The following sections explain each of these data types in greater detail.

### 4.1 Video Data of Participant Interactions

Video cameras in each of the participant stations recorded their team interactions during the VR sessions. Figure 6 shows three members of a team being recorded in their individual spaces.

**Fig. 6** The video record of how participants move in the real world in response to VR stimuli

## *4.2 Screen Capture of the First-Person View in VR*

Each of the laptops running the VR for each participant also had screen recording on-going using the software OBS Studio. This enabled us to capture the point-of-view of each of the participants in VR along with the audio stream of what they were hearing and saying. Figure 7 shows the screen-capture data for each of the three participants shown in Fig. 6.

The screen capture data is the primary data stream used for analyzing the interactions of the participants since it is the sole data stream which has audio from all team members. The individual views of the participants are synchronized into a single video using Adobe Premier and that data is used for further interaction analysis.

## *4.3 Body Tracking Data*

VR devices collect position data for the headset and hand controllers in order for the user to see and interact with the virtual content. This content can be analyzed for behavioral data, e.g., how much hand movement participants made, or where

**Fig. 7** The screen capture record of how participants move in the virtual world in response to VR stimuli

participants were turning their heads. In order to collect this data, a script was written interfacing with High Fidelity, the social VR software, and sending this data to a server set up by the research team.

The tracking data included each participant's head and hands position and rotation, resulting in 18 degrees of freedom captured. As the hand rotation data was available in High Fidelity only relative to the avatar, the avatar position and orientation was collected as well. Each sample also contained which computer was sending this data, a timestamp for sending the data, a timestamp for receiving the data, a Boolean for whether the headset was being worn at that moment, and a session ID randomly generated each time the program started up. Table 3 shows a sample of the body-tracking data collected during this study. This body tracking data can be analyzed to determine non-verbal body synchrony between participants as an indication of the quality of interpersonal engagement in the teams. Figure 8 is a graphical representation of this data, from the top view of a virtual space within which the participants movements occurs.

### *4.4 Questionnaire Data*

The participants were given a reflection questionnaire after each task they performed in VR. These questions were used to enable the participants reflect on their experience during the tasks. Specifically, how their emotions changed with time,

**Table 3** The tracking data included each participant's head and hands position and rotation, resulting in 18 degrees of freedom captured. This was analyzed to determine non-verbal body synchrony between participants

| | | | Position | | |
|---|---|---|---|---|---|
| Time | Controller | Axis | Participant #1 | Participant #2 | Participant #3 |
| Time index t | Head | x | −55.9299267031063 | −57.318668508777 | −57.1221098300835 |
| | | y | −10.0938253129704 | −10.3657169482962 | −10.2098038724192 |
| | | z | 66.4407447319469 | 65.4062341584805 | 66.7885751023844 |
| | Left hand | x | −56.1781179427618 | −57.356659012303 | −57.1285479379235 |
| | | y | −10.3335173903721 | −10.3366765370743 | −10.5874666754728 |
| | | z | 66.4272388298801 | 65.7415120297263 | 67.1413602303299 |
| | Right hand | x | −56.1995620727539 | −57.3903198242188 | −57.1610832214355 |
| | | y | −9.98645210266113 | −10.0158252716064 | −9.87399196624756 |
| | | z | 66.2813034057617 | 65.5811920166016 | 66.9226531982422 |

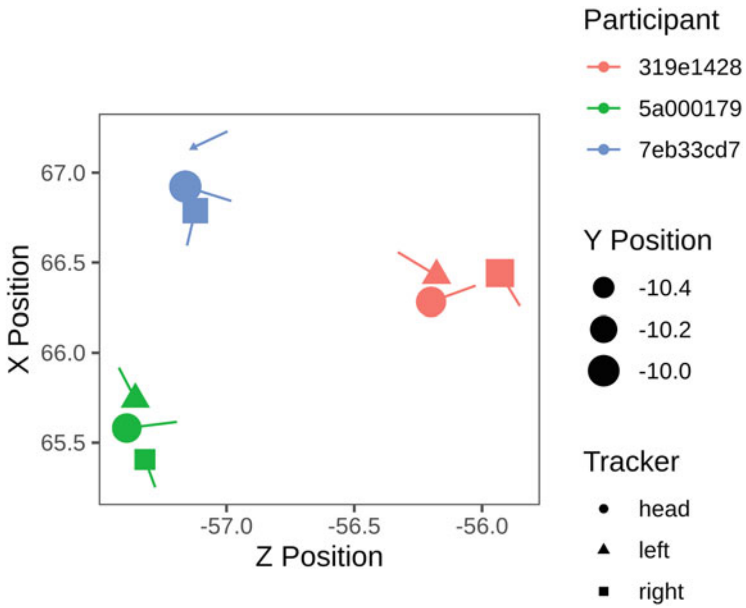



**Fig. 8** Top view of the shared virtual space containing all three participants

the degree of closeness they felt to their team members, their perception of team effectiveness, and their ability to be their authentic selves that is, their level of comfort being themselves during the session.

**Fig. 9** The participants during a sample debriefing session

### *4.5 Verbal Debrief Video*

At the end of the experiment, all three participants were assembled in a room and collectively debriefed about their experience performing design tasks in VR. Figure 9 shows the setting.

During the debrief participants shared their views on the technological affordances of VR for doing design work as well as what they would like to see in the future regarding design thinking in VR.

## 5 Experiment: Preliminary Data Analysis

The multiple streams of data gathered afford us the opportunity to study design team behavior in different VR environments to a great level of detail. Specific to our guiding question, we will be examining the following sub-questions:

1. What are the key characteristics of environment for a design thinking team activity that need to be considered for their influence on design team performance?
2. What are the key characteristics of tasks for a design thinking team activity that need to be considered as influencing design team performance?
3. How could we model the relationship between environment and task characteristics and their influence on team interaction quality and outcome performance?

As the reader may imagine, we have a very large dataset and our analysis will take a while to complete. Here, we would like to present our preliminary analysis of the first sub-question.

We took the tracking data presented in Table 3 and computed the synchrony score for each team for each of the sessions. The computation of each synchrony score is as follows. First, define the position data tracked by the VR headset as $x_{p,\,t}$, a 3D vector of head position of participant $p$ at time index $t$. Calculate the motion $m_{p,\,t}$ with the simple equation

$$m_{p,t} = \| x_{p,t+1} - x_{p,t} \|_2$$

representing the Euclidean distance traveled between time indices $t$ and $t + 1$. Referring to $m_p$ as the vector of motion of participant $p$ over all time points, and *Spearman* as Spearman's rank correlation, the final synchrony score of the team is given as

$$sync = \frac{Spearman\,(m_1, m_2) + Spearman\,(m_2, m_3) + Spearman\,(m_1, m_3)}{3}$$

The results are presented in Table 4.

Next, we tried to see if there was a correlation between the synchrony scores and the environment. We used a Kruskal-Wallis ordinal test which showed that the teams in the conference room had significantly higher synchrony ($H(1) = 7.056$, $p = 0.0079$) than the teams in the garage (Fig. 10). This was unexpected and surprising. At this time, we do not really have a good explanation for this result, and we will need to do more analysis. From an experimental viewpoint it is useful to see that the design of the virtual environment resulted in a detectable difference in behavior of the participants—in this case the synchrony.

## 6 Discussion and Summary of Analysis

The result of the preliminary analysis is summarized in Fig. 11 where we show the design of the environment in a table above the correlation measures. At this point we do not know what specific feature of the environment affected the synchrony. These could range anywhere from:

- the size of the room
- the elevation of the room
- the roughness of the room
- the sense of proximity to other buildings

**Table 4** Synchrony measure for the teams for each session for each environment. The blank cells represent sessions when the data was not captured

| | Synchrony | | | |
|---|---|---|---|---|
| | Decision making task | | Product concept generation task | |
| Team number | Conference room | Garage | Conference room | Garage |
| 1 | | | | |
| 2 | | | | |
| 3 | | 0.067 | 0.052 | 0.058 |
| 4 | 0.066 | 0.024 | 0.084 | 0.033 |
| 5 | | | | |
| 6 | 0.07 | 0.019 | 0.081 | 0.053 |
| 7 | | | | |
| 8 | | | | |
| 9 | 0.054 | 0.026 | 0.194 | 0.021 |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | 0.154 | 0.048 | | 0.049 |
| 14 | 0.064 | | | 0.055 |
| 15 | 0.157 | 0.06 | 0.168 | 0.095 |
| 16 | | | | |
| 17 | 0.084 | 0.081 | 0.031 | 0.035 |
| 18 | | | | |
| 19 | | 0.04 | 0.023 | 0.017 |
| 20 | | | | |
| 21 | | | | |
| 22 | 0.05 | | 0.105 | 0.077 |
| 23 | | | 0.111 | 0.087 |
| 24 | | 0.082 | | 0.042 |

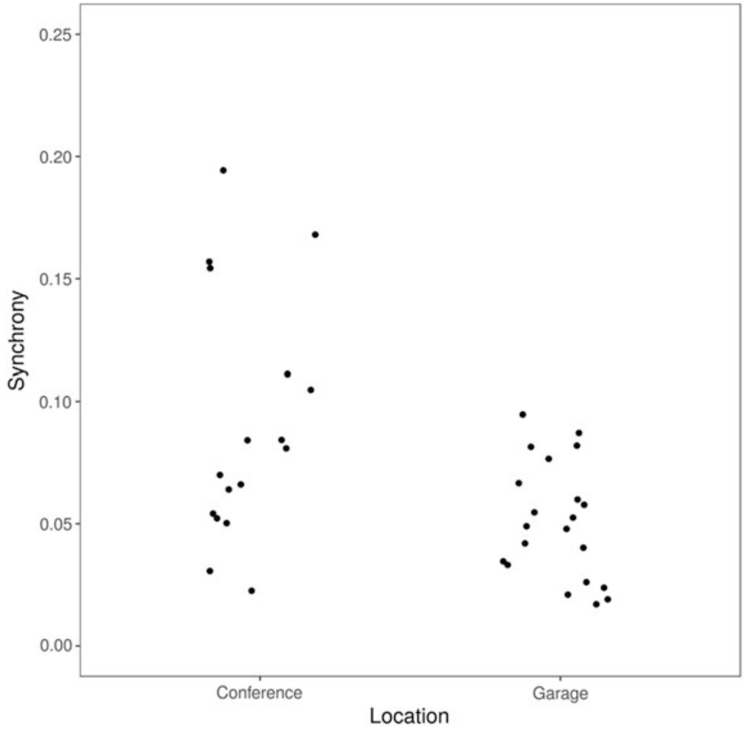



**Fig. 10** Based on a Kruskal-Wallis ordinal test, teams in the conference room had significantly higher synchrony ($H(1) = 7.056$, $p = 0.0079$)

## 7 Synthesis[1]

Despite this lack of immediate explanation, the process of searching for an explanation led to the development of a conceptual model which could be used as a probe to troubleshoot the external factors affecting Design Performance in a Virtual Reality Environment. The model is illustrated in Prototype #1, Fig. 12.

[1]This approach—going from a problem discovered while analyzing data to a design synthesis mode is inspired by Stephen Kline's chain linked model of innovation (Kline 1995), where he described the limitations of the linear model of innovation and pointed out that "most innovations come from human designs, not from science. Moreover, science at most enables innovations; it does not complete them". In his model he defined a parameter, a pathway C as Enabling of designs by science and questions arising in science from problems in design (p. 184). In essence, the chain-linked model with its multiple feedback loops is more than just a model of co-evolution of science and design; or problem and solution. It is also a co-evolution of questions asking, design thinking, problem solving, and frame making. Thus, we have deviated from the scientific norm of going from analysis to discussion, to instead go from analysis to synthesis, in an attempt to overcome the lack of data to explain the results of our analysis. pp. 182–193.

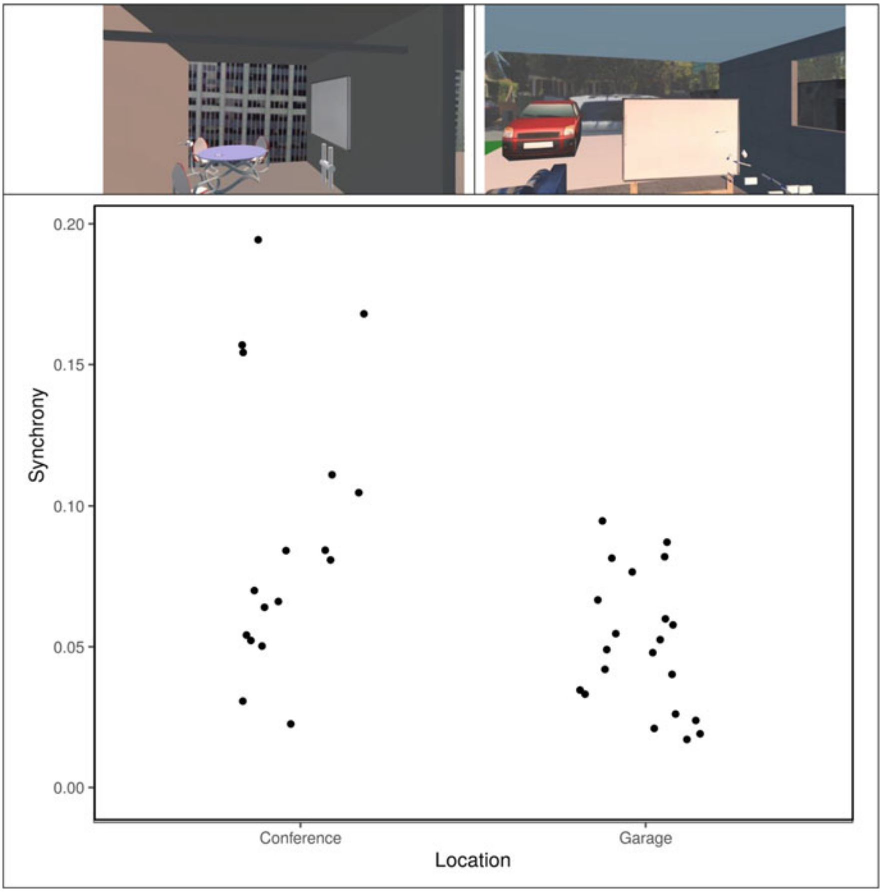



**Fig. 11** A conceptual illustration of the relationship between the design of the environment and the level of synchrony between the teams

## *7.1 Prototype #1*

The trouble shooting model builds on our previously published quadratic model of reciprocal causation for monitoring, improving, and reflecting on design team performance (Sonalkar et al. 2017). Specifically, it pays attention to three concepts not previously made explicit in the model—stigmergy, synchrony, and scaffolding, and considers a minimum of two-person teams. We have called it a trouble shooting model because we developed it in quest of an explanation for the results of the preliminary analysis.

Stigmergy is defined as a mechanism of indirect coordination, through the environment, between agents. Interpersonal synchrony refers to instances when the movements of two or more people overlap in time and form. It is to be distinguished

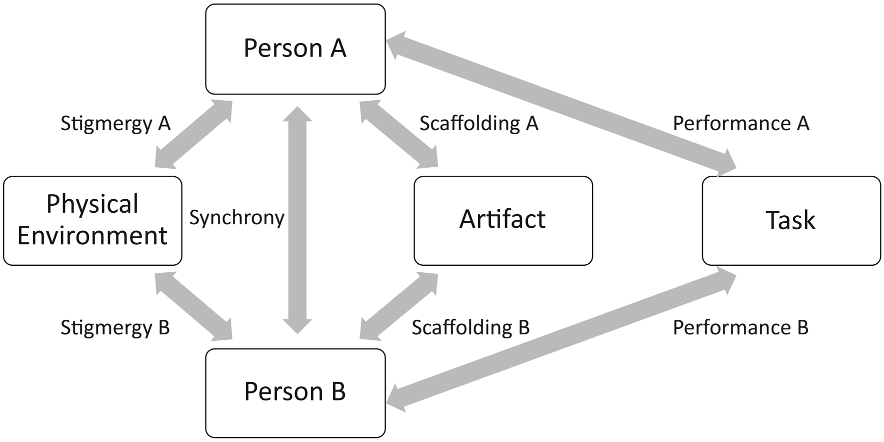



**Fig. 12** Prototype #1: A conceptual model for troubleshooting the external factors affecting design performance in a social virtual reality environment

from mimicry, whereby one person imitates or copies another. Lastly, scaffolding comes from the fields of construction and education. In education, scaffolding refers to instructional techniques used to support student learning so they can move progressively toward stronger understanding and, ultimately, greater independence in the learning process. In construction, scaffolding are the artifacts used to support people and material in the construction or repair of buildings and other large structures. In general, the artifact is called the scaffold, and is understood to be transient. Finally, the consideration of two-persons, as opposed to one person in the quadratic model (Sonalkar et al. 2017), or three persons in our experiments, allows us to introduce the concept of interpersonal synchrony, while keeping the model simple and more easily understood. Our calculation of synchrony used a three-person model where we had to consider multiple pair-wise synchrony calculation.

The troubleshooting model is different from and complementary to models that focus on internal factors, and by taking the two into consideration—i.e. external and internal we believe Virtual Reality closes an important gap in design measurement research and enables us to develop more comprehensive measures of design performance. In considering several models of behavior and performance, the two that appear to have stood the test of time are Bandura's model of cognitive motivation and performance (Bandura 1998) and Fishbein and Yzer's integrated model of behavior prediction (Fishbein and Yzer 2003). An adaptation of Bandura's model in shown in Fig. 13. Here the model has been expanded to include and have placeholders for memory, desire, social response, mindset, and re-entrant mapping. What we have found particularly appealing about Bandura's model is the focus on forethought, which is critical to design thinking and innovation. We also found the focus on retrospective reasoning to be useful, because there are many instances in design where we ask designers reflect on their experience, and/or to suspend

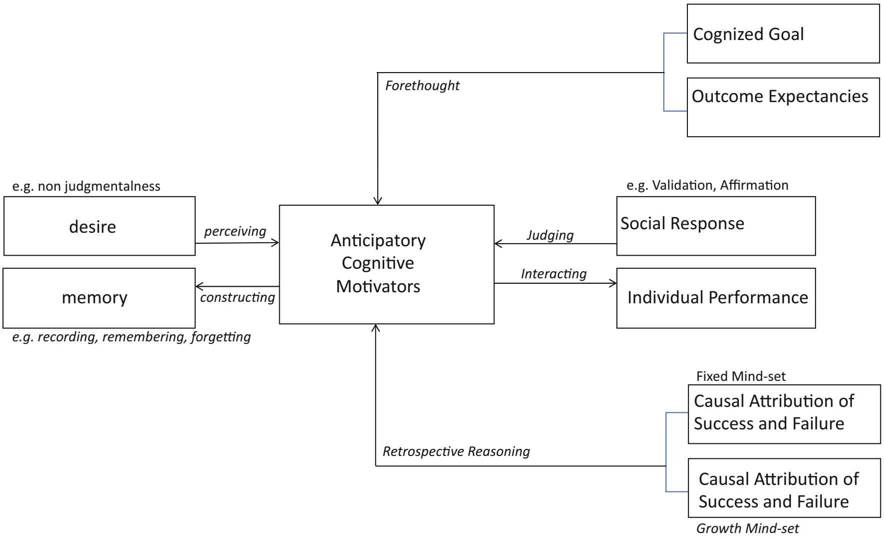



**Fig. 13** A representation of the relationship between cognitive motivation and performance based on cognized goals, outcome expectancies, and causal attributions. Adapted from Bandura (1998)

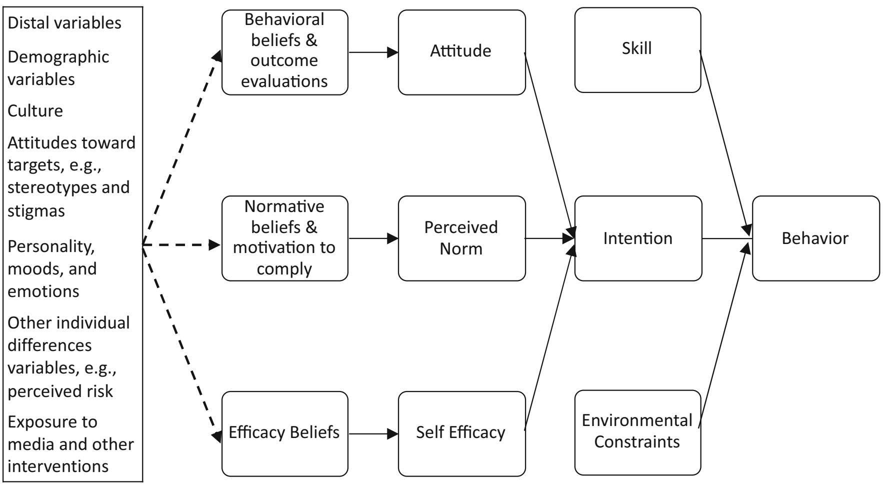



**Fig. 14** An integrated model of behavior prediction. Source: Fishbein and Yzer (2003)

judgment. Thus, this is a simple model that could be used to model the instructions and suggestions made by design educators and design coaches.

The Integrated Behavior Model by Fishbein and Yzer, shown in Fig. 14, brings together three main theories that identify a limited number of variables that have been widely used in health behavior research and interventions. These theories are the health belief model, social cognitive theory, and theory of reasoned action (Fishbein and Yzer 2003). The model incorporates some of Bandura's research on self-efficacy and goes further to account for the influence of a person's skill, environmental constraints on behavior, and distal variables such as exposure to media. This model has undergone a lot of iteration. We liked for example the version presented by Daniel E. Montaño and Danuta Kasprzyk (2008) in Glanz et al.'s Health Behavior and Health Education: Theory, Research, and Practice. However, we felt it would be too elaborate to present here.

We have had to combine Bandura's model with that of Fishbein and Yzer because the context of their work was different. Fishbein and Yzer seemed to have worked primarily in the health care and media communication sector. The reader will observe that the aspect of motivation represented in their model is "motivation to comply," and from the direction of the arrows, at least conceptually, the distal variables appear to be driving behavior. Bandura on the other hand seemed to have worked primarily in the education sector, and to a lesser extent in the health or communication sector. In his model, motivation is dependent on an individual's goals, expectations, and attributions of successes and failures, and has a direct bearing on the individual's performance. With the understanding that a person's skill is linked to performance and this in turn depends on (1) how the task is decomposed or scaffolded, (2) the presence or absence of a coach, and (3) the level of effectiveness of the coach, an attempt can be made to integrate all three models as shown in prototype #2, Fig. 15.

We believe this model will enable us to account for both the quantitative data we collected as well as the qualitative data. As clumsy as it may look, we are undaunted because as Sunny Auyang observed in her study of engineering theories: "A synthetic theory, which brings knowledge from two sciences to bear on a single topic, is more than the sum of its parts, because it must introduce novel concepts to fill in the gaps, establish interfaces, and reconcile different approximations" (Auyang 2004).

### *7.2 Provisional Resolution of the Clumsiness of Prototype #2*

We observe that the entity "person" is represented in several ways in prototype #2. In fact, each of the components includes at least one person, so that implicitly the model has four people. One way to resolve this is to make a distinction between a person and their learned culture. Some of the elements comprising "learned culture" are included in Fishbein and Yzer's model under—the term distal variables. Another term that could be used instead of learned culture is the term common ground. However, we anticipate a situation in which we have two people who have a minimum overlap of their common grounds. In other words, we believe a minimum overlap of common grounds is necessary for design work to be done, and if there is no common ground, our model of "persons" must have the capacity and ability to generate a common ground. Person could be an alien, robot, or avatar. Bearing

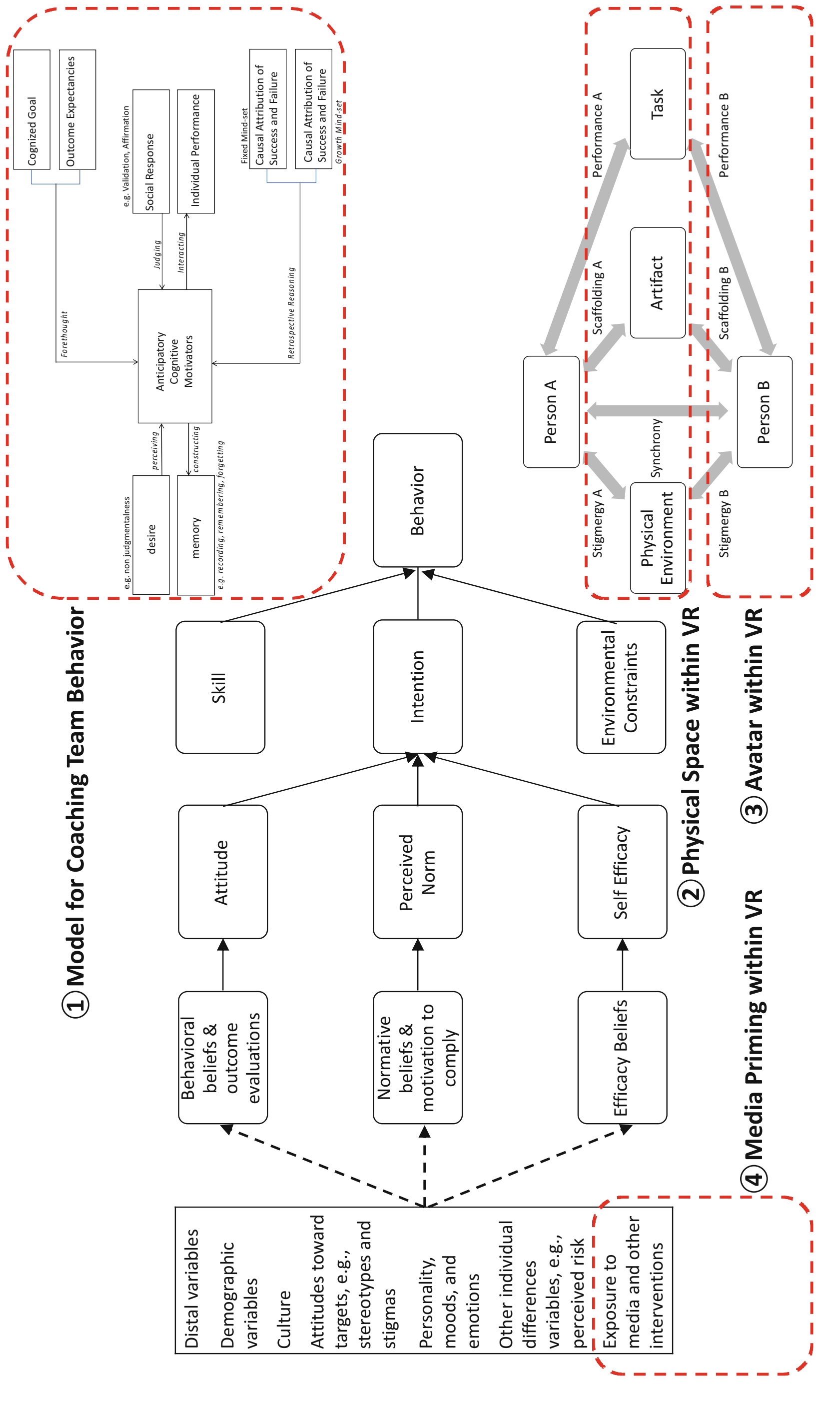



**Fig. 15** Prototype #2: First attempt at a comprehensive model of environment modification, media priming, behavior prediction, and design coaching

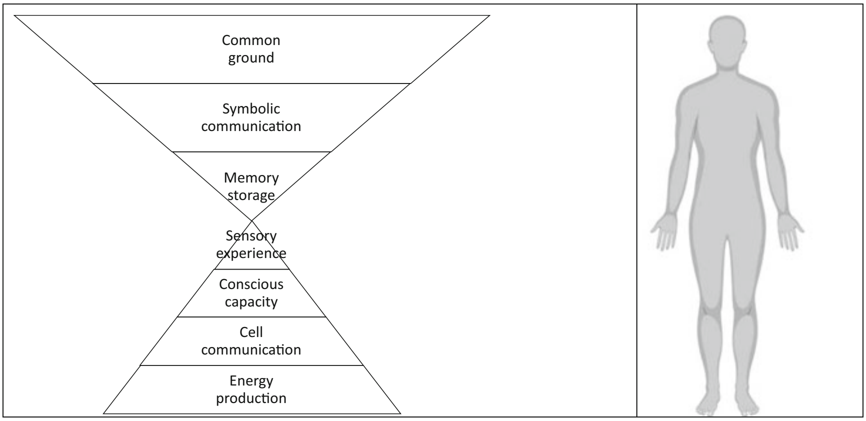



**Fig. 16** Model of learned culture comprising primarily of common ground and sensory experience

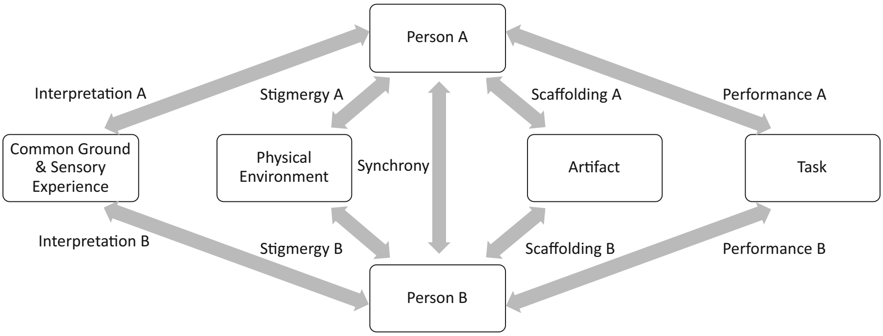



**Fig. 17** Prototype #3: A conceptual model for troubleshooting the external factors affecting design performance in a social virtual reality environment

this in mind, we defined a person as an entity with six basic functions. These are cell communication/energy storage + conscious capacity/activity + sensory feeling/expression + memory formation/storage + symbolic association/communication + common ground generation/degeneration. This model is shown in Fig. 16.

Given this model of learned culture, we can simplify prototype #2, to prototype #3 which is shown in Fig. 17.

We believe that prototype #3, will give us the possibility to improve the design of the virtual environment and more specifically to answer the types of questions we posed earlier, namely: what specific feature of the environment affected the synchrony; where answers could range from:

- the size of the room
- the elevation of the room
- the roughness of the room
- the sense of proximity to other buildings

Since we have developed this model based on Bandura's model of reciprocal causation, we feel that each of the components in the model are multi-directionally related. Thus, a variable like the "size" of the room will depend on an individual's previous experience and cultural associations.

The reader is reminded that the environment is now being created computationally, which makes its manipulation much easier than we could do in the physical—and truly gives us the possibility of many new questions which have been more difficult to pose. We believe this troubleshooting model will be a useful guide to designing more effective simulation environments for learning and for improving design performance.

## 8 Conclusion

This paper began by highlighting the unpredictability and open-ended nature of design. We then examined the limitations of ongoing research efforts and the promise offered by virtual reality. Building on this promise, we conducted an experiment involving 17 teams, and very early found a strong correlation between the type of environment and the degree of synchrony within teams. The crises in trying to explain this correlation led to the development of an expanded model of behavioral prediction that included environment. The model was large and clumsy; however, we were able to reduce it to two models. A person model independent of the environment, and a situation model dependent on the environment. We believe that through repeated use we will be able to increase the fidelity of the models. In this way, we see that social virtual reality could become an indispensable tool for improving design performance.

## References

Auyang, S. Y. (2004). *Engineering—An endless frontier*. Cambridge, MA: Harvard University Press.

Bandura, A. (1998). Personal and collective efficacy in human adaptation and change. In J. G. Adair, D. Belanger, & K. L. Dion (Eds.), *Advances in psychological science: Vol. 1. Personal, social and cultural aspects* (pp. 51–71). Hove: Psychology Press.

Fishbein, M., & Yzer, M. C. (2003). Using theory to design effective health behavior interventions. *Communication Theory, 13*(2), 164–183.

Ford, L. K., Jr. (1993). Frontier democracy: The turner thesis revisited. *Journal of the Early Republic, 13*, 149.

Friedmann, J. (1967). *A general theory of polarized development, internal report—The ford foundation urban and regional advisory program in Chile*. Chile: Santiago.

Hwang, V. W., & Horowitz, G. (2012). *The rainforest: The secret to building the next silicon valley*. Los Altos Hills, CA: Regenwald.

Jung, M. F. (2016). Coupling interactions and performance: Predicting team performance from thin slices of conflict. *ACM TOCHI, 23*(3), 18.

Jung, M. F., Chong, J., & Leifer, L. J. (2012). Group hedonic balance and pair programming performance: Affective interaction dynamics as indicators of performance. In *Proceedings of CHI 2012*. New York: ACM Press.

Kline, S. J. (1995). *Conceptual foundations for multidisciplinary thinking*. Stanford, CA: Stanford University Press.

Mabogunje, A., Leifer, L. J., Levitt, R. E., & Baudin, C. (1995). ME210-VDT: A managerial framework for improving design process performance. In *Proceedings of the Frontiers in Education Conference*, Atlanta.

Montano, D. E., & Kasprzyk, D. (2008). Theory of reasoned action, theory of planned behavior, and the integrated behavioral model. In K. Glanz, B. K. Rimer, & K. Viswanath (Eds.), *Health behavior and health education*. San Francisco, CA: Jossey-Bass.

Saxenian, A. (1994). *Regional advantage: Culture and competition in silicon valley and route 128*. Cambridge, MA: Harvard University Press.

Sonalkar, N., Mabogunje, A., & Leifer, L. (2013). Developing a visual representation to characterize moment-to-moment concept generation in design teams. *International Journal of Design Creativity and Innovation, 1*(2), 93–108.

Sonalkar, N., Mabogunje, A., & Cutkosky, M. (2017). Quadratic model of reciprocal causation for monitoring, improving and reflecting on design team performance. In L. Leifer, C. Meinel, & H. Plattner (Eds.), *Design thinking research: Making distinctions—Collaboration versus cooperation*. London: Springer.

Stomph-Blessing, L. T. M. (1991). *Analyzing design: A comparison of approaches*. Unpublished report presented at ICED 91, International Conference on Engineering Design, Zurich.

Understanding evolution: More on punctuated equilibrium. Retrieved January 27, 2020, from https://evolution.berkeley.edu/evolibrary/article/side_0_0/punctuated_01

# The Neuroscience of Team Cooperation Versus Team Collaboration

**Stephanie Balters, Naama Mayseless, Grace Hawthorne, and Allan L. Reiss**

**Abstract** In this book chapter, we present our scientific approach for applying the methods of fNIRS hyperscanning to decode distinct qualities of team interaction. Specifically, we are interested in detecting states of inter-brain synchrony that correlate with the behavioral states of *cooperation* and *collaboration*—terminologies which have been previously introduced as separate states in design thinking literature. We propose that the differentiation between those two concepts holds great promise for a better classification of team interaction, and a more thorough understanding of the dynamics leading to improved performance and (design) results. It is our hope that this work will provide more accurate and valuable information on human social interaction within working teams in the design thinking and related areas.

## 1 Cooperation Versus Collaboration

In an earlier version of this book series, Leifer and Meinel (2018) raised the question whether it is necessary to make a critical distinction between *cooperating* and *collaborating* in the pursuit of design-thinking-guided breakthrough-innovation. The authors argue that "*Design thinking in practice demands an iterative cycle of creative collaboration, agreeing to disagree until some of those concepts (ideas) are really worth further attention. Then follows tangible prototyping to yield informed decisions based on human experience with the prototypes. With the design challenge re-framed and a workable prototype in hand we can proceed to use efficient cooperation to 'make it real'*" (Leifer and Meinel 2018, p. 4). With this distinction, Leifer and Meinel conceptualize *cooperation* and *collaboration* as vital,

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yet different, parts of a successful design thinking process leading to innovative outcomes.

The impact of team interaction, with respect to the quality of a team's innovative design outcome, has gained growing awareness among design thinking educators, practitioners, and researchers. Concepts like team agility, multidisciplinarity, cross-functionality, and empathy are being studied, to only name a few (Gebert et al. 2006; Sarker and Sarker 2009; Leifer and Steinert 2011; Köppen and Meinel 2015); and results from related research studies demonstrate that certain team dynamics indicators are indeed strongly correlated with long-term innovative performance (Tang 1991; Kress and Schar 2011; Jung et al. 2012). And yet, with respect to *cooperation* and *collaboration* specifically, the question still remains: it is necessary to make a critical distinction between *cooperating* and *collaborating* in the pursuit of design-thinking-guided breakthrough-innovation?

It is our aim to attempt to find an empirical answer to this very question. Before examining complex design (thinking) tasks in this pursuit, we began with the first (systematic) step of designing a controlled team task which comprises the assembly of a predefined 3D puzzle of a wooden airplane. For this first step, we borrowed and operationalized content-related definitions of the two terminologies from organizational management science. Nissen et al. (2014), introduce *cooperation* and *collaboration* as two different forms of interaction, and provide the analogies of 'taskwork' and 'teamwork' as distinctive features. Based on their literature review of proposed theories in the field, the authors conclude that "*collaboration and teamwork are similar because they are both characterized by strong linkages and interdependency between members of a group or a team. In contrast, both cooperation and taskwork are characterized by group members or team members being autonomous and independent during the innovation process*" (Nissen et al. 2014, p. 473). As shown in Table 1, Nissen et al. specify that *cooperation* is specified by the division of labor for a defined task; by the sharing or transferring of information among actors in a group; by weak linkages between the team members; and by team members working in different contexts. On the other hand, they define *collaboration* as joint problem solving for a common task; by a more open-ended

**Table 1** Key dimensions of cooperation and collaboration as derived from Nissen et al. (2014, p. 475)

| General dimensions | Taskwork and cooperation | Teamwork and collaboration |
|---|---|---|
| Distribution of tasks and responsibilities | Separate assignments/distribution of tasks and delineation of responsibilities | Joint problem solving/community and common tasks |
| Type of task | Defined tasks | More open tasks |
| Linkages between the team members (degree of interactions, dialogue, etc.) | Weak linkages | Strong linkages |
| Context | Team members work in different contexts | Team members work in a common context |

task; by a strong linkage between team members; and by the fact that team members work in a common context.

Within the scope of this book chapter, we will borrow the definitions from Nissen et al. (2014) as described above. However, we have excluded their 'type of task' dimension to make the definitions of *cooperation* and *collaboration* more applicable to our specific context.

## 2 Understanding *Cooperation/Collaboration*: Measurable Constructs

One approach to better understand *cooperation* and *collaboration* as part of dynamic teamwork and related 'success' and performance, is the quantification of measurable constructs. For that matter, we cluster a variety of potentially regulating constructs broadly based on five categories (see Fig. 1): (1) physiological constructs such as heart rate, blink rate, skin conductance or hormonal changes (Mønster et al. 2016); (2) behavioral constructs such as eye gaze, body movements, verbal and non-verbal interactions, task performance (Sonalkar et al. 2013; Lasecki et al. 2014; Cannon and Edelman 2019); (3) outcome construct levels of cooperation/collaboration based on subjective or objective measures, satisfaction, or product of interaction (Dong et al. 2004; Kress et al. 2012; Sjöman et al. 2015); (4) individual moderators such as socioeconomic status, age, sex/gender, ethnicity, and culture (Ancona and Caldwell 1992; Caldwell and O'Reilly 2003; Baker et al. 2016); and, (5) neuroscientific constructs, such as inter-brain synchrony (IBS) between interacting partners engaged in the task (Mayseless et al. 2019). In the current report, we focus

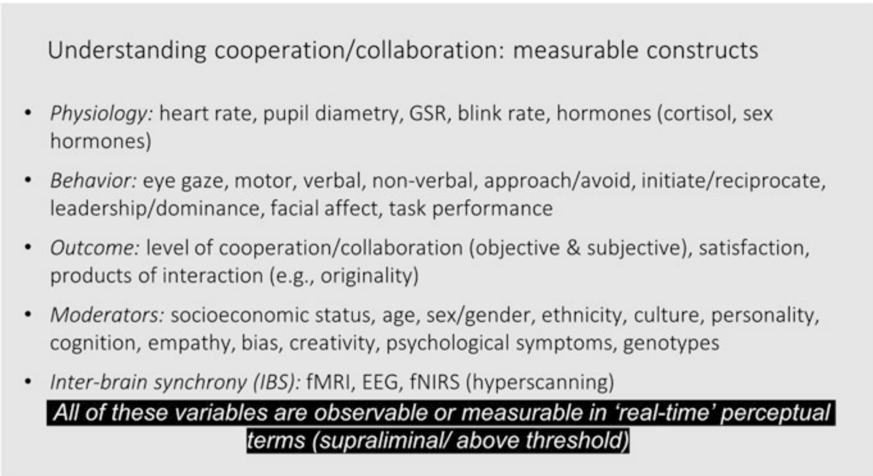


**Fig. 1** In this book chapter, we focus on inter-brain synchrony as a measure in the field

on the neuroscientific construct by examining IBS as one measure in the field. Beyond this scope, we argue that a consideration of many constructs is needed in order to generate a holistic model of team dynamics incorporating *cooperation* and *collaboration*.

## *2.1 Neuroscientific Construct: Hyperscanning*

During the last decade, neuroscience has introduced a technique, *hyperscanning* (see Fig. 2), which enables the measurement of brain activations of more than one individual, at the same time (Wang et al. 2018). Hyperscanning allows researchers to measure the sub-components of social interactions occurring in groups by means of inter-brain synchrony. The assessment of IBS allows systematic decoding of the underlying neurological mechanism with respect to human behavior during joint attention, communication, coordinated musical performance, and other group interaction such as design thinking sessions (Mayseless et al. 2019). The number of individuals measured at the same time is solely limited by the scale and scope (and affordability) of brain measurement equipment, and computer power. Furthermore, an experimental methodology and task which allows the researchers to distill a stimulus-response across subjects is also required. As such, hyperscanning provides a unique opportunity for the design thinking community to ultimately track brain states and changes when principles, techniques, and concepts with respect to team dynamics are applied.

As shown in Fig. 2 (*left*), the first hyperscanning study was conducted in the fMRI scanner in 2002 (Montague et al. 2002). Thereafter, functional magnetic imaging (fMRI) and electroencephalogram (EEG) hyperscanning studies followed focusing, among others, on joint attention and coordinated body movements (Saito et al. 2010; Dumas et al. 2010; Lachat et al. 2012). In 2011–2012, the first functional near-infrared spectroscopy (fNIRS) hyperscanning studies were conducted focusing on the synchronous activity of two people's prefrontal cortices during a cooperative

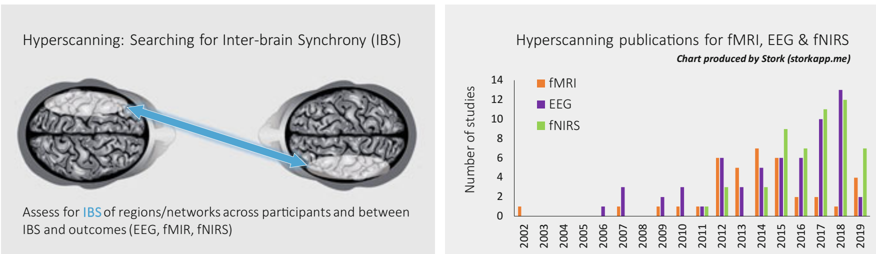


**Fig. 2** Example of hyperscanning of the left brain areas of two individuals (left); and hyperscanning publications from 2002 to June 2019 (right). The Stork-search considered PubMed data and searched for 'hyperscanning' in the title and abstract only

'button press' task (Funane et al. 2011; Cui et al. 2012). As can be seen in Fig. 2 (*right*), the number of studies using hyperscanning techniques, and incorporating IBS in their measurements, have grown considerably since.

### *2.2 Distinction Between Cooperation and Collaboration in Neuroscience*

To investigate if and how the field of neuroscience distinguishes between the two terms, we researched all past and current literature published up to the date of December 11, 2019. Specifically, we executed a google scholar search and used three search queries, namely 'hyperscanning collaboration', 'hyperscanning cooperation', and 'hyperscanning collaboration cooperation'. We inspected the first 20 entries for each combination of keywords and included all peer-reviewed journal publications in the English language within the fields of neuroscience and neuropsychology. In total, we identified 23 publications with a total of 1424 citations. Thirteen papers used solely the terminology *cooperation* and did not mention *collaboration* in their manuscripts (Cui et al. 2012; Liu et al. 2016; Cheng et al. 2015; Pan et al. 2017; Baker et al. 2016; Osaka et al. 2015; Balconi and Vanutelli 2017a, b; Astolfi et al. 2010, 2011; Nozawa et al. 2016; Duan et al. 2015; Vanutelli et al. 2016); while one publication contains only the terminology *collaboration* and the term *cooperation* is not used at all (Woolley et al. 2007). Seven other publications used both terminologies interchangeably (Toppi et al. 2016; Liu et al. 2017; Babiloni and Astolfi 2014; Cha and Lee 2019; Gvirts and Perlmutter 2019; Mu et al. 2018; Mayseless et al. 2019); and two publications used neither *cooperation* nor *collaboration* throughout their manuscripts, however, listed parts of the above-mentioned papers in their references (Dai et al. 2018; Dumas et al. 2011). Notably, none of the observed articles from the field of neuroscience includes a specific distinction between *cooperation* and *collaboration*, nor a specific definition of either terminology.

We propose to borrow the concepts of *cooperation* and *collaboration* from the team dynamics literature (as described in Sect. 1), and to apply these to the field of neuroscience, and hyperscanning studies in particular. We suggest that the differentiation between the two concepts of *cooperation* and *collaboration*, holds great promise for a better classification of team interaction, and a more thorough understanding of the dynamics leading to those team interactions that are associated with improved performance and (design) results.

### 2.3 *Functional Near-Infrared Spectroscopy (fNIRS) for Assessing IBS*

The study presented in this book chapter uses functional near-infrared spectroscopy to investigate neural synchrony (Fig. 3). fNIRS is a non-invasive optical imaging device that measures cerebral blood flow changes, similar to fMRI. In that sense, fNIRS builds on a rich and established empirical and data-processing foundation from the field of fMRI. fNIRS also has the advantage of being portable, low cost (compared to fMRI), and less prone to movement artifacts than the other two imaging methods (Monden et al. 2012). In addition, fNIRS provides higher temporal resolution than fMRI (Cui et al. 2012), and higher spatial resolution than electroencephalography (EEG). Due to the fact that fNIRS is less prone to motion artifacts (due to the underlying measurement technique but also due to enhanced motion artifact correction methods) and is more portable and cost effective, it can easily be applied in paradigms that require more holistic and natural settings such as group interactions. Indeed, an increasing number of fNIRS hyperscanning studies with reference to IBS have been recently published. These studies investigate IBS during both verbal, semi-verbal and non-verbal interactions (Jiang et al. 2012; Osaka et al. 2015; Funane et al. 2011; Cui et al. 2012; Holper et al. 2012). Previous hyperscanning studies using fNIRS have repeatedly found increased IBS to be related to enhanced levels of interaction between team members (Cui et al. 2012; Liu et al. 2016; Miller et al. 2019), as well as interactions with gender diversity of the team (Baker et al. 2016).

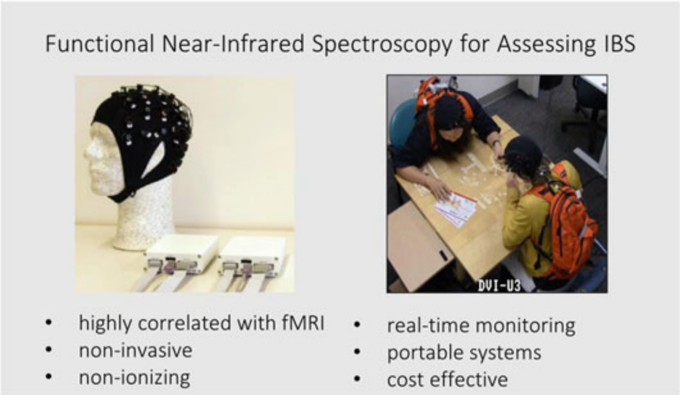


**Fig. 3** Benefits of using fNIRS in assessing IBS

## 3 Methodology

In this work, we describe the methods and procedures that we are planning to use in order to derive distinct qualities of team interaction via fNIRS hyperscanning. Actual data analysis and related results are not part of this book chapter. Specifically, we are interested in detecting states of inter-brain synchrony that correlate with the states of *collaboration* and *cooperation,* and hence, provide an objective assessment of either state. In order to achieve this, we focus on team interaction in a non-restrictive environment and asked participants to engage in a joint task of assembling a predefined 3D model of a wooden airplane (Fig. 4). For our investigation, we use the control task of an existing data set from our study that originally aimed at examining real-life creative problem-solving activities within teams (Mayseless et al. 2019). Though, we ultimately aim at understanding the effects of *collaboration* and *cooperation* during creative design (thinking) sessions, our investigation starts with the analysis of a 3D model building task because the task includes a distinct number of subtasks along with a quantifiable outcome.

**Participants** We invited a total of 56 participants (27 females, age: $32.09 \pm 6.95$) to the study, resulting in a number of 28 dyad pairs. All participants were right-handed, healthy, and had normal or corrected-to-normal hearing and vision. Participants of the same dyad were not previously acquainted. Participants had no prior experience in design (thinking). We excluded three dyads due to noisy data, resulting in following dyad gender distribution: nine male-male, eight female-female, and eight female-male pairs.

**Procedure** We recruited participants via local advertisements and email lists from Stanford University. After welcoming the participants on the day of the experiment, we obtained each participant's signed consent form, and we equipped

**Fig. 4** Participants assembling the 3D airplane model

each participating pair with the measurement devices. Participants of each dyad were seated on opposite sides of a square table, facing each other (Fig. 4). The experimental procedure consisted of one 10-min creative design thinking session and one 10-min long control 3D model building session. We counterbalanced the tasks across dyads. After the experiment, the experimenters guided the participants into two separate rooms, and instructed them to complete the following additional questionnaires assessing creative ability, and general intelligence: the Figural TTCT-F Torrance Test of Creative Thinking (Torrance 1974); Alternate Uses Task (Guilford 1967); and the Wechsler Abbreviated Scale of Intelligence-II (Wechsler 2011). The procedure was approved by the University's Institutional Review Board. Each participant received $75 as compensation for their participation. The total length of the procedure averaged 3 h per dyad.

**Tasks** For the design task, participant pairs were instructed (verbally) to design a way to motivate people to vote and to build a physical artifact to express the outcome. The artifact could be constructed using any design or material of the pair's choice. We equipped the participants with a selection of materials (i.e., paper, pencils, and post-it notes), and gave them 10 min to complete the design task. We informed the participants that they would be asked to explain their concepts at the end of the design session. For the control 3D model building task, we asked participants to work together on assembling a 3D model of a wooden airplane. We specifically chose the control task to establish parameters for creative design while still requiring each pair to cooperate/collaborate with each other.

**Subjective Cooperation Index** After each task, participants rated the level of overall cooperation of the team pairing, the cooperation rating of themselves and of their partner, and their success of the task—each on a scale of 1 (least) to 5 (most). For the design task, participants provided further details about their final product in written form.

**Performance and Outcome** After 10 min, we measured the assembly status of the 3D model by counting the remaining (unused) parts on the table; or respectively measured the time the pair needed to complete a full 3D model.

**fNIRS Data Acquisition** We used the NIRx Tandem NIRSport (LLC NIRx Medical Technologies) for the experiment. The system comprises a total of 32 optodes (16 sources, 16 detectors). We divided these optodes between the two participants, and clustered the 16 optodes of each participant (8 sources, 8 detectors) forming 22 channels covering left frontal, temporal and parietal regions (Fig. 5b). We decided to focus on the left hemisphere as previous studies reported left activations related to creative abilities (Fink et al. 2009; Gonen-Yaacovi et al. 2013). We positioned the optodes following 10–20 system locations. We used individually-sized caps to maintain a constant optode distance across participants to accommodate for different head sizes (Okamoto et al. 2004). We chose a channel length of 3 cm as recommended by (Strangman et al. 2013). Additionally, we attached plastic supports between each source-detector pair to enhance measurement precision over time, and

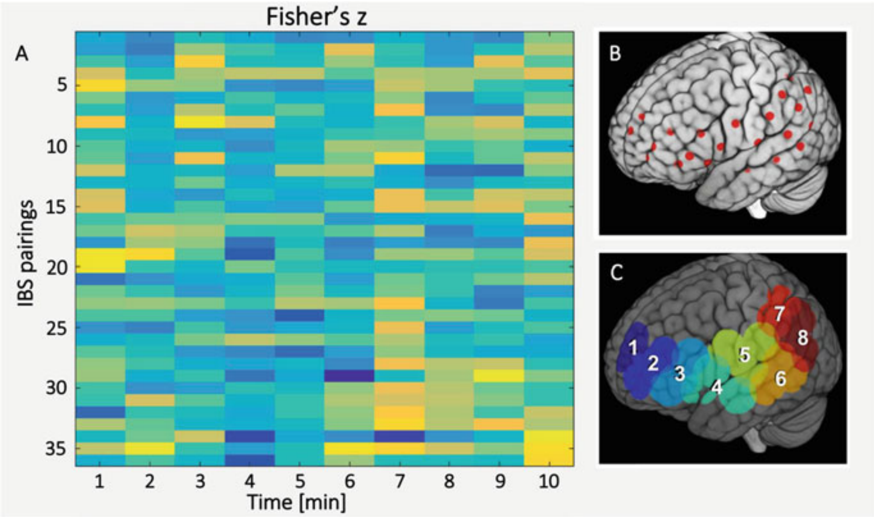


**Fig. 5** (**a**) Example of one dyad data of coherence measure of IBS for the 10 min task averaged across 1 min segments (x axis) in 36 ROI pairings (y axis). (**b**) NIRS setup with the 22 channels (eight sources, eight detectors) covering left frontal, temporal and parietal regions. (**c**) ROIs based on source localization

across participants. We used two wavelengths (760 and 850 nm), and sampled at a frequency of 7.81 Hz.

**fNIRS Data Analysis and Inter-Brain Synchrony Analysis** For data processing, we used the HOMER2 package (Huppert et al. 2009) in Matlab. First, we corrected optical density data for motion artefacts using a wavelet motion correction procedure (Molavi and Dumont 2012). We converted optical density data to changes in oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) values using the modified Beer–Lambert law (Wyatt et al. 1986). Next, we visually inspected the resulting data for each channel and excluded channels with excessive noise from further analysis. We converted the HbO and HbR values to z-scores, and calculated the average values for eight regions to consider different brain morphologies across the entire participant cohort: (1) Superior Frontal Gyrus (SFG), (2) Anterior Prefrontal Cortex (aPFC), (3) Inferior Frontal Gyrus (IFG), (4) anterior Superior Temporal Gyrus (aSTG), (5) Precentral Gyrus (PG), (6) posterior Superior Temporal Gyrus (pSTG), (7) Inferior Parietal Lobule (IPL) and (8) Temporoparietal Gyrus (TPJ). Finally, to create an inter-brain synchrony measure, we used the Wavelet Transform Coherence (WTC) package (https://www.mathworks.com/matlabcentral/fileexchange/47985-cross-wavelet-and-wavelet-coherence) in Matlab. WTC has been successfully applied to identify locally phase-locked behavior between two time-series by measuring cross-correlation between the time-series as a function of frequency and time (Baker et al. 2016; Cui et al. 2012; Torrence and Compo 1998). The WTC between each combination of ROIs was calculated (64 combinations:


**Fig. 6** (**a**) Participants while detaching puzzle pieces, (**b**) reading the instructions, (**c**) searching for parts on the table, and, (**d**) assembling the plane

8ROIs × 8ROIs), and the IBS between the same ROI pairings was then averaged. This resulted in 36 IBS pairings (see Fig. 5a).

**Behavioral Observation and Coding** We recorded the experiment with four cameras, capturing all angles of the room. We followed the three-step protocol for behavior observation coding as described by Bakeman and Gottman (1986). Three experimenters developed a coding scheme to distill a set of behavioral categories. We chose a hybrid approach (Weingart et al. 2005), where the coding scheme is constructed from behavioral features observed during carefully viewing and reviewing the videos (bottom-up approach), combined with top-down elements from theories in neuroscience. For this process, we used videos from pilot data. All three experimenters were females ($M = 41.33$, $SD = 8.08$) with backgrounds in Neuroscience (PhD), Engineering Design (PhD), and Design Thinking Practice/Education (11 years of experience). In total, we selected six categories (Fig. 6), including:

- C1—detaching puzzle pieces from wooden sheet (detach)
- C2—reading instructions (read)
- C3—searching for parts on the table (search)
- C4—assembling parts (assemble)
- C5—task-related discussion (discuss)
- C6—task-unrelated discussion/chatting (chat).

In a subsequent training session, we will collectively watch practice videos (from pilots) in order to clarify confusion. In the final step, we will 'code' the videos of the 10 min long building task of the 28 dyads whenever both participants of a dyad executed any of the six categories *congruently*. Selectively, we will test inter-rater agreement (Coan and Gottman 2007) through the process to refine our coding scheme. For coding, we will use the open source Behavioral Observation Research Interactive Software (https://boris.readthedocs.io). Designated keys on the computer keyboard for each category C1–C6 will facilitate the coding (as seen in Fig. 7). We will extract the created time-series and process the data further in MATLAB.

**State Definition and Hypotheses** Based on our behavioral observations, we define the following states (S1–S3):

- ***S1. No cooperation/collaboration***: at least one of the participants is not engaged in a joint task

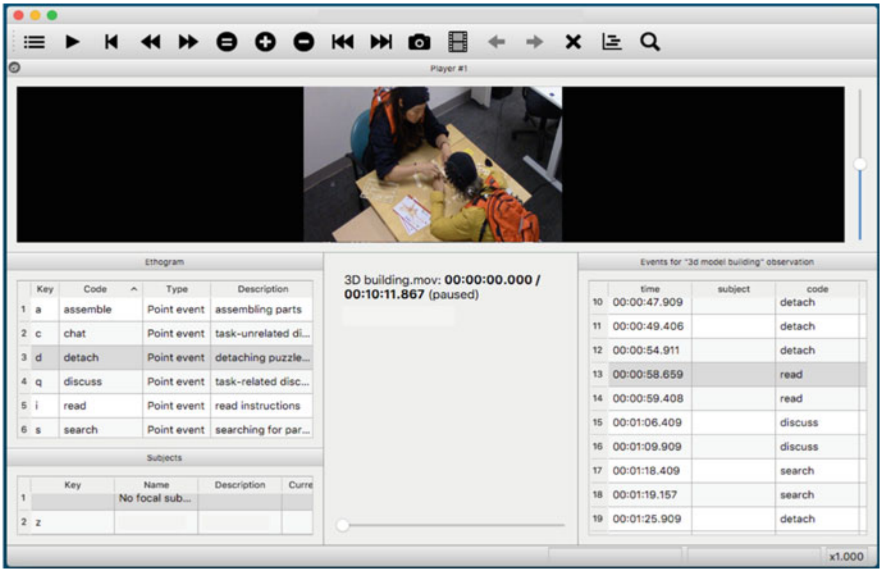


**Fig. 7** Screenshot of video coding

- ***S2. Cooperation***: both participants are engaged in a joint task but do not have joint attention
- ***S3. Collaboration***: both participants are engaged in a joint task and have joint attention

The terminology ‘task’ refers to the 3D model building task as a whole project, and not to its individual subtasks (i.e., detaching puzzle pieces from wooden sheet, reading instructions, searching for parts on the table, etc.). The ***no cooperation/collaboration*** state is designated for cases where one or both participants are engaging in any activity that does not support the assembly process (e.g., such as a participant engaging in task-unrelated small talk). During ***cooperation***, both participants are engaged in a subtask that supports the progress of the 3D model building, but do not have joint attention. This could, for example, apply to sequences where people work independently on assembling separate parts of the airplane, or if one participant reads out loud the instructions to find the position for ‘part 11’, while the other is physically testing where ‘part 5’ belongs. During ***collaboration***, both participants work on a joint (sub-)task with joint attention. This could mean that both participants simultaneously detach puzzle pieces from the wooden sheet, or simultaneously read the instructions regarding the same next step. In addition, collaboration also occurs when both participants are engaged in different subtasks, e.g., participant 1 reads the instructions for ‘part 5’ while participant 2 follows the instructions and assembles ‘part 5’. In the latter example, both participants focus on same assembly step (joint attention), while being engaged in the joint task ‘constructing the 3D model’.

Based on these definitions, it is our intent to understand the underlying mechanisms and differences in neural processes involved in these 'pair states'. By means of our experiment, we intend to address the following experimental hypothesis:

***H1: during collaboration there is an increase in IBS compared to cooperation.***

To allow testing of this hypothesis, we will run an additional video coding procedure to code for states (S1–S3) in addition to the video coding aiming at detecting categories (C1–C7).

## 4 Planned Analysis and Conclusion

In order to test our hypothesis, we will execute the video coding analyses across all dyads and conduct a regression analysis using the classified team's interactions epochs (i.e., *cooperation* and/or *collaboration*), epochs of categories, and calculated IBS. In addition, we will test the effect of each pair's sex diversity on our hypothesis as well as individual differences in personality measures. A special focus will examine the effects of either condition on success and task performance. Are teams successful when they *collaborate* or *cooperate*? Or is it an interplay between *cooperation* and *collaboration* that makes teams succeed? And how does that interplay relate to the (innovative) success of design (thinking) tasks?

In future work, we are interested in examining the effects of design training on these constructs, and intend to explore the design space of brain-computer interfaces that may allow for tailored just-in-time interventions to enhance team performance. Following the success of the present investigation, we plan to extend the methods and measures presented in this chapter to a more complex setup, that is, the hyperscanning of three people simultaneously. It is our hope that this work will provide new and valuable information on human social interaction within working teams in the design thinking and related areas.

## References

Ancona, D. G., & Caldwell, D. F. (1992). Demography and design: Predictors of new product team performance. *Organization Science, 3*, 321–341.

Astolfi, L., Toppi, J., Fallani, F. D. V., Vecchiato, G., Salinari, S., Mattia, D., et al. (2010). Neuroelectrical hyperscanning measures simultaneous brain activity in humans. *Brain Topography, 23*(3), 243–256.

Astolfi, L., Toppi, J., Fallani, F. D. V., Vecchiato, G., Cincotti, F., Wilke, C. T., et al. (2011). Imaging the social brain by simultaneous hyperscanning during subject interaction. *IEEE Intelligent Systems, 26*(5), 38.

Babiloni, F., & Astolfi, L. (2014). Social neuroscience and hyperscanning techniques: Past, present and future. *Neuroscience and Biobehavioral Reviews, 44*, 76–93.

Bakeman, R., & Gottman, J. M. (1986). *Observing interaction: An introduction to sequential analysis*. Cambridge: Cambridge University Press.

Baker, J. M., Liu, N., Cui, X., Vrticka, P., Saggar, M., Hosseini, S. H., & Reiss, A. L. (2016). Sex differences in neural and behavioral signatures of cooperation revealed by fNIRS hyperscanning. *Scientific Reports, 6*, 26492.
Balconi, M., & Vanutelli, M. E. (2017a). Cooperation and competition with hyperscanning methods: Review and future application to emotion domain. *Frontiers in Computational Neuroscience, 11*, 86.
Balconi, M., & Vanutelli, M. E. (2017b). Interbrains cooperation: Hyperscanning and self-perception in joint actions. *Journal of Clinical and Experimental Neuropsychology, 39*(6), 607–620.
Caldwell, D. F., & O'Reilly, C. A., III. (2003). The determinants of team-based innovation in organizations: The role of social influence. *Small Group Research, 34*(4), 497–517.
Cannon, D. M., & Edelman, J. (2019). *Prediction of design team performance on a conceptual design task using an automatable, topic-independent analysis of language use*. In ASME 2019 international design engineering technical conferences and computers and information in engineering conference. American Society of Mechanical Engineers Digital Collection.
Cha, K. M., & Lee, H. C. (2019). A novel qEEG measure of teamwork for human error analysis: An EEG hyperscanning study. *Nuclear Engineering and Technology, 51*(3), 683–691.
Cheng, X., Li, X., & Hu, Y. (2015). Synchronous brain activity during cooperative exchange depends on gender of partner: A fNIRS-based hyperscanning study. *Human Brain Mapping, 36*(6), 2039–2048.
Coan, J. A., & Gottman, J. M. (2007). The specific affect coding system (SPAFF). In *Handbook of emotion elicitation and assessment. Series in affective science*. Oxford: Oxford University Press.
Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage, 59*(3), 2430–2437.
Dai, R., et al. (2018). Holistic cognitive and neural processes: A fNIRS-hyperscanning study on interpersonal sensorimotor synchronization. *Social Cognitive and Affective Neuroscience, 13*(11), 1141–1154.
Dong, A., Hill, A. W., & Agogino, A. M. (2004). A document analysis method for characterizing design team performance. *Journal of Mechanical Design, 126*, 378–385.
Duan, L., Dai, R., Xiao, X., Sun, P., Li, Z., & Zhu, C. (2015). Cluster imaging of multi-brain networks (CIMBN): A general framework for hyperscanning and modeling a group of interacting brains. *Frontiers in Neuroscience, 9*, 267.
Dumas, G., Nadel, J., Soussignan, R., Martinerie, J., & Garnero, L. (2010). Inter-brain synchronization during social interaction. *PloS one, 5*(8), e12166
Dumas, G., Lachat, F., Martinerie, J., Nadel, J., & George, N. (2011). From social behaviour to brain synchronization: Review and perspectives in hyperscanning. *IRBM, 32*(1), 48–53.
Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., et al. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping, 30*(3), 734–748.
Funane, T., Kiguchi, M., Atsumori, H., Sato, H., Kubota, K., & Koizumi, H. (2011). Synchronous activity of two people's prefrontal cortices during a cooperative task measured by simultaneous near-infrared spectroscopy. *Journal of Biomedical Optics, 16*(7), 077011.
Gebert, D., Boerner, S., & Kearney, E. (2006). Cross-functionality and innovation in new product development teams: A dilemmatic structure and its consequences for the management of diversity. *European Journal of Work and Organizational Psychology, 15*(4), 431–458.
Gonen-Yaacovi, G., De Souza, L. C., Levy, R., Urbanski, M., Josse, G., & Volle, E. (2013). Rostral and caudal prefrontal contribution to creativity: A meta-analysis of functional imaging data. *Frontiers in Human Neuroscience, 7*, 465.
Guilford, J. P. (1967). *The nature of human intelligence*. New York: McGraw-Hill.
Gvirts, H. Z., & Perlmutter, R. (2019). What guides us to neurally and behaviorally align with anyone specific? A neurobiological model based on fNIRS hyperscanning studies. *The Neuroscientist, 26*(2), 108–116.

Holper, L., Scholkmann, F., & Wolf, M. (2012). Between-brain connectivity during imitation measured by fNIRS. *NeuroImage, 63*, 212–222. https://doi.org/10.1016/j.neuroimage.2012.06.028.
Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics, 48*(10), D280–D298.
Jiang, J., Dai, B., Peng, D., Zhu, C., Liu, L., & Lu, C. (2012). Neural synchronization during face-to-face communication. *Journal of Neuroscience, 32*(45), 16064–16069.
Jung, M., Chong, J., & Leifer, L. (2012). Group hedonic balance and pair programming performance: Affective interaction dynamics as indicators of performance. In: *Proceedings of the 2012 ACM annual conference on Human factors in computing systems* (pp. 829–838).
Köppen, E., & Meinel, C. (2015). Empathy via design thinking: Creation of sense and knowledge. In *Design thinking research* (pp. 15–28). Cham: Springer.
Kress, G., & Schar, M. (2011) Initial conditions: The structure and composition of effective design teams. In *Proceedings of the 18th international conference on Engineering design (ICED11)* (Vol. 7, pp. 353–361).
Kress, G., Steinert, M., & Price, T. (2012, March). *Cognition as a measure of team diversity*. In 2012 2nd interdisciplinary engineering design education conference (IEDEC) (pp. 67–72). IEEE.
Lachat, F., Hugueville, L., Lemarechal, J. D., Conty, L., & George, N. (2012). Oscillatory brain correlates of live joint attention: A dual-EEG study. *Frontiers in Human Neuroscience, 6*, 156. https://doi.org/10.3389/fnhum.2012.00156.
Lasecki, W. S., Gordon, M., Koutra, D., Jung, M. F., Dow, S. P., & Bigham, J. P. (2014, October). Glance: Rapidly coding behavioral video with the crowd. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (pp. 551–562). ACM.
Leifer, L., & Meinel, C. (2018). Introduction: Reflections on working together—Through and beyond design thinking. In *Design thinking research* (pp. 1–12). Cham: Springer.
Leifer, L. J., & Steinert, M. (2011). Dancing with ambiguity: Causality behavior, design thinking, and triple-loop-learning. *Information Knowledge Systems Management, 10*(1–4), 151–173.
Liu, N., Mok, C., Witt, E. E., Pradhan, A. H., Chen, J. E., & Reiss, A. L. (2016). NIRS-based hyperscanning reveals inter-brain neural synchronization during cooperative Jenga game with face-to-face communication. *Frontiers in Human Neuroscience, 10*, 82.
Liu, T., Saito, G., Lin, C., & Saito, H. (2017). Inter-brain network underlying turn-based cooperation and competition: A hyperscanning study using near-infrared spectroscopy. *Scientific Reports, 7*(1), 8684.
Mayseless, N., Hawthorne, G., & Reiss, A. L. (2019). Real-life creative problem solving in teams: fNIRS based hyperscanning study. *NeuroImage, 203*, 116161.
Miller, J. G., Vrtička, P., Cui, X., Shrestha, S., Hosseini, S. H., Baker, J. M., & Reiss, A. L. (2019). Inter-brain synchrony in mother-child dyads during cooperation: An fNIRS hyperscanning study. *Neuropsychologia, 124*, 117–124.
Molavi, B., & Dumont, G. A. (2012). Wavelet-based motion artifact removal for functional near-infrared spectroscopy. *Physiological Measurement, 33*(2), 259.
Monden, Y., Dan, H., Nagashima, M., Dan, I., Tsuzuki, D., Kyutoku, Y., et al. (2012). Right prefrontal activation as a neuro-functional biomarker for monitoring acute effects of methylphenidate in ADHD children: An fNIRS study. *NeuroImage: Clinical, 1*(1), 131–140.
Mønster, D., Håkonsson, D. D., Eskildsen, J. K., & Wallot, S. (2016). Physiological evidence of interpersonal dynamics in a cooperative production task. *Physiology and Behavior, 156*, 24–34.
Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., et al. (2002). Hyperscanning: Simultaneous fMRI during linked social interactions. *NeuroImage, 16*(4), 1159–64. https://doi.org/0.100/img.2002.1150.
Mu, Y., Cerritos, C., & Khan, F. (2018). Neural mechanisms underlying interpersonal coordination: A review of hyperscanning research. *Social and Personality Psychology Compass, 12*(11), e12421.

Nissen, H. A., Evald, M. R., & Clarke, A. H. (2014). Knowledge sharing in heterogeneous teams through collaboration and cooperation: Exemplified through Public–Private-Innovation partnerships. *Industrial Marketing Management, 43*(3), 473–482.

Nozawa, T., Sasaki, Y., Sakaki, K., Yokoyama, R., & Kawashima, R. (2016). Interpersonal frontopolar neural synchronization in group communication: An exploration toward fNIRS hyperscanning of natural interactions. *NeuroImage, 133*, 484–497.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., et al. (2004). Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10–20 system oriented for transcranial functional brain mapping. *NeuroImage, 21*(1), 99–111.

Osaka, N., Minamoto, T., Yaoi, K., Azuma, M., Shimada, Y. M., & Osaka, M. (2015). How two brains make one synchronized mind in the inferior frontal cortex: fNIRS-based hyperscanning during cooperative singing. *Frontiers in Psychology, 6*, 1811.

Pan, Y., Cheng, X., Zhang, Z., Li, X., & Hu, Y. (2017). Cooperation in lovers: An f NIRS-based hyperscanning study. *Human Brain Mapping, 38*(2), 831–841.

Saito, D. N., Tanabe, H. C., Izuma, K., Hayashi, M. J., Morito, Y., Komeda, H., et al. (2010). "Stay tuned": Inter-individual neural synchronization during mutual gaze and joint attention. *Frontiers in Integrative Neuroscience, 4*, 127.

Sarker, S., & Sarker, S. (2009). Exploring agility in distributed information systems development teams: An interpretive study in an offshoring context. *Information Systems Research, 20*(3), 440–461.

Sjöman, H., Steinert, M., Kress, G., & Vignoli, M. (2015, July 27–30). Dynamically capturing engineering team interactions with wearable technology. In *DS 80-11 proceedings of the 20th international conference on Engineering design (ICED 15) Vol 11: Human behaviour in design, design education*, Milan (pp. 153–162).

Sonalkar, N., Mabogunje, A., & Leifer, L. (2013). Developing a visual representation to characterize moment-to-moment concept generation in design teams. *International Journal of Design Creativity and Innovation, 1*(2), 93–108.

Strangman, G. E., Li, Z., & Zhang, Q. (2013). Depth sensitivity and source-detector separations for near infrared spectroscopy based on the Colin27 brain template. *PLoS One, 8*(8), e66319.

Tang, J. C. (1991). Findings from observational studies of collaborative work. *International Journal of Man-Machine Studies, 34*(2), 143–160.

Toppi, J., Borghini, G., Petti, M., He, E. J., De Giusti, V., He, B., et al. (2016). Investigating cooperative behavior in ecological settings: An EEG hyperscanning study. *PLoS One, 11*(4), e0154236.

Torrance, E. P. (1974). *The Torrance tests of creative thinking-TTCT Manual and Scoring Guide: Verbal test A, figural test*. Lexington, KY: Ginn.

Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society, 79*(1), 61–78.

Vanutelli, M. E., Nandrino, J. L., & Balconi, M. (2016). The boundaries of cooperation: Sharing and coupling from ethology to neuroscience. *Neuropsychological Trends, 19*, 83–104.

Wang, M. Y., Luan, P., Zhang, J., Xiang, Y. T., Niu, H., & Yuan, Z. (2018). Concurrent mapping of brain activation from multiple subjects during social interaction by hyperscanning: A mini-review. *Quantitative Imaging in Medicine and Surgery, 8*(8), 819.

Wechsler, D. (2011). *WASI-II: Wechsler abbreviated scale of intelligence*. PsychCorp.

Weingart, L. R., Olekalns, M., & Smith, P. L. (2005). Quantitative coding of negotiation behavior. *International Negotiation, 3*(9), 441–456.

Woolley, W. A., Hackman, R. J., Jerde, T. E., Chabris, C. F., Bennett, S. L., & Kosslyn, S. M. (2007). Using brain-based measures to compose teams: How individual capabilities and team collaboration strategies jointly shape performance. *Social Neuroscience, 2*(2), 96–105.

Wyatt, J., Delpy, D., Cope, M., Wray, S., & Reynolds, E. (1986). Quantification of cerebral oxygenation and haemodynamics in sick newborn infants by near infrared spectrophotometry. *The Lancet, 328*(8515), 1063–1066.

# Organizational Learning Through a Process of Framing Orientations in Group Discourses

**Andrea Rhinow, Holger Rhinow, Claudia Nicolai, and Ulrich Weinberg**

**Abstract** In this paper we endeavor to explore how organizational learning unfolds on the level of group discourses.

Research in organizational learning ranges from small groups to large corporations. A useful framework to observe organizational learning is the exploration-exploitation concept by James March (Organization Science 2(1):71–87, 1991). Studies that are based on this concept primarily focus on the analysis of learning as an explorative activity that creates specific outcomes, for example new ideas, products, and strategies. In addition, another concept by Nonaka et al. 1996 describes organizational learning as a spiral between the modes of externalization, combination, internalization, and socialization between individuals, groups and the organization as a whole (SECI model). How this learning process is unfolding within those levels is rarely described, which is why our focus is on an analysis of learning processes as they occur in situ, at the level of group discourses.

The authors analyzed video material from various group sessions and applied the documentary method (Bohnsack, Qualitative analysis and documentary method in international educational research. B. Budrich, Opladen, 2010) as a method of reconstructive social research to explore learning in situ, as it unfolds in the interactional group discourse.

The authors argue that learning processes in group discourses are triggered by incongruences between frames of orientations of the individuals involved. However, not all incongruences initiate learning processes. Whether or not learning occurs, depends on the group's interactions—namely their ability and willingness to switch from a communicative to a meta-communicative level of their discussion. Only on this level of communication, are individual framings of orientations likely to be reflected, negotiated or even newly created.

The meta-communicative level is where learning as an explorative activity happens. In our examples, different orientations towards the next task of a group

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are discussed in various ways in order to get to a framing of the group's orientation towards that next task. In contrast, the communicative level is where an existing framing of the group's orientation towards the next task guides the execution process as exploitative activities.

This work can be regarded as a pre-study to our current work in progress: the analysis of group discourses to explore the effect of design thinking on learning in groups.

## 1 Organizational Learning on Group Discourses

Organizational learning is considered to be an important ability in the face of survival in turbulent times. Prior research illustrates how balancing organizational learning and execution can lead to structural changes as well as distinct novel outcomes, such as innovations that can potentially ensure an organization's mid- to long term survival (O'Reilly III and Tushman 2004).

What has remained vague in research up to now is how organizational learning empirically occurs at the level of interactions between individuals (in groups). Can we observe organizational learning in situ, as it happens? Can we find out what fosters or hinders organizational learning in group interactions? Answers to these questions may be relevant for understanding how organizations can improve their group- or teamwork to foster learning-related outcomes such as innovations.

Previous research on organizational learning is closely linked to the concept of exploration and exploitation (March 1991). In this concept, two distinct types of activities co-exist, yet also compete for the same resources, such as budget, focus or personal energy. Exploration comprises activities such as "search, variation, risk taking, play" and "innovation" (p. 71, ibid.). Exploitation on the other hand comprises activities like "refinement" or "execution" on "certainties" (ibid.).

In the context of the exploration-exploitation concept, organizational learning can be understood as a mode of exploration (March 1991). Learning leads to knowledge that is manifested in organizational "code" such as "instruction, indoctrination, and exemplification" (p. 74, ibid.). The model suggests that individual beliefs can contribute to the organizational code and thereby lead to organizational learning that is mutually shared by all individuals. Organizational learning thereby does not occur by way of one individual to another directly but indirectly through code (p. 75, ibid.). The model further suggests that learning is a form of adjusting an individual belief system by acknowledging that the current belief does not adequately capture reality.

The aspect of organizational learning in the exploration-exploitation concept (ibid.) is described in theory. Further research confirms the model by observing outcomes that would imply the existence of explorative and exploitative activities. For example, the invention of a new machine indicates that explorative activities occurred, while the refinement of an existing machine indicates that exploitative activities occurred (Levinthal and March 1981). In this concept the notion of learning is defined as an explorative activity. On the other hand, exploitative activities are based on the exploitation or application of previous learning processes inherent in existing personal or structural knowledge.

Previous empirical research offers various explanations at which level explorative and exploitative activities happen in organizations. These studies distinguish explorative and exploitative activities by comparing their outcomes. They argue, for example, that innovation projects or innovation units can be defined as temporary explorative activities while standard operating procedures are to be considered as permanent exploitative activities (Levinthal 1997; Baum et al. 2000; Burgelman 2002; Benner and Tushman 2002, 2003; He and Wong 2004; Siggelkow and Rivkin 2006). Other studies generalize the concept at the level of different investment strategies (Wadhwa and Kotha 2006) or the unique explorative nature of corporate ventures (Christensen 1998).

More recent studies take a slightly different approach by comparing explorative and exploitative outcomes at the level of group interactions (Taylor and Greve 2006; Le Bretton-Miller and Miller 2006). The studies suggest that groups that successfully manage to balance explorative and exploitative activities create more innovative outcomes than other groups and individuals (Taylor and Greve 2006). The difference in performance increases when groups have a more diverse working background (Taylor and Greve 2006). These studies conclude the existence of explorative and exploitative activities based on distinct outcomes.

In Nonaka et al. (1996) SECI model, organizational learning is primarily defined by a distinct process in which implicit individual knowledge is externalized, combined, internalized and socialized to become knowledge, manifested in structures, manuals, plans, objects. The externalization is crucial to ensure that knowledge becomes accessible to other individuals inside the organization. In this organizational context, knowledge-creation in companies “is not a specialized activity” anymore, but rather “a way of behaving, indeed, a way of being, in which everyone is a knowledge worker” (Nonaka 1991, p. 97).

The question remains how exactly “knowledge” (Nonaka et al. 1996) or “beliefs” (March 1991) move from being an implicit and cognitive entity into an explicit entity, which can be combined, internalized and socialized between individuals in a group and potentially translated into an updated version of the organizational “code” (ibid.), for example a new work task, a prototype for an idea or a process (see Scheer et al. 2012; Rhinow et al. 2012; Scheer et al. 2014), or a refined process that is openly available to other individuals.

## 2 Framing Orientations in Group Discourses

The research presented here aims to observe if and how organizational learning occurs at the level of interaction between individuals in groups. The first author of this paper therefore carried out in situ observations of group discourses in an organization. Her approach contrasts with the above-mentioned outcome-based observations, as it focuses on the modus operandi of group interactions. The modus operandi is documented in the groups discourse. The group participants might have had similar experiences towards their discussed topic or not (Przyborski 2004, p. 316), and therefore they might have similar orientations or not. Differences in orientations are referred to as incongruence of framing (Bohnsack 2010). The modus operandi of the group is based upon the groups' frame of orientation that becomes constitutional for the group (constitutional framing, Bohnsack 2020), and the organizational "code" (March 1991) of the group that eventually gets internalized and socialized (Nonaka et al. 1996). An incongruence of framing between group participants needs to be externalized and discussed on a meta-communicative level to get to a constitutional framing of the groups' orientation that guides their modus operandi.

Group discourses can illustrate four distinct framings of orientation:

1. **Introduced framings that remain implicit**: An implicitly introduced framing of orientation(s) that is successfully imposed on the group discourse without being reflected upon at a meta-communicative level—a hidden heteronomous framing (Bohnsack 2012).
2. **Introduced framings that become explicit**: An implicitly introduced framing of orientation(s) that becomes the subject of the groups' meta-communicative discourse. The group is now made aware of the introduced framing(s) and may for example favor one framing over another or simply explore and agree on the given framing—a heteronomous framing (Bohnsack 2012).
3. **A new framing of orientation that becomes explicit**: Groups can explicitly discuss and reflect upon incongruences and thereby jointly develop a new frame of orientation (combination of knowledge, Nonaka et al. 1996). The framing of a new orientation results from a discourse at a meta-communicative level within the group—a so-called *Rahmung* (Bohnsack 2012).
4. **A new framing of orientation that remains implicit:** Groups might generate new frames of orientation implicitly without explicitly formulating them (for example using latent interventions through coaching). Because of its subconscious character, such a frame remains undiscussed and implicit.

The act of following an introduced orientation without reflection would qualify as an exploitative activity—for example a group may execute a given task without debating its value or relevance.

In our empirical data of group discourses, we aim to reconstruct the way groups come to a constitutional framing of orientation.

The research is guided by the hypothesis that two sequential phases need to occur in order to enable organizational learning at the level of group discourses:

1. Phase of externalization of orientations: Orientations of individuals need to be externalized in order to be discussed on a meta-communicative level. Thereby incongruences of frames become explicit, which makes learning through mutual framing of a groups orientation possible. Introduced frames of orientation(s), but

also new frames of orientation, which remain implicit, would already inhibit a learning process in this phase.

2. Phase of framing of orientation: If orientations are made explicit on a meta-communicative level, they can be discussed on a meta-communicative level. A learning process occurs if the group either decides explicitly for an introduced framing or creates a new framing.

## 3 Data Collection

The following examples are part of a data collection conducted within a larger research project called "Visual Diagnostics" at the Hasso Plattner Institute in Potsdam. The video data exceeding a period of 3 years were collected from a variety of groups (500+ hours of video documenting group discourses) that collaborate within innovation and research projects at HPI School of Design Thinking (n = 14) and at the Charité Berlin (n = 6).

The video-analysis is part of a dissertation project in sociology that applies the documentary method (Bohnsack 2010) to reconstruct the discourse of groups working together in projects.

In the documentary method, the discourse of a group is regarded as a document of the groups' *modus operandi*. The research presented focuses on exploring different ways of learning in groups. Learning in groups is assumed to be guided by groups' *orientations* towards a specific topic that is discussed in their discourse.

The research presented here analyzes three examples of group discourses that are concerned around framing the next step of the project. All groups consist of four scientists, who came together in a group session to discuss the next steps of the project. Example A and B show the discourse of a group working around the topic of bone healing (group bone), whereas example C shows the discourse of a group working on a patient case of a slipped disc (group spine). For our purposes the topics are of minor interest, the process of learning is our main research interest here. As scientists, the group members are following individual goals that are meant to be helpful for their career path—some are doing their PhD, whereas others aspire to a publication, and again others are mainly interested in the reputation of the research project. These various motivations lead to all of the participants having different orientations that are incongruent to a certain degree. All three discourses occurred in ongoing projects, after previous tasks have been executed by individuals (exploitation). The examples illustrate different qualities in discourses. In example A the discourse stays at the communicative level, while in example B and C the respective discourses switch from a communicative to a meta-communicative level to discuss different orientations. Example B shows a discourse in which an individual orientation is neglected while example C shows how the group frames a new orientation.

Following the documentary method (Bohnsack 2010), reconstruction of a discourse is conducted in a two-step interpretation which includes:

1. transcribing the original data collected on video and audio using the transcription conventions (see below)
2. paraphrasing the discourse shown in parts of the original transcript through a so-called formulating interpretation
3. interpreting the discourse with regard to the process of learning and the mechanisms of externalizing and discussing incongruences through a so-called reflecting interpretation (Bohnsack 2010)
4. comparing the interpretation of all three examples, with conclusions made on the groups' process of organizational learning

Transcription Conventions

| | |
|---|---|
| └ | start of overlap onset |
| ┘ | *end of overlap onset* |
| *(.)* | *short pause under one second* |
| *( . . . )* | *short pause of three seconds* |
| *(x)* | *pause of (x) seconds* |
| *NEIN* | *upper case indicates shouting* |
| . | *stopping fall in tone, not necessarily end of sentence* |
| , | *rise in tone* |
| *?* | *high rise in tone* |
| *( )* | *unintelligible* |
| *[points to handout]* | *additional information provided by the researcher* |
| *Capital letters* | *indicate beginning of a new utterance [capital letters do not necessarily follow a full stop, as a full stop indicates a fall of intonation and not the end of a sentence]* |

(*adapted from* Przyborski 2004)

## 4 Three Ways of Framing Orientations Exemplified

The different examples illustrate three different group discourses captured on audio and transcribed following the transcription conventions (Przyborski 2004). In all three examples, groups discuss next steps in ongoing projects. Example A shows a group discourse in which an introduced framing remains implicit (*Verdeckte Fremdrahmung, i.e. hidden heteronomous framing*). Example B shows a group discourse in which two framings are being introduced, made explicit and a mutual decision is made in favor of one framing of orientation (*Fremdrahmung, i.e. heteronomous framing*). Example C shows a group discourse in which a new framing of orientation is created (*Rahmung, Framing*).

**Example A: Framing an Orientation for the Next Step of Developing a Strategy for Future Research**

The context of the following discourse took place at a regular group meeting. The preceding meeting was dedicated to mapping different future research options based on the participants' knowledge and existing research in their field of bone research. This mapping was summarized on a handout for this session.

Example A starts with a description of the agenda of that session introduced by Maria (1–9), the organizer of this session. According to Maria, the main agenda point is to reflect on the outcome of the last session (4), which she provided as a handout summarizing the options for next steps discussed by the group in the last meeting (5), and to agree on this or edit the handout if needed (6–9).

1 Maria Wir haben im Grunde genommen heut [folgendes] auf der Agenda, wir
2 haben heute nicht Zeit alles zu machen, ich würde trotzdem gerne
3 beides anreißen (.) die Sache ist, dass hatten wir schon ne ganze Weile
4 vor eh einmal noch die [letzte Sitzung] zum Abschluß zu bringen.
5 [Maria shares a handout of the last session with the group]
6 vielleicht guckt ihr euch das einfach kurz an und dann (.) können wir
7 vielleicht darüber sprechen ob ihr damit einverstanden seid und das
8 auch so seht oder ob ihr da ganz andere Sachen mitgenommen habt aus
9 dem letzten Treffen.

*Tentative translation into English:*

*1 Maria Today, we have, more or less, the following on our agenda. we*
*2 don't have time to finish it all, but I would like to*
*3 touch on both things (.) for a while now, we would like*
*4 to bring the last session to finalization.*
*5 [Maria shares a handout of the last session with the group]*
*6 Maybe you can take a quick look at this (.) so that we*
*7 can talk about if you agree with the contents or*
*8 if you have any different takeaways*
*9 from the last session*

Maria's proposal is followed by Tom asking for clarification (10). Tom wants to know exactly what Maria is asking from the group. Maria repeats her proposal in more detail by describing the handout of the last meeting outcome she wants the group to revisit (11–12).

10 Tom ((räuspern)) Was möchtest du jetzt genau wissen?
11 Maria Aehm, guck mal in dem handout habe ich es für euch nochmal
12 aufgezeigt . . . [Maria ergänzt weitere Erklärungen zum handout]

*Tentative translation into English:*

*10 Tom ((clears his throat)) So, what do you want to know exactly?*
*11 Maria Um, look at the handout where I tried to*
*12 show what we did . . . [Maria continues to elaborate on the handout]*

At this point Frank interrupts Maria (13). Frank wants to skip Maria's proposal (14) and already starts to discuss the upcoming publications by addressing Beate as well (15–19). Frank thereby stops the group from reflecting on their options about their program strategy provided in the handout and proposed by Maria before (1–9). He directly turns the discourse towards one of the options that is based on their strategy on comments from a journal on their latest publication (20–22). Beate joins in on Frank's proposal by providing information about that rejected publication (23–25). Tom also joins in on Frank's proposal by validating Beate's information (26).

| | |
|---|---|
| 13 Frank | Also ich ((räusper)) (2) also son bisschen würde ich da jetzt vielleicht |
| 14 | lieber diesen blöden Punkt ja jetzt erstmal auslassen um loslegen |
| 15 | zu können, und so ein bisschen aufzuräumen. ähm, Beate, wir warten |
| 16 | jetzt auf die Reaktionen von ähm, den Reviewern, |
| 17 | heisst wir haben das Paper da eingereicht ähm oder du reichst es gerade |
| 18 | ein, ne? |
| 19 Beate | Ja |
| 20 Frank | [das andere Paper ist jetzt abgelehnt worden mit der Begründung] weil |
| 21 | ähm im Prinzip ist doch alles sowieso schon bekannt und warum wir |
| 22 | uns überhaupt noch mit solchen Fragen jetzt beschäftigen. (.) |
| 23 Beate | Ja (.) also vor allem weil es [die Forschungsfragen] ja klinisch ja bekannt ist hat |
| 24 | sie das halt nicht so interessiert das genauer anzuschauen. also den hats gereicht |
| 25 | das mans radiologisch sieht [und nicht wissenschaftlich begründet] |
| 26 Tom | Ja genau |

*Tentative translation into English:*

| | |
|---|---|
| *13 Frank* | *So for me ((clears throat)) (2), I would like to maybe to* |
| *14* | *leave out this silly point for now and actually get started. um, Beate, we are* |
| *15* | *now waiting* |
| *16* | *for the reviewers' reactions um that means we already sent it the paper* |
| *17* | *um, or you are going to send it in* |
| *18* | *right?* |
| *19 Beate* | *Yes* |
| *20 Frank* | *[the other paper was rejected with the comment] because* |
| *21* | *um in principle everything is known already and so why do we* |
| *22* | *bother with working on those questions anyway. (.)* |
| *23 Beate* | *Yes (.) in particular because it [the research questions] is clinically known al* |
| *24* | *ready, so they didn't find it interesting to look into them further. so for them it* |
| *25* | *was enough to be able to see it radiologically [without scientific investigation]* |
| *26 Tom* | *Yes exactly* |

**Interpretation of Example A**

Example A begins with a proposal to initiate a meta-communicative discourse that would allow every group member to externalize his or her orientation towards the next steps of the project. Maria asks everyone to share their orientation, which can be understood as a proposal to jointly explore the situation (and the different orientations) with regard to framing possible next steps.

While Maria argues for a discourse on a meta-communicative level on previous group results that describe potential next steps, Frank argues for and decides upon taking a discourse on a communicative level that focuses on a previously defined option—following the comments of a reviewer. The incongruence between the two orientations remains implicit as neither Maria nor Frank provide reasoning to their propositions or bring their different orientations to explication. The group joins in Frank's orientation by discussing their publications and the comments of the reviewer in more detail. The group does not explore the different orientations of the group represented in the options laid out in the handout and (re-)enters exploit mode.

If the group had declined Frank's orientation and followed Maria's proposal of a meta-communicative discourse on framing the next step, the group would have jointly explored their options, thereby learning from each other's orientations, instead of following a dominant orientation without getting to know the others orientations at all. A jointly generated framing of the next step would have been the result. However, this mode would have only been possible if the other participants' would have contributed their orientation actively in a more time consuming discussion and with the need for more resources. The work of the preceding session, in which options for next steps represented in the handout were jointly discussed, could also be considered a left out opportunity for an explorative follow-up activity where participants learn from each other's orientations. Instead Frank's dominant orientation frames the discourse of the group and gets them directly into exploit mode.

In summary, example A illustrates an incongruence about which orientations should guide the framing of the next task for the project. Maria proposes discussing the groups' orientation on a meta-communicative level, whereas Frank wants to base it on the comments of reviewers of a journal. Frank chooses his orientation for the group by opening up the discussion about those reviewer comments, which is followed by Tom and Beate. In this way, the group does not discuss their options—meaning their potentially different orientations, on a meta-communicative level. The group's orientation is framed by Frank, which we call a dominance of framing. The implicit framing remains implicit as the consecutive discourse is guided by this framing of orientation—a so-called *verdeckte Fremdrahmung*, i.e. a hidden heteronomous framing, based on a dominance of framing also referred to as *Rahmungsmacht* (Bohnsack 2017) (Table 1).

**Table 1** Example A—Framing of an orientation for the next step of developing a Strategy for Future Research

| Example A | Continuous exploitation/task orientation through implicit introduction | | |
|---|---|---|---|
| Sequence | Communication of orientation #1 | Communication of orientation #2 | Implicit introduction of #2 by dominance of framing |
| Content | "… I would like to touch on both things …" (Line 2/3) | "… I would like to leave out this silly point for now and actually get started." (Line 13/14) | "… in principle everything is known already."—"Yes" (Line 21–23) |

**Example B: Framing an Orientation for the Next Step Within a Specific Project**
Example B shows the same *group bone* at a later stage of the same meeting as in example A. The group is discussing a new topic, which is the next step in a specific project of Tom's.

The example starts with Tom proposing a method he would like to try out within his project with his materials (1–2). He also states that his proposed method was already used by a colleague, Amelie, with her model (1–2).

1 Tom Ich würde was Amelie macht, mit ihrem Modell, auch nochmal mit
2 anderen Materialien, die hier schon eingesetzt wurden (.) nochmal angucken.

*Tentative translation into English:*

*1 Tom I would like to do the same as Amelie did with her model, but I would like to look at it*
*2 using other materials than those that were already used (.)*

Frank reacts by indicating a problem that would occur with the metal Tom uses (3–5). Beate seemingly confirms Frank's reaction (6). Frank repeats his doubts on using the same method as Amelie, saying that using the metal againwould cause "too much bias" (7–8).

3 Frank Das Problem ist also mit Metall sind wir da am Ende unserer Möglichkeiten
4 wir kommen nicht zu der Auswertmöglichkeit so sehe ich das so habe ich das
5 vorhin verstanden?
6 Beate └ ja ja also … ┘
7 Frank wir kommen nicht zu der Auswertmöglichkeit die ähm Amelie hat weil wir
8 einfach zu viel ähm bias durch das Metall

*Tentative translation into English:*

*3 Frank The problem is with using metal is that we run out of possibilities*
*4 and we don't achieve our evaluation possibilities, as I understand it.*

*5 that's how I understood it earlier.*
*6 Beate └ Yes, yes so . . . ┘*
*7 Frank we are not getting to the same analysis as Amelie did*
*8 because of too much bias resulting from using the metal*

Tom points out that it would still be worthwhile as one could get insights about the characteristics of the material, e.g. the structure of the collagen (9). Tom elaborates on how such insights can be made by adding information about the material interaction of the collagen and minerals (10–14). Beate agrees repeatedly (13/15). This leads Frank to ask specific questions about the material in order to understand Tom's idea of generating insights through the use of Amelie's method (16/19/21/23). Tom answers and elaborates on the project status (17–18/20/22/24–25). Finally, Frank validates Tom's proposal (26).

9 Tom Aber wir können die Kollagenkomponentenstruktur uns angucken. wir wissen
10 dass das Mineral (.) eine gewisse, also das ein die Orientierung des Kollagens
11 meistens mit der Orientierung der Mineralfläche übereinstimmt ( . . . ) das ist halt
12 extrem aufwendig bei den großen Poren, aber ich glaube da könnte man auch
13 Beate ja
14 Tom einiges rausholen
15 Beate ja
16 Frank Also sehr viel größer glaubst du gehen die [die Poren] nicht?
17 Tom Nee, die gehen definitiv nicht sehr viel größer man kommt vielleicht bis 150
18 Mikrometer und dann ist Schluss
19 Frank Und jetzt sind wir bei 100?
20 Tom Jetzt sind wir bei 110 ja
21 Frank 110. Aber die hattest du jetzt als optimal dargestellt?
22 Tom Ja
23 Frank oder willst du jetzt auch 150 noch testen?
24 Tom Das diskutieren wir jetzt ob das überhaupt möglich ist, weil das ja heisst dass
25 der Herstellungsprozess geändert werden muss
26 Frank └ Mhm (bejahend), ok ┘ dann machen wir es so

*Tentative translation into English:*

*9 Tom But we can have a look at the structure of the collagen. we know that*
*10 the mineral (.) has got a certain, so the orientation of the collagen*
*11 is identical to the orientation of the structure of the mineral ( . . . ) that is*
*12 extremely complex in regard to the size of the pores, but I also think one could*

*Beate Yes*
*Tom get something out of it*
*Beate Yes*
*Frank So you don't think that they [the pores] can get much bigger?*
*Tom No, they are definitely not getting bigger. maybe up to 150 micrometer and that's it*
*Frank And currently we are at 100?*
*Tom Currently we are at 110.*
*Frank 110. But you have shown this as the optimum?*
*Tom Yes*
*Frank Or do you want to test the 150 as well?*
*Tom We are now discussing if this is actually possible because it would mean that we would have to change the process*
*Frank └ Mhm (validating), ok ┘ let's do it then*

**Interpretation of Example B**

The incongruence of orientations towards what would be the next step of the experiment is accompanied by a knowledge gap between individual participants. This gap becomes explicit and aligned through questioning and answering between the group members.

Example B illustrates how different levels of knowledge towards a project might lead to different orientations towards the project's next step. The participants regard possible outcomes differently based on knowledge that is initially exclusive for Tom and later shared with Frank and other participants. Tom knows aspects of the material that led him to envision certain outcomes when using his proposed method. On the other hand, Frank envisions the outcome differently, even problematically, until Tom shares his knowledge about the material and elaborates on his vision of the outcome. Tom and Frank achieve a shared understanding of the material and the use of the method through Frank's knowledge of Tom's orientation gained by using a discourse organization of questions and answers. Tom and Frank end with a mutual agreement on the usefulness of the proposed method through their established, shared understanding.

The discourse to get to this shared understanding of the orientation is characterized by an externalization of the different orientations and an agreement to favor one of the introduced orientations as the framing for the group. In this way, the group gets to learn and understand all orientations involved. In this example, the framing was reached by a discussion on the meta-communicative level through a sequence of questions and answers. Another possibility would have been to base the framing of the next step on either Tom or Frank's orientation without discussing each orientation on a meta-communicative level, simply through trust or dominance. This would leave the other party doubtful about the decision.

This example illustrates the generation of a congruence of frames by heteronomous framing (Bohnsack 2012). Two framings of orientation are being presented and discussed at a meta-communicative level. Different individuals

**Table 2** Example B—Framing of an orientation for the next step within a specific project

| Example B | Temporary exploration/learning through agreement on an orientation | | | |
|---|---|---|---|---|
| Sequence | Communication of orientation #1 | Communication of orientation #2 | Discussion on meta-communicative level | Agreement on orientation #1 |
| Content | "I would like to do the same as Amelie did ... with other materials" (Line 1/2) | "The problem is with using metal is that we run out of possibilities" (Line 3–5) | "But we can have a look at the structure of the collagen" (Line 9) und "So you don't think that they can get much bigger?" (Line 16) | "We are now discussing if this is possible because it would mean that we have to change the process." "Mh, ok" (Line 24–26) |

compare and finally decide to agree upon one framing in favor of another framing (Table 2).

**Example C: Framing an Orientation for the Next Step of Tackling a Specific (Patient) Case**

The group works on a patient case given through a task description sheet (including the background of the patient) by the initiator of the project. The group previously separated into subgroups with the goal of finding out what is needed to tackle the patient case. The discourse begins right after the group meets again to share results.

One sub-group, Moh and Bibi share their outcome with the other sub-group Sebastian and Ole. Moh begins by describing what is needed to tackle the patient case. They present the patient information, and the problems of the patient's disease (1–4). Bibi confirms Moh's proposal through repetition (5).

1 Moh First we need um (.) to get some information ( . . . ) I think we should have
2 this before the um (.) [looking at Bibi] first we need some
3 information um about the patient and um the background and symptoms
4 of the pain. and then we should um (.) get the problems (.)
5 Bibi oh yes, the problems um

Sebastian interrupts by stating that there is not any more information available, except for the information given in the task description sheet (6–7). Moh clarifies his statement by indicating towards the information on the task sheet (8–9). Sebastian presses Moh and Bibi to provide an answer on how to tackle the patient case (10–11).

6 Sebastian Sorry to interrupt, but we won't get more information about the
7 patient.
8 Moh No, [I mean] this information [points to a task sheet with information about the
9 patient given in the case]

| | |
|---|---|
| 10 Sebastian | I can totally follow you, but my question is what are you doing about |
| 11 | it? |

Moh is about to introduce what Bibi and he came up with (12), when Bibi interrupts him. She states that they came up with a description of a process on how to develop a treatment (13–14). Sebastian summarizes what he thinks Moh and Bibi did as being “project management” (15–16), which is validated by Bibi (17). Sebastian continues to say that what he expected the two to do was to “check for the treatment” and “indicate a direction” for the group to continue working on while giving background information on the usefulness of that direction (18–20).

| | |
|---|---|
| 12 Moh | First we |
| 13 Bibi | Um, we did the working um working process [points to paper with their |
| 14 | notes] |
| 15 Sebastian | Basically you guys did project management (.) so that we are clear on |
| 16 | what we are doing |
| 17 Bibi | Yes |
| 18 Sebastian | But I did actually (.) somehow expect that you guys [would] check on the |
| 19 | treatment and indicate which direction we go and say what you already |
| 20 | determined, giving reasons |

Ole joins in and points out that they should now at least “focus on the treatment step” (21). Moh reacts to Ole’s suggestion by pointing out the “treatment step” in his process model (22–23). Sebastian reacts with seeming impatience by stating loudly that he “KNOWS” (24). To him, there is a misunderstanding of the task between the two sub-groups (25–26). Moh reacts by repeating his understanding of the task as following the steps of the process to get treatment, which starts with getting information about the patient and his symptoms (27). Sebastian states that for him this task has already been done (28).

| | |
|---|---|
| 21 Ole | But NOW we should actually focus here on the treatment step |
| 22 Moh | We are here [pointing to the step treatment in his graphic]. we should |
| 23 | get the treatment. |
| 24 Sebastian | I KNOW, but I’m just trying to get a grasp of what you did, because I |
| 25 | am a bit afraid at the moment that both of our sides totally |
| 26 | misunderstand what our target is here. |
| 27 Moh | We should follow these steps to describe the patient and symptoms |
| 28 Sebastian | I thought we did that already? |

Bibi clarifies why Moh and her came up with the description of the process model (29–30). Now, Sebastian builds on Bibi’s statement by suggesting they use their process as an argument for a later solution (31–32). Moh validates Sebastian’s new thought and proposes to now work on the actual treatment together (33). Ole and Sebastian confirm (34–35).

| | |
|---|---|
| 29 Bibi | So, we have done this because in this book there is a working example |
| 30 | on how to solve a disease, and this process is described here. |
| 31 Sebastian | Ok, so we can use this to argue for why we come up with a specific |
| 32 | solution. |
| 33 Moh | Yes, so should we work on the solution now? What do you say? |
| 34 Ole | Yes |
| 35 Sebastian | [nodding his head] |

**Interpretation of Example C**

Example C shows an incongruence of task-orientation between two sub-groups, affecting the modus operandi of each sub-group, and represented in the following discourse between the two sub-groups. One sub-group worked on a process model for a future treatment solution. The other sub-group worked on the actual treatment solution. Only when they start to present their outcomes, the incongruence of the orientations towards the task becomes explicit. Through externalizing their different orientations, the other part of the group challenges the outcome through questioning. In order to solve their now explicit (task-) incongruence, the group elaborates on their orientations on the meta-communicative level until they get to a stage of understanding each other's task orientation. The state of understanding becomes apparent in a mutual decision to combine both orientations towards a new one, framing the group's next step: using the process model as an argumentation tool and now working on the treatment solution together.

This example shows how an implicit incongruence had an effect on the modus operandi, and finally on the expected outcomes of the two sub-groups. Through sharing their outcomes the incongruence became explicit and only then did the group overcome the incongruence through a discussion on the meta-communicative level by reasoning their orientations towards a shared understanding.

In summary, example C shows an explication of an incongruence about the task orientation of the sub-groups. This incongruence is explored through an externalization of different orientations. The incongruence becomes solved through a new framing of orientation that would result in an agreement—an integration (in Nonaka's words a combination) of two orientations. Example C illustrates a generation of a congruence of frames by integration (Bohnsack 2012)—a jointly created new framing of an orientation through a discourse at a meta-communicative level (Table 3).

## 5 Conclusion

The three examples illustrate how groups in similar situations deal with differences in orientations—incongruences of framing—differently.

**Table 3** Example C—Framing of an orientation for the next step of tackling a specific (patient) case

| Example C | Temporary exploration/learning through a creation of an orientation | | | |
|---|---|---|---|---|
| Sequence | Communication of orientation #1 | Communication of orientation #2 | Discussion on meta-communicative level | Creation of new orientation #3 |
| Content | "We did the working process" (Line 13) | "[I expected you to] check for the treatment" (Line 18/19) | "We have done this because in the book here . . . "(Line 29) | "We can use this [working process] for arguing . . . " and "We work on the solution treatment [afterwards]" (Lines 31–33) |

The discourse in example A exemplifies how an introduced framing of an orientation remains implicit and is not discussed on a meta-communicative level. Instead, the group's discourse is implicitly guided by an introduced framing—a so-called *verdeckte Fremdrahmung, i.e. hidden heteronomous framing*—by one person of the group (Frank). The opportunity to compare the orientation with another orientation is dismissed, as well as the chance to frame a new orientation altogether.

Example B illustrates how two introduced frames or orientations are made explicit and get discussed on a meta-communicative level. The group eventually agrees to favor one introduced framing of orientation after elaborating on both of their incongruences—a generation of a congruence of frames by heteronomous framing. All individuals that were involved in the discourse learned about others' orientation and their reasoning. One individual learned about his individual knowledge gaps and decided to eventually agree upon another framing of orientation where those knowledge gaps were answered through elaboration by the rest of the group. Another individual learned that the former individual would initially favor a different framing of orientation because crucial knowledge was not available to that individual.

Example C illustrates how a new framing of orientation was created through an agreement to combine two existing orientations. The group learned about its different orientations by discussing them on a meta-communicative level.

The group in example A is not learning, instead it is able to execute a given orientation or "belief" (March 1991). The group is exercising an exploitative activity. Both groups in example B and C are learning. They are having a meta-communicative discussion and are thereby exercising an explorative activity.

The examples indicate that organizational learning in group discourses is based on the successful execution of a sequential approach that comprises externalization and framing. The discourse in example A remains on a communicative level and is focused on exploitation. The learning process in examples B and C happens on a meta-communicative level and thereby temporarily changes its activities from exploitation to exploration.

The research elaborates on the idea of organizational learning as an explorative activity that can occur temporarily as groups switch from task-related discussions, on a communicative level, to reflection of their status quo on a meta-communicative level, at which framings of orientations are made explicit. Orientations can be congruent without the necessity of exploration, or they can be incongruent with a need for exploration to enable learning. Last, incongruences can stay implicit without any reflection on a meta-communicative level, which would mean that exploitation continues as some kind of business as usual.

Last but not least, for learning to happen externalization of orientations is obligatory, as is a discussion of those orientations on the meta-communicative level. The groups learning is represented in a mutually shared framing of the groups' orientation that was explicitly introduced and discussed on a meta-communicative level, or it could even be newly created through the groups' discussion. The latter accounts for what Nonaka et al. (1996) describe as a combination of explicit knowledge with other explicit knowledge in their SECI model of organizational learning. However, in our understanding, for learning to take place as an explorative activity on a group level a combination is not always necessary. Exploring different orientations (externalized knowledge, Nonaka et al.) and discussing them on a meta-communicative level within the group to get to the groups (constitutional) framing by jointly preferring one orientation over the other (as in example B) accounts for the groups' learning about each other's orientations, even when the different orientations are not combined.

Based on these findings, our upcoming research is going to reconstruct group discourses in projects in which design thinking as an institutional framing is influencing the modus operandi of the group. Considering explication of orientations as a key element of design thinking methodology, a major influence on the mode of framing orientations can be hypothesized.

## References

Baum, J. A. C., Li, S. X., & Usher, J. M. (2000). Making the next move: How experiential and vicarious learning shape the locations of chains' acquisitions. *Administrative Science Quarterly, 45*(4), 766–801.

Benner, M. J., & Tushman, M. (2002). Process management and technological innovation: A longitudinal study of the photography and paint industries. *Administrative Science Quarterly, 47*(4), 676–707.

Benner, M. J., & Tushman, M. (2003). Exploitation, exploration, and process management: The productivity dilemma revisited. *Academy of Management Review, 28*(2), 238–256.

Bohnsack, R. (2010). Documentary method and group discussions. In R. Bohnsack, N. Pfaff, & W. Weller (Eds.), *Qualitative analysis and documentary method in international educational research* (pp. 99–124). Opladen: B. Budrich. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-317339.

Bohnsack, R. (2012). Orientierungsschemata, Orientierungsrahmen und Habitus. In K. Schittenhelm (Ed.), *Qualitative Bildungs- und Arbeitsmarktforschung* (pp. 119–153). Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-531-94119-6_5.

Bohnsack, R. (2017). Praxeologische Wissenssoziologie. Opladen/Toronto.

Bohnsack, R. (2020). *Professionalisierung in praxeologischer Perspektive*. Opladen/Toronto: utb/Barbara Budrich.

Burgelman, R. A. (2002). Strategy as vector and the inertia of coevolutionary lock-in. *Administrative Science Quarterly, 47*(2), 325–357.

Christensen, C. M. (1998). The evolution of innovation. In R. Dorf (Ed.), *Technology management handbook*. Boca Raton, FL: CRC Press.

He, Z.-L., & Wong, P.-K. (2004). Exploration vs. exploitation: An empirical test of the ambidexterity hypothesis. *Organization Science, 15*(4), 375–497.

Le Breton-Miller, I., & Miller, D. (2006). Why do some family businesses out-compete? Governance, long-term orientations, and sustainable capability. *Entrepreneurship Theory and Practice, 30*(6), 731–746.

Levinthal, D. A. (1997). Adaptation on Rugged Landscapes. *Management Science, 43*(7), 895–1045.

Levinthal, D. A., & March, J. G. (1981). A model of adaptive organizational search. *Journal of Economic Behavior and Organization, 2*, 307–333.

March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization Science, 2*(1), 71–87. Special Issue: Organizational Learning: Papers in Honor of (and by) James G. March (1991).

Nonaka, I. (1991, November–December). The knowledge-creating company. *Harvard Business Review*.

Nonaka, I., Takeuchi, H., & Umemoto, K. (1996). A theory of organizational knowledge creation. *International Journal of Technology Management., 11*(7–8), 833–845.

O'Reilly, C. A., III, & Tushman, M (2004, April). The Ambidextrous Organization. *Harvard Business Review.*

Przyborski, A. (2004). *Gesprächsanalyse und dokumentarische Methode*. Qualitative Auswertung von Gesprächen, Gruppendiskussionen und anderen Diskursen. Wiesbaden.

Rhinow, H., Köppen, E., & Meinel, C. (2012, July). Prototypes as boundary objects in innovation processes. In *Conference Paper in the Proceedings of the 2012 International Conference on Design Research Society (DRS 2012)*, Bangkok.

Scheer, A. (now Rhinow), Menning, A., von Helldorf, E., Rhinow, H., & Nicolai, C. (2014). *The knowledge handling notation: Building an interface to design conversation diagnosis*. DTRS 10: Design Thinking Research Symposium 2014, Purdue University.

Scheer, A. (now Rhinow), Noweski, C., & Meinel, C. (2012). Transforming constructivist learning into action—Design thinking in education. *Design and Technology Education, 17*(3), 8–19.

Siggelkow, N., & Rivkin, J. W. (2006). When exploration backfires: Unintended consequences of multilevel organizational search. *Academy of Management Journal, 49*(4). https://doi.org/10.5465/amj.2006.22083053.

Taylor, A., & Greve, H. R. (2006). Superman or the fantastic four? Knowledge combination and experience in Innovative Teams. *Academy of Management Journal, 49*(4), 723–774.

Wadhwa, A., & Kotha, S. (2006). Knowledge creation through external venturing: Evidence from the telecommunications equipment manufacturing industry. *Academy of Management Journal, 49*(4), 819–835.

# Did It Have to End This Way? Understanding the Consistency of Team Fracture

**Mark E. Whiting, Allie Blaising, Chloe Barreau, Laura Fiuza, Nik Marda, Melissa Valentine, and Michael S. Bernstein**

**Abstract** Was a problematic team always doomed to frustration, or could it have ended another way? In this paper, we study the consistency of team fracture: a loss of team viability so severe that the team no longer wants to work together. Understanding whether team fracture is driven by the membership of the team, or by how their collaboration unfolded, motivates the design of interventions that either identify compatible teammates or ensure effective early interactions. We introduce an online experiment that reconvenes the same team without members realizing that they have worked together before, enabling us to temporarily erase previous team dynamics. Participants in our study completed a series of tasks across multiple teams, including one reconvened team, and privately blacklisted any teams that they would not want to work with again. We identify fractured teams as those blacklisted by half the members. We find that reconvened teams are strikingly polarized by task in the consistency of their fracture outcomes. On a creative task, teams might as well have been a completely different set of people: the same teams changed their fracture outcomes at a random chance rate. On a cognitive conflict and on an intellective task, the team instead replayed the same dynamics without realizing it, rarely changing their fracture outcomes. These results indicate that, for some tasks, team fracture can be strongly influenced by interactions in the first moments of a team's collaboration, and that interventions targeting these initial moments may be critical to scaffolding long-lasting teams.

## 1 Introduction

Each of us can remember a team that we would rather not work with again. While teams are a relational structure that can support complex interdependence (Hackman 1980; Van De Ven et al. 1976), successful interdependence requires that team

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members engage in behaviors that are discretionary, pro-social, non-programmed, and at times risky, including asking questions, revealing ignorance, ceding power, putting in extra effort, offering their own ideas, monitoring each other, and holding each other accountable (Edmondson 2012; Anderson and West 1998; Hoegl and Gemuenden 2001; Marks et al. 2005; Morrison et al. 2011). The result is that teams can be motivating and supportive—team members are trusted confidants all pulling together—or they can just as easily be demoralizing and unfair, when team members' fates are tied to others they cannot count on. In the latter case, people will resist, resent, or actively undermine teams (Langfred 2007; Mueller 1994; Sprigg et al. 2000; Vallas 2003). Ultimately, many members of the team may not want to work together again (Emery and Trist 1969).

What causes teams to no longer want to work together? In this paper we study this phenomenon, which we call *team fracture*. We define team fracture as a loss of a team's viability (Bell and Marentette 2011)—one that is so dramatic that collaborators do not want to work together again. In this paper, we focus on online teams, including virtual (remote) teams as well as teams of crowd workers, as a lens whose technological mediation allows us to study team fracture. These online teams are increasingly prevalent in the literature and in practice (Salehi and Bernstein 2018; Valentine et al. 2017; Lykourentzou et al. 2017; Kittur et al. 2013), and computer-mediated collaborations have been noted especially for their high levels of antisocial behavior and conflict (Daft and Lengel 1986; Cheng et al. 2017; Hinds and Bailey 2003; Suler 2004). Understanding the causes of team fracture in these environments helps us diagnose what can be done to avoid negative affective fallout, and to design platforms that help prevent it. For example, teams in organizations will sometimes fall into states of low viability. Whether or not fracture is inevitable given the people on a team, which would suggest the need to reform membership, or is avoidable, which would suggest the need for mediation and attempts to improve existing team dynamics, knowing more about the underlying causes of fracture will dramatically help teams achieve their goals and minimize friction.

Investigating fracture and its causes in online teams is central to broadening our understanding of computer-supported cooperative work (CSCW) toward a fuller understanding of the affective dimensions of collaboration that can make the team experience either a joy or an albatross. This perspective informs core questions in the CSCW community, including why distance matters (Olson and Olson 2000), why remote teams experience increased levels of conflict (Hinds and Bailey 2003), and how the future of crowd work might evolve (Kittur et al. 2013). The understanding also illuminates opportunities for design to scaffold and encourage behaviors in the initial moments of a team's collaboration that minimize the chances of fracture. For example, interventions might detect early predictors of fracture, suggest how a team can improve their language or behavior, or even help fractured teams repair their dynamics.

When a team fractures, members try to make sense of the unpleasant experience and are likely to make personal attributions about teammates: "he is too critical"; "she is too authoritative"; "they do not put in equal work"—with the implication that it would be impossible to ever succeed in a team with such individuals. Indeed, some research studies do suggest that some teams will reliably perform less well than others (Woolley et al. 2010). Are some teams doomed from the start? If it were possible to rewind time, reset the social dynamics, and try again, would the team get along better, or was the fracture inevitable given the people involved?

In this paper, we perform an online experiment that reconvenes teams a second time without them realizing that they have worked together before. Our method allows us to study the consistency of fracture when prior team dynamics are masked. We developed an online discussion system that performs a two-way masking of participants' identities (Fig. 1). In our experiment, participants are grouped into teams for a first task, then into new teams for a second task, a third team for a third task, and so on. Participants see their own pseudonyms as persistent across rounds in the discussion system. However, in reality, our system changes participants' pseudonyms each round and dynamically replaces any mentions (or near misses) of each others' pseudonyms. The result is that participants see their own identity as static and unchanging—leading them to assume the same of others—when, in reality, they are interacting with old teams under new pseudonyms. With participants thinking that this was a new group, the collaboration begins anew without strong attributions carried over. When participants are debriefed and told that two of the teams they worked with were in fact composed of the same people, they correctly guess at only slightly above chance rate (21.5% accuracy vs. 17% chance). We allowed team members to privately blacklist any of their teams from future interactions; if half of the members blacklisted a team, we recorded that team as fractured. We then measured whether the fracture outcome was consistent between the team's first and second convening. We replicate this design across three different tasks drawn from separate areas of McGrath's circumplex (McGrath 1984): a creative task, an intellective task, and a cognitive conflict task.

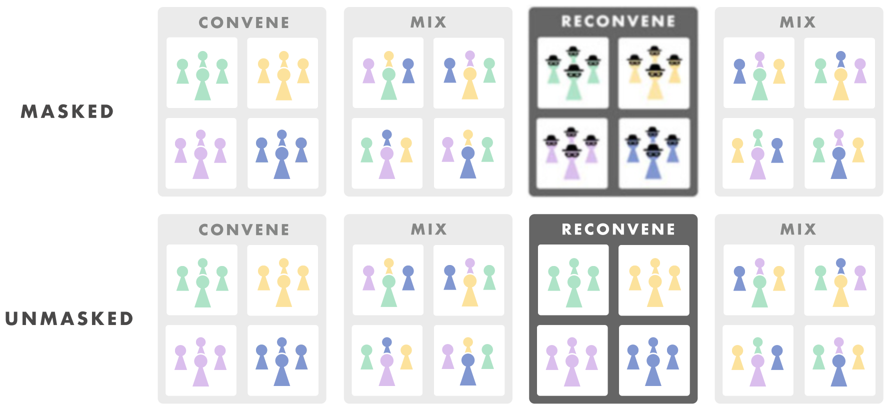


**Fig. 1** To evaluate the consistency of fracture, participants repeatedly collaborate in rounds. When reconvened with the same collaborators, identities are masked or unmasked via pseudonyms. Masked teams appear as a new collaboration, while unmasked ones revisit a previous collaboration

We find that the consistency of team fracture is strongly polarized by task. There appears to be little middle ground: tasks either result in extremely consistent fracture, or in extremely inconsistent fracture, even though team dynamics have been reset in all cases. For all tasks, teams in a control condition that use static pseudonyms, and thus retain a memory of their shared experience, are consistent 72–88% of the time. For the cognitive conflict task and intellective task, when the team dynamics are masked, teams almost always replay the same dynamics they developed last time without realizing it, resulting with consistent fracture outcomes 73% and 75% of the time, the same rate as unmasked teams. However, for the creative task, it might as well have been a completely different team: masked teams in the creative task only have consistent fracture outcomes 48% of the time—essentially changing their original fracture outcome at the same rate as a coin flip.

That team fracture consistency is so strongly polarized by task opens up substantial questions for CSCW. Performance can be substantially and stably predicted across tasks by team constructs such as collective intelligence (Woolley et al. 2010); however, it seems that fracture exhibits different patterns. In classic results on online collaboration (Olson and Olson 2000), task type is less commonly strongly theorized; our result suggests further emphasis on exploring how these results in computer-supported collaboration vary across task types.

Our result provides opportunities for designs to support improved team interaction. For tasks where fracture becomes reversible and path dependent, our result suggests that effective process and platform design can influence the outcome, and that team collaboration platforms (e.g., Slack) can have substantial effects on team viability. For example, on tasks similar to our creative task, teams must design their collaboration to be sensitive to how their early behaviors could cascade into positive or negative outcomes. A computational platform might, for example, help them keep tabs on behaviors associated with negative attributions. Further, ad-hoc teams drawn together rapidly from crowdsourcing marketplaces have attributed teams falling apart to team composition and membership errors (e.g. Lykourentzou et al. 2017; Salehi et al. 2017); our results suggest that for certain tasks, giving the team a fresh start might be as beneficial or even more beneficial than selective membership. In addition, this work suggests a clear need for theorizing the mechanisms that produce affective outcomes such as fracture. For example, platforms supporting creative work would benefit from scaffolds ensuring early pro-social situations, reducing the probability of fracture. Platforms that recruit ad-hoc or crowd teams may especially benefit from more effective rapid onboarding and team-forming.

## 2 Related Work

Team structures set up a complex interdependence (Hackman 1980; Van De Ven et al. 1976). Members share responsibility and credit for a joint outcome, and must coordinate efforts and combine ideas to accomplish that shared work (Aube and Rousseau 2005; Ilgen et al. 2005; Saavedra et al. 1993). Such open-ended interdependence is a risky and complex social relationship, and members of various teams end up with completely polarized experiences. On one hand, when the interdependence is met with a synergistic motivation or with mutually developmental ideation, the results can be better than a sum of the parts, and the team can become an affirming, productive social group to which members are excited to return (Gladstein 1984; Larson 2010). On the other hand, when members' time and rewards are so closely intertwined, then unequal effort or lack of respect can be particularly unpleasant, meaning team experiences can just as often deliver demoralizing injustices that have members swearing to never work together again (Flaherty and Moss 2007; Jehn and Mannix 2001; Brown et al. 2014; Valentine 2018; Langfred 2007). These experiences motivate our research question: When a team fractures, did it have to end that way?

**Research Question 1** *How consistent is team fracture when membership is fixed but existing attributions are erased?*

Many researchers have explored the potential and the social risk of working in teams, asking when and why some groups become cohesive and viable while others are characterized by betrayals so dramatic that members will not continue working together. This paper builds on the research literature examining these specific affective experiences working in teams. In this literature, *team viability* is defined as the capacity of a team to be sustainable and continue to succeed, and measures both the satisfaction of teammates with their membership and their behavioral intent to remain in the team (Bell and Marentette 2011; Cooperstein 2017; Hackman 1980). In this paper, we define *team fracture* as a related construct that operationalizes members' affective reaction to being part of a team with such low viability that members would choose not to continue collaborating. One reason that these and related variables are of interest is because they are correlated to, but not the same as, team performance (Mach et al. 2010; Barrick et al. 1998). Team performance variables measure task outcomes, such as quality, efficiency, or productivity (Dalton et al. 1998; LePine et al. 2008). Teams that are performing well often have high viability, but there are many conditions under which teams may perform well but still fracture, including toxic norms, seeming toxic personalities, bullying, overwork, unequal contribution, or performance pressure (Hoel et al. 2003; Driskell et al. 1999). Many of these factors are situational, but when a team begins to fall apart, members are likely to make personal attributions about teammates personalities being the underlying cause (Bell and Marentette 2011; Hackman 1980).

Team viability and team fracture are particularly relevant for online and virtual teams, but the relationship between known antecedents and team viability or team fracture are also moderated by computer-mediated communication (Olson and Olson 2000). Antecedents of in-person teams becoming cohesive with high viability include positive shared experience, member demographic similarity, and group prestige or entry difficulty (Beal et al. 2003; Bell 2007; Marks et al. 2001; Reagans et al. 2004). When team members share these properties, they often develop emergent emotional states of group belonging, group pride, and task commitment, states in which they want to continue their working relationship together (Cooperstein 2017; Tse and Dasborough 2008; Marks et al. 2001). However, online teams are often working under conditions that are not characterized by these known antecedents. They often lack in-person social cues about shared demographics or shared emotions, struggle more with emotional and social entrainment, use asynchronous communication, and in many cases are working together for the first time (Hinds and Bailey 2003; Zakaria et al. 2004). In these contexts, cohesion and viability often form through sparse social relationships, and thus emerge through members' interactions in online environments, for example as they use similar language or "bursty" communication pattern (Riedl and Woolley 2017; Gonzales et al. 2010).

This prior research provides some insight into the challenges to team viability, and the reasons why online teams might fracture. In this paper, we aim to integrate this research, which closely implicates the way that online groups interact to their ultimate viability or fracture, with team members' known propensity to make personal attributions for failed social interactions. If we hold all conditions constant, would the same online team always fracture? Is team fracture inevitable in some teams, as our tendencies toward personal attributions might suggest?

## *2.1 Interaction Patterns, Viability, and Fracture in Online Teams*

Prior research thus demonstrates that for online teams, group social outcomes such as cohesiveness, viability, and fracture emerge largely through their specific interactions, because their social relationships outside of these interactions are non-existent or limited. This general finding is intriguing because it suggests that if online team members can get their interactions right, they are likely to have an affirming social experience. But online teams are known to be rife with conflict and misunderstanding precisely because the interactions are so spare and lack so much context and social cuing (Hinds and Bailey 2003; Zakaria et al. 2004; Kankanhalli et al. 2006). Together these ideas begin to suggest that the trait characteristics of team members, such as emotional intelligence, social sensitivity, narcissism, or insensitivity are likely to matter for team viability, because these team member traits shape how they interact (Van Vianen and De Dreu 2001; Woolley et al. 2010). Indeed, foundational work on team collective intelligence has consistently shown that team member social capabilities do predict consistent interaction patterns in teams, and consistent levels of team performance across a variety of tasks (Woolley et al. 2015; Woolley et al. 2010).

Together, this literature suggests that person-specific attributions and path-dependent accretions of actions and affect can impact the outcome. The memory of these actions will carry over to the next time the team works together, which is likely to increase the consistency of the fracture outcome when the team is aware that they are reconvening. So, we hypothesize:

**Hypothesis 1 (H1)** *Masked teams (i.e., teams who think they are working with a new team, but are working together again) will have less consistent viability and fracture than unmasked teams (i.e., teams who know they are working together again).*

**Hypothesis 2 (H2)** *Masked teams will have near random odds of repeat fracture outcomes.*

This paper thus builds on prior work by contributing the construct of team fracture, a behavioral measure of it, and a study of the situations in which it is predictable. Prior methods do not attempt to answer questions of how repeatable (or inevitable) team social dynamics are. In general, once you have been burned by an arrogant or power-hungry team member, you walk into the next interaction with that group already on your guard. The social hierarchy has been set in motion, power struggles have emerged, and assessments of personalities well-formed.

Our research introduces a novel technique that provides insight into this question of the inevitability of team fracture. We draw conceptual inspiration from parallel world studies such as MusicLab (Salganik et al. 2006), which randomized people into multiple worlds where the download counts for songs were independent in each world. Likewise, we sought to create multiple parallel instances of the same team. However, prior methods created these parallel worlds by randomizing different people into each world, which is infeasible for us—different people would mean that the team is different. So, we introduce a new method: two-way masking of participants' pseudonym identities. Our intent is to give the same exact group of people multiple chances to construct a team interaction pattern and a cohesive viability or fracture from scratch and to see how consistent their interactions and outcomes are. If successful, we hope that this method could be applied to other team-based social processes such as status and norm development.

## 3 Method

Our research aim is to determine the extent to which a similar fracture outcome emerges when collaborators interact without awareness that they have worked together before. So, we seek a masked membership design that allows us to hide collaborators' interaction histories.

To temporarily hide interaction histories, we introduce a novel deception experiment that leverages pseudonyms so that participants believe that they are working with new collaborators when they are in fact working with prior collaborators. This mechanism relies on repeated group interactions, during which all users appear with pseudonyms at all times.

By default, teams are allocated based on social golfer matching (Harvey 2001), such that each collaboration consists of members who have never interacted before. With this mechanism, each participant interacts with every other participant at most once, unless they are working together for a second time as part of the experiment. In those cases, their interaction will be either *masked*, hiding identities through dynamic pseudonym replacement so that it appears the repeat interactions are with new participants, or *unmasked*, maintaining the same pseudonyms over time so that it is clear when the collaboration is reconvened.

To mask interactions, we developed a chat collaboration platform that facilitates multi-person discussions (Fig. 2). Our system replaces members' pseudonyms before routing each message out to recipients. It automatically generates pseudonyms in *adjectiveAnimal* format (Salehi et al. 2015), e.g., *conventionalHorse* or *fastFrog*. Participants see their permanent pseudonym, and are not made aware of any new pseudonyms assigned to them when masked. Our system maintains an internal identifier for each participant, as well as the participant's permanent pseudonym and the current public pseudonym assigned to them for the duration of their current collaboration. Because members' private and public pseudonyms may differ, one challenge with our method is that participants may be called on by a pseudonym that they do not perceive as their own. To address this, our system identifies any mentions of their own private pseudonym and replaces it with the public pseudonym on the recipient's client, and likewise replaces any mentions of others' public pseudonyms that they send out with the recipient's private pseudonym. The system uses three strategies to achieve this: (1) an edit distance algorithm to account for misspellings, (2) a starts-with identifier to catch incomplete phrasings of the pseudonym, and (3) an autocomplete interface, similar

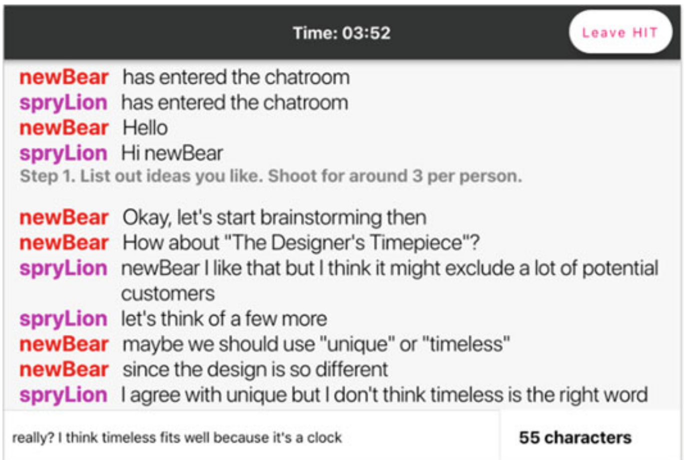


**Fig. 2** Participants collaborated in a synchronous chat room environment on one of three different kinds of tasks. This example shows a team doing the ad writing task, collaborating to write a short online advertisement

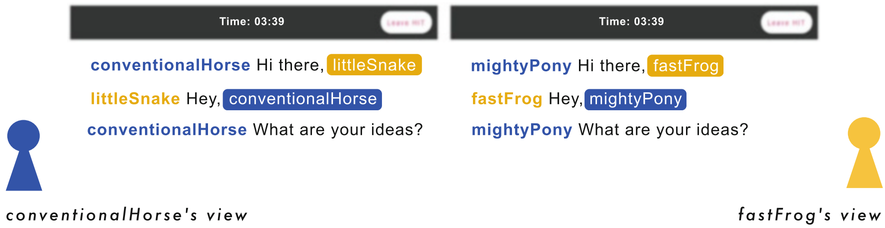


**Fig. 3** Chats are converted so all parties see the appropriate unique pseudonyms, and spelling mistakes or typos are automatically corrected, to avoid revealing the manipulation

to those found in tools like Slack, that makes it convenient and faster for users to tab-complete a name than to type it themselves, making errors less likely. Repeated iteration and prototyping established that these algorithmic and interface techniques together prevented any leaked pseudonyms in our dataset.

To prevent participants from noticing this manipulation, the system keeps each participant's own pseudonym static from their own point of view even while it changes from everyone else's point of view (Fig. 3). For example, a participant might see themselves with their usual *conventionalHorse* pseudonym and people mentioning them in the chat as *conventionalHorse*. However, to another member of the group, they would be perceived as *mightyPony*. Similarly, they might believe they are interacting with *littleSnake* when in fact that is the masked name pertaining to *fastFrog*.

The identities of participants are entirely isolated from their private pseudonyms, and their public pseudonyms can be replaced, so that others think they are a new collaborator when they are actually not, allowing us to reset the team to a clean slate. In the masked condition teams reconvene with new public pseudonyms, while in the unmasked condition the public pseudonyms remain the same between reconvened rounds of the experiment.

We included a manipulation check question at the conclusion of the study. When debriefing participants in the masked condition, we told them that two of the groups they worked with were actually the same people. We then asked them to identify which collaborators were actually the same (the first group and the third group, the first group and the fourth group, etc.). If the manipulation were weak or if other signals from the team's interactions bled through, participants would be able to guess correctly. If not, they would guess at roughly a chance rate of accuracy.

## 3.1 Tasks

Participants were organized into groups of four to perform a series of tasks in a series of rounds. They were given 10 min in each round to work with their group on the task. At the end of each round, participants were moved onto a new group.

We ran the same study design independently across three different tasks in McGrath's task circumplex (McGrath 1984): creative tasks (type 2), intellective tasks (type 3), and cognitive conflict tasks (type 5). These three task types span three of the four quadrants in the circumplex: creative tasks represent generating ideas and plans, intellective tasks represent choosing a solution, and cognitive conflict tasks represent negotiating the solution to a conflict of viewpoints. By replicating the same study design across a broad swath of the task circumplex, we seek to understand how general any effects are.

For the creative task, we draw from related work (Salehi et al. 2017; Dow et al. 2010) to ask collaborators to write short online text advertisements for product campaigns from Kickstarter. In this setup, participants collectively author a 30 character byline advertisement. In each round, all collaborators worked on advertisements for the same Kickstarter project. At the end of the round, the team collectively decided on a final advertisement and one member submitted it on behalf of the team. Teams wrote ads for different Kickstarter projects in each round, so they would never repeat the exact same task.

In the intellective task, participants were asked to correctly answer a series of questions without looking up the solutions online, instead debating with their group members on what the answers to the questions could be (Woolley et al. 2010). Prompts included estimating the number of states that border the Gulf of Mexico, the percentage of the U.S. population that goes online at least once a week, and the height in feet of Mount McKinley. At the end of each round, the team collectively decided on their final answers and one member submitted a final list of answers on behalf of the team. Teams answered different questions of the same form in each round, so they would never repeat the exact same task.

The cognitive conflict tasks asked a team to allocate funds between a number of competing programs which were each designed to appeal to particular personal values (Watson et al. 1988). In each round participants were provided three program options and were asked to collectively decide on how they would choose to allocate a fund of $500,000. At the end of the round, the team collectively decided on a final allocation and a statement of their reasoning and one member submitted it on behalf of the team. The programs' options were rotated such that each round contained a new set of options and a new combination of values.

Each participant was recruited for one of the tasks and completed four rounds of that task: two rounds of work with the same group, and two rounds of work with new groups. The order of these rounds was balanced across groups, so that, for example, the repeated group might occur in the first and third rounds, or second and fourth, and so on. To avoid leaking the manipulation, we excluded all orderings where the same collaborators worked together for two adjacent rounds. So, all participants were reconvened with the same team a second time, but the rounds in which this happened would vary. Rotating membership between teams required that four people be participating in each task. Each group of four was randomized to condition and then proceeded together through each round, interacting in different combinations to form nonoverlapping teams such that each participant worked with each other participant in exactly one collaboration.

In the *masked* condition, when the collaboration was reconvened, the pseudonyms were masked so that participants would be unaware they were working with the same group. In the *unmasked* condition, the pseudonyms were not masked, so participants would recognize each others' usernames.

## *3.2 Measures*

Fracture, in our conceptualization of it, is related to team viability (Bell and Marentette 2011). So, at the end of each round, each participant filled out a 14-item viability scale drawn from prior work (Cooperstein 2017). This scale inquired about participants' affect toward current and future interactions with their group. By our definition of the term, team fracture is associated with lower average team viability scores. As the team viability scale is recent, we also explored the first of the remaining steps required for formal validation.

To complement attitudinal data, we sought a behavioral measure of fracture. After all rounds were completed, participants were told there was a chance they might work with one more group, randomly drawn from the groups that they had worked with already. For each of their prior groups, participants were given the option to privately exclude that group from their set of candidates. We defined a team as fractured when at least half of a group's members privately excluded that group from future rounds. Our motivation for choosing half the team was that this represented a nontrivial number of opinions, not just a single unhappy participant.[1]

To understand how much insight team members had into each others' fracture votes (Prelec 2004), we also asked each team member what they thought others on their team would say to this fracture question.

To understand the relationship between fracture and performance, we measured task performance in the creative and intellective tasks. Cognitive conflict tasks do not offer clear performance measures. For the creative ad writing task, each advertisement was added to a campaign for the product on Google Ads. We turned off any optimization, ensuring that ads were seen at the same rate. After 48 h, we recorded each ad's click through rate (CTR) as a measure of the group's performance (Salehi et al. 2017; Dow et al. 2010). For the intellective tasks, we measured the percent difference each teams answers were from the correct answer, and recorded the median of these values for each team interaction. These two tasks then had individual measures which could capture performance relative to others doing that task.

[1]To test the robustness of our effects, we analyzed the impact of varying this percentage in our analysis code and conducting otherwise identical analysis, e.g., one person voting to fracture at 25%, or a supermajority at 75% of the group voting to fracture. The main results remained consistent. So, we report the results for $\geq$50% in this paper.

### 3.3 Participants

Participants were recruited from Amazon Mechanical Turk. Worker location was restricted to the United States to satisfy language requirements, and we required that all workers had completed at least 100 tasks. Participants were paid $12 per hour for taking part in the experiment, and were incentivized to complete the entire study by receiving a majority of their payment as a bonus at the end of the experiment. We invited workers to sign up ahead of time, then join a waiting room when the task began (Lasecki et al. 2014). The waiting room prompted participants to stay engaged by asking them to respond to questions from a chatbot at regular intervals. Once a sufficient number of participants was active in the waiting room, the main experiment activity would begin.

To ensure that there were enough teams to satisfy the non-overlapping membership constraint, we recruited panels of 16 people at once. Each panel would proceed through the task rounds together. Each panel was randomized between masked and unmasked conditions.

## 4 Results

Our results reflect 468 individuals who participated in all four rounds of the study in 79 masked and 61 unmasked teams of 3–4 members. We filtered out teams from the analysis if they lost at least one member due to a disconnection or disinterest during the study, since this would mean that the team's second convening was missing a member, which would undermine the manipulation. Of remaining teams, 55 performed cognitive conflict tasks, 54 performed creative tasks and 31 performed intellective tasks. The final participant pool was 47.71% female, with an average age of 38.00 years ($SD = 11.54$).

### 4.1 Manipulation Check

Participants worked with four different groups, hence, there are $\binom{4}{2} = 6$ combinations of teams that participants might guess were the repeat teams. A random guessing strategy would be $\frac{1}{6} = 17\%$. Masked participants correctly guessed which teams they had worked with 21.50% of the time, a small amount above chance guessing. We also considered the manipulation on the team level, and found that 65.74% of unmasked teams had correct guesses from at least half their members, while only 15.31% of masked teams guessed correctly.

## 4.2 How Consistent Is Fracture?

The consistency of fracture in reconvened teams was evaluated by counting the times that teams switched their fracture state, i.e., half or more voted to fracture the first time they interacted but fewer than half voted to fracture the second time, or vice versa. Overall, masked teams changed their fracture outcomes 64.56% of the time, whereas unmasked teams changed fracture outcomes 81.96% of the time. However, broken out by task, the outcomes appear strongly polarized. Teams in cognitive conflict tasks ($masked = 73.33\%$, $unmasked = 80.00\%$) and intellective tasks ($masked = 75.00\%$, $unmasked = 72.72\%$) had high consistency for masked teams, at about the same rate as unmasked teams. In contrast, teams in creative tasks ($masked = 48.28\%$, $unmasked = 88.00\%$) had low consistency, at about a coin toss probability of changing. A logistic regression of each task confirms that masked teams are more inconsistent than unmasked teams in the cognitive conflict task, but not the other two tasks. We show this in Table 1 for the creative tasks, Table 2 for the intellective tasks, and Table 3 for the cognitive conflict tasks (Fig. 4).

This data confirms H1 for the creative task but refutes it for the cognitive conflict and intellective ones, which suggests that during a creative collaboration, a negative

**Table 1** In the creative task, unmasked teams were significantly more consistent in their fracture outcome than masked teams

| | *Dependent variable* |
|---|---|
| | Consistency |
| Unmasked | 2.061** |
| | (0.719) |
| Intercept | −0.069 |
| | (0.372) |
| Observations | 54 |
| Log likelihood | −29.257 |
| Akaike inf. crit. | 62.514 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

**Table 2** In the intellective task, unmasked and masked teams were not significantly different in their fracture consistency

| | *Dependent variable* |
|---|---|
| | Consistency |
| Unmasked | −0.118 |
| | (0.851) |
| Intercept | 1.099* |
| | (0.516) |
| Observations | 31 |
| Log likelihood | −17.692 |
| Akaike inf. crit. | 39.384 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

**Table 3** In the cognitive conflict task, much like the intellective task, unmasked and masked teams were not significantly different in their fracture consistency

| | *Dependent variable* |
|---|---|
| | Consistency |
| Unmasked | 0.375 (0.648) |
| Intercept | 1.012* (0.413) |
| Observations | 55 |
| Log likelihood | −29.908 |
| Akaike inf. crit. | 63.815 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

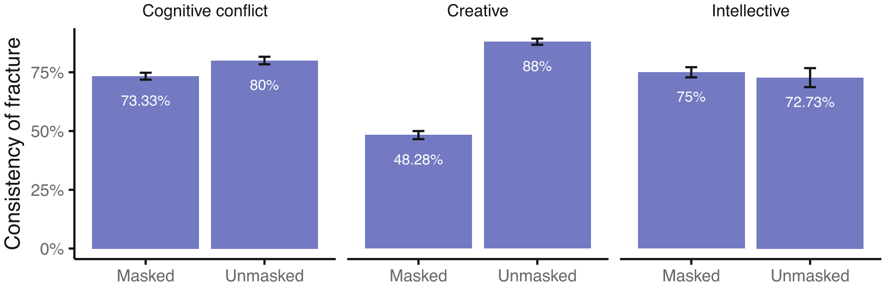


**Fig. 4** Unmasked teams exhibited high consistency in their fracture outcomes, 73–88% across tasks. Masked teams were strongly polarized in the consistency of their fracture outcomes: teams in cognitive conflict and intellective tasks were both strongly consistent at 73%, which is essentially the same consistency as unmasked teams; teams in creative tasks were strongly inconsistent at 48%, essentially as consistent as a coin flip

outcome with a particular set of collaborators may have been substantially driven by path-dependent behaviors.

Baseline fracture rates provide a useful comparison point. When participants in any condition were collaborating with a team that they would not be seeing again, there was a 24% chance of fracture. So, the consistency we might expect in fracture outcomes between two different teams would be the probability of two fractures plus the probability of two non-fractures, $p^2 + (1 - p)^2 = 0.52$, roughly even odds. We investigated any possible temporal trends in fracture rates, which would indicate a learning effect or calibration period. While there is some variation by round in these fracture rates, the difference is not significant ($\chi^2(3) = 4.50$, $p = 0.21$). The emergent trend is that the first round had the lowest fracture rate. However, both conditions experienced one of their repeated collaborations in the first round equally, so this is unlikely to affect our conclusions.

To test our behavioral fracture measure's alignment with prior constructs in the literature, we compared fracture outcomes to participants' responses on the team viability scale (Cooperstein 2017). The mean viability score was 56 ($\sigma = 9$) out of a possible total of 70. A t-test confirmed that mean viability scores between teams that

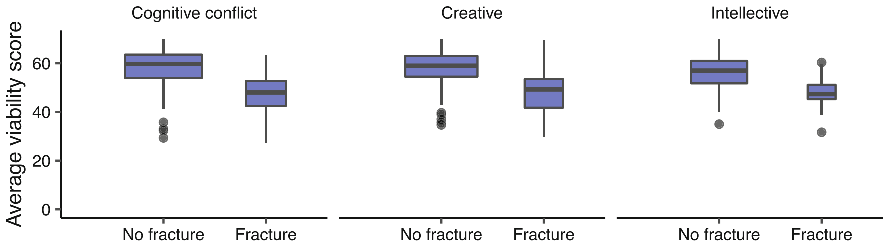


**Fig. 5** Collaborations that fractured had lower self-reported viability across all tasks

fractured ($\mu = 48, \sigma = 8$) was lower than teams that did not fracture ($\mu = 57, \sigma = 7$): $t(167.86) = 11.44, p < 0.000$, with a large effect size (Cohen's $d = 1.2$). Figure 5 illustrates this difference.

The 14-item team viability scale used in this paper (Cooperstein 2017) has not yet been formally validated, so we conducted an exploratory factor analysis (EFA) on the results from 214 teams who completed the scale after their team interaction. Data were screened for multivariate assumptions (normality, linearity, homogeneity, and homoscedasticity). All conditions were met, with slight but not intractable problems with linearity. Following EFA guidelines (Preacher and MacCallum 2003), we first ran Bartlett's test which indicated correlation adequacy ($\chi^2(91) = 5055.522, p < 0.001$) and Kaiser-Meyer-Olkin (KMO) test which indicated sampling adequacy $MSA = 0.97$. A parallel analysis, scree plot and screening of factor values greater than 1.0 and 0.7 (Old Kaiser and New Kaiser criterion respectively) all suggested one overall factor. Our one-factor model has moderate fit with root mean square error of approximation (RMSEA) at 0.10 with a 90% CI: [0.091, 0.119], and excellent Tucker Lew Index (TLI): 0.957. Our one-factor model achieved a simple structure with each item loading on one and only one factor, and a raw Cronbach's alpha of 0.99 (indicating high reliability). These exploratory results suggest that team viability could be best measured as a single-dimension. Future research is needed to complete remaining phases of the scale development and validation process (Hinkin 1995).

### *4.3 Do Individuals Contribute to Fracture?*

To what extent does membership influence fracture? To answer this, we trained a logistic regression to predict whether the group would vote to fracture the first time they met. We included two main variables: the task condition, and a categorical (dummy) variable identifying each participant in the study. We then measured the AUC—area under the receiver operating curve—as an indication of how well this classifier performed. A baseline model that only had access to condition information had an AUC of 0.55, indicating relatively poor performance. In comparison, the model that also had access to the individual's identity had an AUC of 0.76, indicating a more accurate prediction. This result suggests that membership does influence fracture. In particular, specific individuals are either associated with voting to fracture (malcontents) or in causing others to vote to fracture (poor collaborators).

### 4.4 Is Fracture Evident from Discussion?

We performed an exploratory qualitative analysis of the discussions in the chat logs of teams in the masked condition between their first and second meeting.

We saw few overt signals of fracture, suggesting that private opinions and public behavior differ. However, occasionally, we found that some interactions in chat logs signaled a team's shift. For example, during their first interaction, one team, with a mean viability score of 47.75 and half the members voting to fracture, generated ideas in parallel and with limited interdependence, ultimately just saying which they liked and resulting in teammates overwriting each others' final submissions with no actual consensus:

*First meeting while masked — fractured*
**creativeHippo:** I like Time with a Twist too.
**conventionalHorse:** maybe time telling newly
**conventionalHorse:** time telling beautifully
**mightyFrog:** i kinda like just time with a twist also. simple and to the point
**mightyFrog:** not sure if it needs more
**mightyFrog:** telling time beautifully is nice
**mightyFrog:** or time telling if you prefer
**littleSnake:** LetB: Time with a Twist

In contrast, when this team reconvened later with masked identities, they ended with a mean viability score of 56.75, with no members voting to fracture. Interaction began in much the same way, only this time, a random early event spurred members to pinpoint a common source of inspiration, build upon each others' ideas and provide early feedback:

*Second (reconvened) meeting while masked — not fractured*
**mightyFrog:** something about how it makes you smarter? there's smart water so something about smart tea?
**mightyFrog:** the smart tea for smarties? too corny?
**creativeHippo:** Thats interesting
**conventionalHorse:** All you need is tea
**conventionalHorse:** Smart tea from the sea
**mightyFrog:** oh thats good too
**littleSnake:** i like that one

In the cognitive conflict task, one team that was consistent in its non-fracture outcome was also consistent in waiting to hear multiple voices before making any decisions, achieving a mean viability score of 59.5:

*First meeting while masked — not fractured*
**likelyOtter**: How are we leaning, with regards to spending the funds?
**likelyOtter**: I quite like the idea of establishing a community arts program. What do you

guys think?
**youngFox**: I think the veterans support center would be a much better allocation of funds.
**spryFish**: I would like to give funds to the veterans' center.
**newDeer**: I also agree with the community arts program. It seems like it would benefit the most amount of people.
**spryFish**: I have military in my family.
**spryFish**: I don't have strong feelings about purchasing art. I think the other two options will provide more concrete benefits to people.
**likelyOtter**: Okay, so it seems like we're divided on two options. Can we pretty much rule out number 2 then?
**newDeer**: Yeah, i don't think anyone is for #2.
**spryFish**: We could split the funds evenly between the two we support.
**likelyOtter**: I think that would represent the feelings of the entire room, so I support that.

In their second interaction, the same norm of waiting and hearing multiple perspectives arose, producing a mean viability score of 67.7:

*Second (reconvened) meeting while masked — not fractured*
**likelyOtter**: Libraries are also useful resources to those with low or no income.
**newDeer**: Yeah, #1 and # 2 seem most important. How about 150k for #2?
**spryFish**: Sounds good. 400,000 to number 1 and 100,000 to number 2.
**newDeer**: Yes.
**youngFox**: I could live with a 350,000 and 150,000 split. Everyone else in agreement?
**likelyOtter**: I'm good the 350/150 split
**likelyOtter**: with*
**newDeer**: How about you spryFish
**newDeer**: ?
**spryFish**: Yes
**likelyOtter**: Great!
**youngFox**: We're in agreement!
**spryFish**: I like working with groups with the same values!
**likelyOtter**: Yeah, me too!
**youngFox**: It definitely makes life easier.

Another team in the creative task, collaborated effectively when first convening, with a mean viability score of 58.25 and no member voting to fracture. Members took turns generating ideas and playfully encouraged each other in the brainstorming process.

*First meeting while masked — not fractured*
**unconventionalCat:** would be fun to play on it with "this tea"
**creativeHippo:** Thetis tea from the sea
**unconventionalCat:** you're not a creativeHippo are ya
**unconventionalCat:** you little unconventional creativeHippo you!
**coolWhale:**Tis-Tea the stress be gone cure for all
**creativeHippo:** Tis the time for Tis-Tea was from me
**unconventionalCat:** using sea is a great play on words
**unconventionalCat:** esp. cuz seaweed
**coolWhale:** Tis-Tea the stress be gone cure from the sea.

However, when this same team reconvened, the plainness of one member early on in the interaction stifled the collaborative atmosphere, leading to three of the four members voting to fracture and a mean viability score of 35.

*Second (reconvened) meeting while masked — fractured*
**coolWhale:** The Classy stool to be cool
**unconventionalCat:** meh
**creativeHippo:** Sit Your Pants (it's a play on words)
**coolWhale:** Sit you pants with class
**unconventionalCat:** None B4 Stool N°1
**littleSnake:** Feel winning, use Stool Number One
**unconventionalCat:** i don't even know what that means

In addition to understanding fracture from chat logs, we asked participants to privately explain their choices about with which teams they'd be willing to reconvene. Responses for why someone liked a group interaction included aspects such as group contribution, taking the task seriously, and "clashing."

– "I didn't feel like most of the members took the task very seriously."
– "The discussion was not productive."
– "I didn't feel like we clicked well."
– "Not all participated."

On the other hand, people who indicated that they would like to continue working with a given group mentioned aspects such as feedback, creativity, and communication.

– "Because I feel that we had well thought out ideas and discussion."
– "I think they were great to work with! Everyone participated and was helpful. All were kind as well!"
– "They seemed to focus and give good feedback."
– "The team is creative and work hand in hand."

### *4.5 Behavior Under Fracture*

Although our primary focus is on the viability of the group, one outcome of viable teams is increased performance. Our experiment measured performance signals for the creative ad writing task and the intellective task, and evaluated the magnitude of changes in performance between first and second interactions of the same teams. Figure 6 shows these changes across tasks, by collaborations that exhibited consistent and inconsistent fracture outcomes between rounds. A logistic regression showed that neither task nor fracture consistency were significantly related to performance (Table 4).

Since we could not evaluate performance in all tasks (e.g. cognitive conflict tasks, due to the nature of this task type), we conducted followup analyses about characteristics present in fractured and non-fractured groups, comparing all the task types in this way. These analyses included a measure of chat turn-taking, length of chat discussions, and sentiment analysis of chat contents. However, they did not yield substantially different results between task types or fracture states.

We analysed turn-taking by counting the number of times new chat messages came from a different team member than the previous chat message. Figure 7 shows

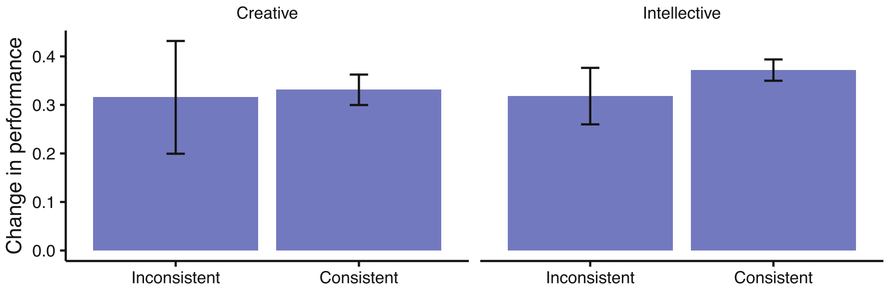


**Fig. 6** Consistency in fracture outcomes was unrelated to change in performance outcomes

**Table 4** Absolute performance change is not statistically predictive to consistency of fracture, suggesting that fracture and performance are not tightly related

| | *Dependent variable:* |
|---|---|
| | Absolute performance change |
| Inconsistent | 0.071<br>(1.208) |
| Intellective | 0.012<br>(1.317) |
| Intellective * consistent | 0.166<br>(1.493) |
| Intercept | −0.774<br>(1.076) |
| Observations | 49 |
| Log Likelihood | −29.385 |
| Akaike Inf. Crit. | 66.770 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

how neither participant masking nor fracture outcome affects the number of turns taken in groups. In a model evaluating task type, fracture consistency as predictors of turns taken in a team interaction, in all cases, no factors were significant ($p > 0.5$).

We also evaluated differences in the Gini coefficient when teams did or did not fracture. The Gini coefficient measures how equally distributed the teams' conversations were, with a 0 indicating perfectly equal contributions and a 1 indicating perfectly unequal contributions. Neither message numbers ($t(156) = 1.2410, p = 0.2165$) nor character counts ($t(156) = 0.7078, p = 0.4801$) demonstrated significantly different Gini coefficients. We interpret this result to indicate that fracture is not associated with how dominant participants are in conversation.

We also analysed sentiment using the *sentimentr* package to generate a score between −1 and 1 for each message sent in any given group interaction, with negative and positive scores representing negative and positive messages, respectively (Rinker 2016). Although sentiment scores varied across different task types, with higher average scores present in cognitive conflict tasks and lower ones

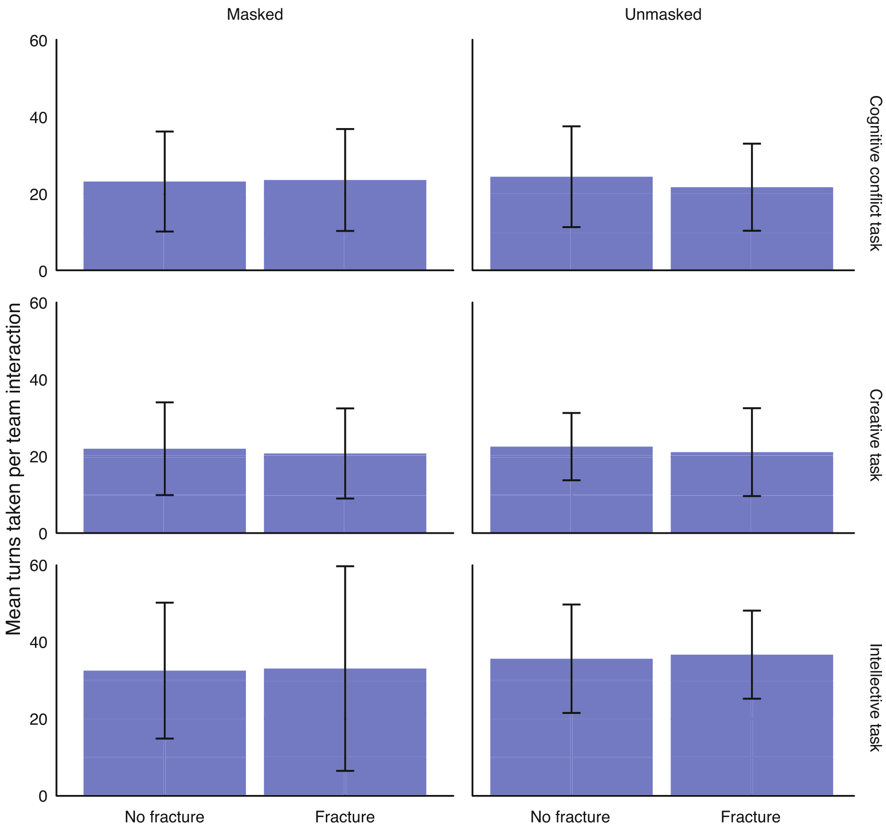


**Fig. 7** The number of turns taken between participants in a chat interaction are consistent across different tasks, different rounds, and different fracture outcomes

expressed in intellective tasks (Fig. 8), there was again no significant difference between fracture and non-fracture outcomes ($p > 0.5$).

Taken together, these posthoc analyses suggest that fracture is not a simple function of sentiment, contribution distribution, or performance, and that progress in measuring and theorizing it will be necessary in future work.

## 5 Discussion

This paper introduces an experimental method for investigating whether history is bound to repeat in fractured collaborations. We find mixed evidence for Hypotheses 1 and 2—in particular, the effect appears to be moderated by task.

Our results, which indicate that team fracture can be substantially path-dependent in some tasks and substantially robust in other tasks, has bearing on CSCW theory.

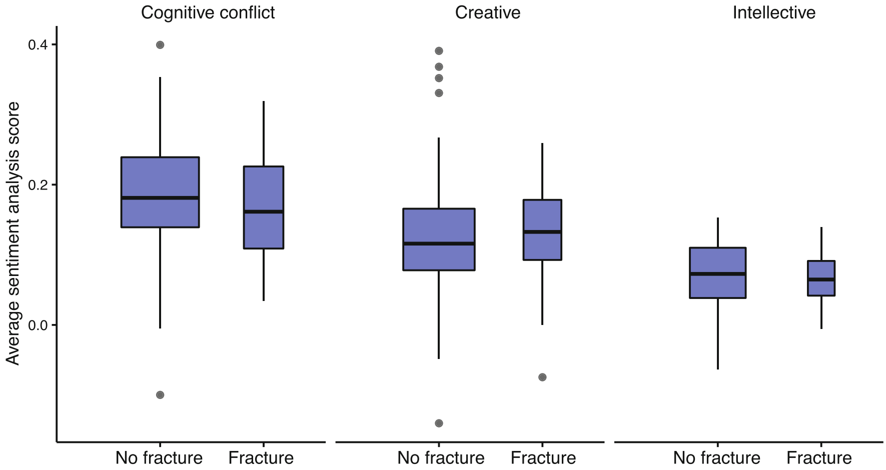


**Fig. 8** Sentiment analysis scores were unrelated to fracture outcomes within task types

CSCW has largely focused its dependent variable on team performance; for example, that remote teams suffer lower performance by a factor of two to one (Olson and Olson 2000), that collective intelligence predicts performance (Woolley et al. 2010; Woolley et al. 2015), that shared awareness can promote more effective information sharing and thus performance (Dourish and Bellotti 1992), and that externally visible conflict can predict performance (Jung 2016). Our results report that performance is statistically orthogonal to an important affective outcome—fracture—that determines whether the team can actually sustain its collaboration. Thus, our work makes clear the need for increased attention on theories of affective and viability-based outcomes in CSCW theory.

The field stands to benefit from theories that extend beyond performance to focus on viability, fracture, and other affective outcomes in team collaboration. Rather than focusing on coordination, or the sheer existence of distance or a mediating channel, these theories will draw focus from other areas such as the psychology of attribution, bias and justice, and computer-mediated communication. For example, CMC has a long history of studying how emotional states can be transmitted. Our results indicate that, at least for the creativity task, *something* unrelated to the task or performance is being communicated via the chat channel which prompts large shifts in the outcome. Identifying this feature and theorizing it will be critical to enabling CSCW to continue to build theories of collaboration that push beyond performance.

We can rule out several theories and explanations given our data. First, there appears to be no difference in baseline fracture rates across tasks, which rules out measurement sensitivity as the issue. Second, fracture is also unrelated to performance in our data, so differences in performance do not appear to be driving the effect. Third, we can rule out some creativity-specific features of the task. The cognitive conflict and intellective tasks are typically deciding a question with an objective right answer, or negotiating between positions. In contrast, the creativity task involved generating new ideas, which suggests that fixation may arise. Fixation (Jansson and Smith 1991), when team members prematurely focus their attention and excitement on one option they have generated in a creative process, could cause members to come into conflict over ideas they like. However, we ran pilot experiments with a creative task that did not require teams to decide on a single idea for the team, but instead, asked them to submit their ideas individually, operationally removing the fixation. The results of this pilot mirrored the results shown in the main creative task. Thus, fixation also does not explain the outcome.

Other explanations arise that cannot be directly tested with our data. For example, there may be effects of the additive vs. integrative nature of the team member contributions. The intellective task and cognitive conflict tasks are additive: the skills and abilities of team members roughly sum. In contrast, design and creativity are integrative: they require combining viewpoints and building on each others' ideas—the experience of being on the team is driven by these integration activities. It is possible that integrative work is more path dependent and sensitive to attributions than additive work.

## *5.1 Limitations*

Our method offers tradeoffs and limitations in its generalizability. First, we focused on teams of four, and it is possible that these dynamics differ with larger groups. Second, we used tasks that are relatively short—while people are effective at making quick judgments of compatibility with team members (Lykourentzou et al. 2017), fracture is very likely to be a time-varying construct. Our method itself likely also has time bounds after which the manipulation becomes apparent, and we have not rigorously tested or characterized those bounds yet. Third, while our method masks old team dynamics, it is not a complete time reversal. In particular, participants are most likely learning from their prior team experiences as they enter each new task. They also likely carry emotional state over from round to round. In other words, if a team fractures viciously, the reconvened and masked team may not know it's the same people, but they may still be gun-shy and try to avoid issues like those that caused problems previously. So, we would never expect to see full consistency in fracture. Fourth, we also want to better explore how norms spread across teams in repeat trials. For example, participants might spread a negative norm as they interact, diffusing an emotional state across teams. Fifth, our definition of fracture focused on attitudes—members' desire to keep working together—but attitudes may not be predictive of a behavioral outcome, such as how well actual teams survive when subsets of the team are inclined to fracture. Moreover, there may be differences based on the proportion of the team that votes to fracture. However, in our analysis of our data stratifying by the percentage of the team voting to fracture, we do not see any strong evidence of impact.

Our experimental approach helps us understand the consistency of team fracture. However, we do not yet have causal evidence of the underlying mechanism that separates creativity tasks from cognitive conflict and intellective tasks. We will continue to work to understand the principles underlying this result.

In this paper, we introduced a conceptualization of team fracture and linked it to team viability. However, we still do not know the full extent of other group and individual level correlates with team fracture. For example, how does individual-level psychological safety (Edmondson 1999) relate to team fracture? Or team member familiarity prior to the convening of the team?

## *5.2 Implications for Design*

Challenges in remote and distributed teams are a central concern for CSCW (Olson and Olson 2000; Hinds and Bailey 2003). The obvious follow-on question, then, is what role can design play in mitigating fracture? One approach is to try and predict it, then alert the team of the risk and give them the resources to mitigate it. Our results suggest that in some cases, characteristics of the task will suggest how at risk a team might be for a fracture that is path dependent and sensitive to accretions of early actions. Those actions are likely to be visible at some level to the platform, for example through the text chat, and might provide levers for prediction and classification. For the tasks where fracture is consistent, systems might investigate whether fracture could be predicted in advance of the team ever convening, such as through analysis of the individual contributions and behavior of team members before they began collaborating.

With precise knowledge of the kinds of tasks and contexts in which situational attributes are more strongly associated with team fracture, context-specific scaffolds can be designed with a focus on encouraging a pro-social collaboration. For example, intervening to encourage a friendly start to a collaboration where fracture is path dependent could mitigate or reduce it substantially.

On the other hand, in group activities where personal attributes are more strongly associated with team fracture, targeted measures to improve collaborator selection may be taken. For example, pretesting or using low-stakes trial group activities would be likely to surface issues before they occur in a high-stakes situation. In an organizational context, this might involve leveraging practice interactions in which a given team's propensity to fracture could be evaluated without risking a mission critical situation.

More unusual process and system interventions might be feasible as well. Using a technique based on this experiment design, one could experiment with a team intervention that masks teams for their initial interactions and intermixes participants until the team stumbles upon a positive outcome, at which point the team can be unmasked and begin collaborating in earnest. Team fracture may be a random draw on some tasks, but once you have what you want, our experiment suggests that you can keep it. Enabling teams to reduce fracture is valuable academically but also as an opportunity for industrial team contexts.

## 6 Conclusion

In this paper, we introduce the construct of team fracture, defined as a loss of team viability so severe that members no longer want to work together on future teams. We introduce an experimental method for temporarily masking a group's interaction history, allowing us to study the consistency with which the group fractures. We find that the consistency of team fracture is strongly polarized by task type. On creative tasks, it might as well have been a completely different team: teams changed their fracture outcomes at a random chance rate. On cognitive conflict and intellective tasks, the team replayed the same dynamics without realizing it, rarely changing their fracture outcomes. These results suggest that unlike team performance, team fracture cannot be strongly predicted only by stable features of team members.

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## References

Anderson, N. R., & West, M. A. (1998). Measuring climate for work group innovation: development and validation of the team climate inventory. *Journal of Organizational Behavior: The International Journal of Industrial, Occupational and Organizational Psychology and Behavior, 19*(3), 235–258.

Aube, C., & Rousseau, V. (2005). Team goal commitment and team effectiveness: The role of task interdependence and supportive behaviors. *Group Dynamics: Theory, Research, and Practice, 9*(3), 189.

Barrick, M. R., Stewart, G. L., Neubert, M. J., & Mount, M. K. (1998). Relating member ability and personality to work-team processes and team effectiveness. *Journal of applied psychology, 83*(3), 377.

Beal, D. J., Cohen, R. R., Burke, M. J., & McLendon, C. L. (2003). Cohesion and performance in groups: A meta-analytic clarification of construct relations. *Journal of Applied Psychology, 88*(6), 989.

Bell, S. T. (2007). Deep-level composition variables as predictors of team performance: A meta-analysis. *Journal of Applied Psychology, 92*(3), 595–615. https://doi.org/10.1037/0021-9010.92.3.595

Bell, S. T., & Marentette, B. J. (2011). Team viability for long-term and ongoing organizational teams. *Organizational Psychology Review, 1*(4), 275–292. ISSN: 2041–3866. https://doi.org/10.1177/2041386611405876. http://journals.sagepub.com/doi/10.1177/2041386611405876

Brown, G., Crossley, C., & Robinson, S. L. (2014). Psychological ownership, territorial behavior, and being perceived as a team contributor: The critical role of trust in the work environment. *Personnel Psychology, 67*(2), 463–485.

Cheng, J., Bernstein, M., Danescu-Niculescu-Mizil, C., & Leskovec, J. (2017). Anyone can become a troll: causes of trolling behavior in online discussions. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing, CSCW '17* (pp. 1217–1230). Portland, OR: ACM. ISBN: 978-1-4503-4335-0. https://doi.org/10.1145/2998181.2998213

Cooperstein, J. N. (2017). Initial development of a team viability measure. *College of Science and Health Theses and Dissertations, 202*. https://via.library.depaul.edu/csh_etd/202
Daft, R. L., & Lengel, R. H. (1986). Organizational information requirements, media richness and structural design. *Management Science, 32*(5), 554–571.
Dalton, D. R., Daily, C. M., Ellstrand, A. E., & Johnson, J. L. (1998). Meta-analytic reviews of board composition, leadership structure, and financial performance. *Strategic Management Journal, 19*(3), 269–290.
Dourish, P., & Bellotti, V. (1992). Awareness and coordination in shared workspaces. In *Proceedings of the 1992 ACM Conference on Computer-supported Cooperative Work CSCW '92* (pp. 107–114). Toronto, ON: ACM. ISBN: 0-89791-542-9. https://doi.org/10.1145/143457.143468
Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., & Klemmer, S. R. (2010). Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. *ACM Transactions on Computer-Human Interaction (TOCHI), 17*(4), 18.
Driskell, J. E., Salas, E., & Johnston, J. (1999). Does stress lead to a loss of team perspective? *Group Dynamics: Theory, Research, and Practice, 3*(4), 291.
Edmondson, A. (1999). Psychological safety and learning behavior in work teams. *Administrative Science Quarterly, 44*(2), 350–383.
Edmondson, A. C. (2012). *Teaming: How organizations learn, innovate, and compete in the knowledge economy*. New York: Wiley.
Emery, F. E., & Trist, E. L. (1969). The causal texture of organizational environments. *Systems Thinking, 1*, 245–262.
Flaherty, S., & Moss, S. A. (2007). The impact of personality and team context on the relationship between workplace injustice and counterproductive work behavior. *Journal of Applied Social Psychology, 37*(11), 2549–2575.
Gladstein, D. L. (1984). Groups in context: a model of task group effectiveness. *Administrative Science Quarterly, 29*(4), 499–517. ISSN: 00018392. http://www.jstor.org/stable/2392936
Gonzales, A. L., Hancock, J. T., & Pennebaker, J. W. (2010). Language style matching as a predictor of social dynamics in small groups. *Communication Research, 37*(1), 3–19.
Hackman, J. R. (1980). Work redesign and motivation. *Professional Psychology, 11*(3), 445.
Harvey, W. (2001). Symmetry breaking and the social golfer problem. In *Proceedings SymCon-01: Symmetry in Constraints, Co-located with CP* (pp. 9–16).
Hinds, P. J., & Bailey, D. E. (2003). Out of sight, out of sync: Understanding conflict in distributed teams. *Organization Science, 14*(6), 615–632. ISSN: 10477039. http://ezp-prod1.hul.harvard.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=heh&AN=11787478&site=ehostlive&scope=site
Hinkin, T. R. (1995). A review of scale development practices in the study of organizations. *Journal of Management, 21*(5), 967–988.
Hoegl, M., & Gemuenden, H. (2001). Teamwork quality and the success of innovative projects: a theoretical concept and empirical evidence. *Organization Science, 12*, 435–449.
Hoel, H., Einarsen, S., & Cooper, C. L. (2003). Organisational effects of bullying. In *Bullying and emotional abuse in the workplace: International perspectives in research and practice* (pp. 145–161).
Ilgen, D. R., Hollenbeck, J. R., Johnson, M., & Jundt, D. (2005). Teams in organizations: From input-process-output models to IMOI models. *Annual Review of Psychology, 56*, 517–543.
Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies, 12*(1), 3–11.
Jehn, K. A., & Mannix, E. A. (2001). The dynamic nature of conflict: A longitudinal study of intragroup conflict and group performance. *Academy of Management Journal, 44*(2), 238–251.
Jung, M. F. (2016). Coupling interactions and performance: Predicting team performance from thin slices of conflict. *ACM Transactions on Computer-Human Interaction (TOCHI), 23*(3), 18.
Kankanhalli, A., Tan, B. C. Y., & Wei, K.-K. (2006). Conflict and performance in global virtual teams. *Journal of Management Information Systems, 23*(3), 237–274.

Kittur, A., Nickerson, J. V., Bernstein, M., Gerber, E., Shaw, A., Zimmerman, J., et al. (2013). The future of crowd work. In *Proceedings of the 2013 Conference on Computer Supported Cooperative Work, CSCW '13* (pp. 1301–1318). San Antonio, TX: ACM. ISBN: 978-1-4503-1331-5. https://doi.org/10.1145/2441776.2441923. http://doi.acm.org/10.1145/2441776.2441923

Langfred, C. W. (2007). The downside of self-management: A longitudinal study of the effects tf conflict on trust, autonomy and task interdependence in self-managing teams. *Academy of Management Journal, 50*(4), 885–900.

Larson, J. R. (2010). *In search of synergy in small group performance*. London: Psychology Press.

Lasecki, W. S., Gordon, M., Koutra, D., Jung, M. F., Dow, S. P., & Bigham, J. P. (2014). Glance: Rapidly coding behavioral video with the crowd. In *UIST '14* (pp. 551–562). https://doi.org/10.1145/2642918.2647367

LePine, J. A., Piccolo, R. F., Jackson, C. L., Mathieu, J. E., & Saul, J. R. (2008). A meta-analysis of teamwork processes: tests of a multidimensional model and relationships with team effectiveness criteria. *Personnel Psychology, 61*(2), 273–307.

Lykourentzou, I., Kraut, R. E., & Dow, S. P. (2017). Team dating leads to better online ad hoc collaborations. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing, CSCW '17* (pp. 2330–2343). Portland, OR: ACM. ISBN: 978-1-4503-4335-0. https://doi.org/10.1145/2998181.2998322

Mach, M., Dolan, S., & Tzafrir, S. (2010). The differential effect of team members' trust on team performance: The mediation role of team cohesion. *Journal of Occupational and Organizational Psychology, 83*(3), 771–794.

Marks, M. A., Mathieu, J. E., & Zaccaro, S. J. (2001). A temporally based framework and taxonomy of team processes. *Academy of Management Review, 26*(3), 356–376.

Marks, M. A., DeChurch, L. A., Mathieu, J. E., Panzer, F. J., & Alonso, A. (2005). Teamwork in multiteam systems. *Journal of Applied Psychology, 90*(5), 964.

McGrath, J. E. (1984). *Groups: Interaction and performance* (Vol. 14). Englewood Cliffs, NJ: Prentice-Hall.

Morrison, E. W., Wheeler-Smith, S. L., & Kamdar, D. (2011). Speaking up in groups: a cross-level study of group voice climate and voice. *Journal of Applied Psychology, 96*(1), 183.

Mueller, F. (1994). Societal effect, organizational effect and globalization. *Organization Studies, 15*(3), 407–428.

Olson, G. M., & Olson, J. S. (2000). Distance matters. *Human–Computer Interaction, 15*(2–3), 139–178.

Preacher, K. J., & MacCallum, R. C. (2003). Repairing Tom Swift's electric factor analysis machine. *Understanding Statistics: Statistical Issues in Psychology, Education, and the Social Sciences, 2*(1), 13–43.

Prelec, D. (2004). A Bayesian truth serum for subjective data. *Science, 306*(5695), 462–466.

Reagans, R., Zuckerman, E., & McEvily, B. (2004). How to make the team: Social networks vs. demography as criteria for designing effective teams. *Administrative Science Quarterly, 49*(1), 101–133. ISSN: 0001-8392.

Riedl, C., & Woolley, A. W. (2017). Teams vs. crowds: A field test of the relative contribution of incentives, member ability and emergent collaboration to crowd-based problem solving performance. *Academy of Management Discoveries, 3*(4), 382–403.

Rinker, T. W. (2016). *Sentimentr: Calculate text polarity sentiment* version 0.2.3. University at Buffalo/SUNY. Buffalo, New York. http://github.com/trinker/sentimentr

Saavedra, R., Earley, P. C., & Van Dyne, L. (1993). Complex interdependence in task-performing groups. *Journal of Applied Psychology, 78*(1), 61.

Salehi, N., & Bernstein, M. S. (2018). Hive: Collective design through network rotation. *Proceedings of the ACM on Human-Computer Interaction, 2*(CSCW), 151.

Salehi, N., Irani, L. C., Bernstein, M. S., Alkhatib, A., Ogbe, E., & Milland, K. (2015). We are dynamo: Overcoming stalling and friction in collective action for crowd workers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, CHI '15* (pp. 1621–1630). Seoul: ACM. ISBN: 978-1-4503-3145-6. https://doi.org/10.1145/2702123.2702508

Salehi, N., McCabe, A., Valentine, M., & Bernstein, M. (2017). Huddler: Convening stable and familiar crowd teams despite unpredictable availability. In *CSCW '17* (pp. 1700–1713). https://doi.org/10.1145/2998181.2998300

Salganik, M. J., Dodds, P. S., & Watts, D. J. (2006). Experimental study of inequality and unpredictability in an artificial cultural market. *Science, 311*(5762), 854–856. ISSN: 00368075. https://doi.org/10.1126/science.1121066

Sprigg, C. A., Jackson, P. R., & Parker, S. K. (2000). Production teamworking: The importance of interdependence and autonomy for employee strain and satisfaction. *Human Relations, 53*(11), 1519–1543.

Suler, J. (2004). The online disinhibition effect. *Cyberpsychology & Behavior, 7*(3), 321–326.

Tse, H. H. M., & Dasborough, M. T. (2008). A study of exchange and emotions in team member relationships. *Group & Organization Management, 33*(2), 194–215.

Vallas, S. (2003). Why teamwork fails: obstacles to workplace change in four manufacturing plants. *American Sociological Review, 68*. https://doi.org/10.2307/1519767

Valentine, M. (2018). When equity seems unfair: The role of justice enforceability in temporary team coordination. *Academy of Management Journal, 61*(6), 2081–2105.

Valentine, M. A., Retelny, D., To, A., Rahmati, N., Doshi, T., & Bernstein, M. S. (2017). Flash organizations: Crowdsourcing complex work by structuring crowds as organizations. In *CHI '17* (pp. 3523–3537). https://doi.org/10.1145/30254533025811

Van De Ven, A. H., Delbecq, A. L., & Koenig, R. (1976). Determinants of coordination modes within organizations. *American Sociological Review, 41*(2), 322–338. ISSN: 00031224. http://www.jstor.org/stable/2094477

Van Vianen, A. E. M., & De Dreu, C. K. W. (2001). Personality in teams: Its relationship to social cohesion, task cohesion, and team performance. *European Journal of Work and Organizational Psychology, 10*(2), 97–120.

Watson, R. T., DeSanctis, G., & Poole, M. S. (1988). Using a GDSS to facilitate group consensus: some intended and unintended consequences. *MIS Quarterly, 12*(3), 463–478. ISSN: 02767783. http://www.jstor.org/stable/249214

Woolley, A. W., Chabris, C. F., Pentland, A., Hashmi, N., & Malone, T. W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *Science, 330*(6004), 686–688. ISSN: 00368075. arXiv: arXiv:1011.1669v3. https://doi.org/10.1126/science.1193147

Woolley, A. W., Aggarwal, I., & Malone, T. W. (2015). Collective intelligence and group performance. *Current Directions in Psychological Science, 24*(6), 420–424.

Zakaria, N., Amelinckx, A., & Wilemon, D. (2004). Working together apart? Building a knowledge-sharing culture for global virtual teams. *Creativity and Innovation Management, 13*(1), 15–29.

# Part III
# Design Thinking in Practice: New Approaches and Application Fields

# Design Thinking at Scale: A Multi Team Design Thinking Approach

**Franziska Dobrigkeit, Ralf Teusner, Danielly de Paula, and Matthias Uflacker**

**Abstract** Design Thinking has become an important and widely accepted innovation approach in many companies worldwide. However, it is mostly used in small innovation or research projects, or is outsourced to innovation labs or design agencies. Furthermore, there is little published data on how to leverage Design Thinking for complex applications. Multiple, collaborating development teams are required to construct sophisticated software products for different stakeholder groups. Therefore, similarly to scaled agile development, several Design Thinking teams should be employed in complex software projects to take advantage of parallel work capabilities and to investigate needs and demands of several customers, user and stakeholder groups. However, currently no approaches to scale Design Thinking to multiple teams exist. With this chapter, we aim to tackle this challenge and present a scaled Design Thinking approach, in which multiple teams conceive ideas in a Design Thinking phase and implement the resulting ideas in follow-up projects ultimately converging into one project and product. This approach is validated in an educational context with a master-level seminar and in the resulting follow-up projects in and outside of the curriculum. We discuss our experiences from the case study as well as the benefits and challenges of our approach. With this study we provide first insights on how to scale Design Thinking to multiple teams and how to leverage its capabilities for complex software products.

## 1 Introduction

In recent years Design Thinking has become widely accepted as a method that can achieve radical innovation. Business and management journals have reported on the method (Nussbaum 2004; Beckman and Barry 2007). Efforts to educate students and professionals of different backgrounds in Design Thinking are made around the

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world, e.g. the Stanford,[1] Paris,[2] and Potsdam[3] D.Schools, or the Aalto[4] and Tongji[5] Design Factories. Design companies such as IDEO or major IT companies such as SAP (Bisballe Jensen et al. 2016), IBM (Lucena et al. 2016) and Apple (Thomke and Feinberg 2010) are using Design Thinking for innovation projects.

In case of software companies, the task of conceiving innovative solutions is often outsourced to design agencies or innovation labs. In cases where Design Thinking is actually used inside the main companies, its application is usually restricted to internal or smaller-scale software projects, such as smartphone applications or developments for one specific customer.

Large software projects however, require multiple collaborating teams working in parallel, to construct sophisticated software products targeted at a multitude of different user groups and stakeholders. In such settings it would make sense to scale the Design Thinking phase similar to scaled agile development and employ several design thinking teams. Thus, the teams can take advantage of parallel work capabilities and investigate the needs and demands of several customer, user and stakeholder groups in a shorter amount of time. Additionally, running several Design Thinking teams in parallel allows for the involvement of more developers during this conceptualization phase and thus enables better knowledge transfer and understanding of the product vision and requirements during development.

However, no previous study has investigated how to scale Design Thinking over multiple teams. Accordingly, there is little published data on how to leverage Design Thinking for complex applications in large scale software projects.

In this chapter, we take the first steps to close this research gap and present an initial concept how to scale Design Thinking for multiple teams and later unifying the teams results into one product. Additionally, we present experiences with our approach from a case study in an educational context and discuss the benefits and challenges of our approach.

The rest of this paper is structured as follows: Sect. 2 provides an overview of existing Design Thinking integration approaches in software development and discusses challenges in this field. In Sect. 3, we present our scaled Design Thinking concept, which includes a multi-team Design Thinking workshop series, idea assessments and follow-up projects. A case study using the scaled Design Thinking approach on the topic of improving the software development experience is presented in Sect. 4. In Sect. 5, we discuss the experiences from our case study and conclude the chapter with a summary.

[1]d.school Stanford—http://dschool.stanford.edu/.

[2]Paris-Est d.school—http://www.dschool.fr/.

[3]HPI School of Design Thinking Potsdam—http://www.hpi.uni-potsdam.de/d_school/home.html.

[4]Aalto Design Factory—http://www.aaltodesignfactory.fi.

[5]Tongji Design Factory—http://sfc.tongji.edu.cn.

## 2 Related Work

Over the past decades researchers and practitioners have been discussing how to integrate Design Thinking and software development to accommodate more diverse knowledge, create user-centered and innovative solutions, and address pressing challenges during the software development process. Lindberg et al. (2012) investigated the perception and application of Design Thinking within IT development. Based on interviews with people from the IT-Industry, they identified four general concepts to integrate Design Thinking within software engineering activities. Dobrigkeit et al. discuss two additional approaches based on a literature review of integrated models (Dobrigkeit and de Paula 2019). Table 1 depicts all six models with a brief description. It is notable, that the first three models describe ways to integrate an upfront Design Thinking project or phase into a software development project, while the final three models describe ways to use Design Thinking as a supporting activity during software development.

**Table 1** Possible models to integrate of Design Thinking into IT-development processes based on Lindberg et al. (2012) and Dobrigkeit and de Paula (2019)

| |
|---|
| *Split project model* |
| This model delivers Design Thinking as a service through a specialized Design Thinking team. Their input is then used to kick off software development |
| *Overlapping teams model* |
| This model integrates one or two members of the development team into the Design Thinking team allowing them to bridge the gap between the teams and prevent information loss |
| *Unified project model* |
| This model lets a single team work on both Design Thinking and software development tasks. They gradually switch from Design Thinking to software development when they have sufficiently explored the problem and the solution space |
| *Toolbox model* |
| This model simply introduces Design Thinking as a bundle of creative methods that can be used to solve certain design problems at all stages of the software development process |
| *Continuous design thinking model* |
| This model regularly integrates smaller Design Thinking phases into agile development cycles |
| *Ad-hoc design thinking model* |
| In this model, DT takes on a supporting role during development similar to the toolbox model but is not reduced to single methods. Instead, the process level of Design Thinking can support the application of ad-hoc Design Thinking workshops or phases if required |

## 2.1 Integrated Design Thinking and Software Development Approaches

In reviewing the literature, the same two categories emerged for integrated approaches to Design Thinking and software development. Several researchers and practitioners propose processes that place Design Thinking as an initial phase before software development. The unified project model seems to be the most suggested approach to this scenario (Hildenbrand and Meyer 2012; Grossman-Kahn and Rosensweig 2012; Dobrigkeit et al. 2018; Ximenes et al. 2015; Gurusamy et al. 2016; Glomann 2018; Sohaib et al. 2018). Most approaches are split into two or three phases. Two-phase approaches follow the initial Design Thinking phase with a subsequent development phase (Grossman-Kahn and Rosensweig 2012; Ximenes et al. 2015). Three-phase approaches include a prototype/initial development phase as an intermediary phase (Sohaib et al. 2018; Hildenbrand and Meyer 2012; Dobrigkeit et al. 2018) between the Design Thinking phase and the development phase. Some proposals additionally include suggestions on how Design Thinking can support software teams during development. The Integrated Design Thinking and Agile Framework for Digital Transformation (Gurusamy et al. 2016), the Human-Centered Agile Workflow (Glomann 2018) and DT@XP (Sohaib et al. 2018), for example, suggest a regular integration of smaller Design Thinking phases into agile development cycles and represent the continuous Design Thinking model. Among the ad-hoc Design Thinking models which suggest the use of Design Thinking as necessary in later stages of the development process are InnoDev (Dobrigkeit et al. 2018) and Converge (Ximenes et al. 2015). InnoDev proposes to run Design Thinking phases when new features are added to the scope of the product and makes use of Design Thinking breakouts in case of blockers. Converge suggests the use of Design Thinking "knots" in case when the team needs to solve a specific problem. Such knots are workshops facilitating one step of the Design Thinking process. Additionally, some guides and toolboxes have been developed which can support such ad-hoc use of Design Thinking similar to the suggested toolbox model. For example, the UX Toolbox created by Pedersen (2016) or the DT@IT Toolbox (Dobrigkeit et al. 2020). The UX Toolbox is designed to reduce the workload of UX experts by enabling developers to take on some of the UX work themselves. Similarly, the DT@IT Toolbox is designed to support developers with Design Thinking methods which are helpful during everyday development activities.

In the industry, software companies such as SAP, IBM, and Microsoft are integrating Design Thinking into their processes. Running Design Thinking before development is the most common approach. Examples of the split project model or overlapping team model can be found in projects featuring design agencies or internal design teams working together with a development team in the software company to create a software product. For example, SAP's early approach to integrate Design Thinking into all their divisions was to establish the Design Services Team with the purpose to "to improve the design of SAP software solutions as well as provide the organization with the means to scale up its adoption of Design Thinking" (Holloway 2009). Another common approach to integrate Design Thinking into software companies is the creation of subdivisions for innovation and research projects often called innovation or research labs (Chartron et al. 2011). Because such labs are not based in the company, they can make use of processes and workflows that could not be used inside the main company. This is why such labs are a good way of testing and implementing Design Thinking. Furthermore, these labs usually have small teams that are responsible for a project from the beginning and thus resemble the unified project model (Lindberg et al. 2012). The integrated Design Thinking and Lean Development approach (Hildenbrand and Meyer 2012) or the Nordstrom Innovation Lab process (Grossman-Kahn and Rosensweig 2012) are examples of such setups.

However, the presented approaches have been evaluated either only within smaller projects and teams and often in an educational context, or not at all. The approaches that have been used and evaluated in companies were employed in small scale projects where the project team was separated from the main company. Brenner et al. found that such a separation allows a flexible and fast reaction to changing demands, while also resulting in an "IT of two speeds" (Brenner et al. 2012). The slow development in the main company is separated from the fast and innovative development in the company's innovation divisions. This separation reflects the different degrees of complexity we see in today's IT-companies. There are specific small-scale applications and research projects which do not have to comply with the restrictions and processes companies establish for their large-scale software development. Thus, these projects can be developed by small teams in a start-up like fashion. On the other hand, the development of large and complex software systems such as Enterprise Resource Planning (ERP) or Customer Relationship Management (CRM) systems is subject to different standards, legal constraints, and numerous non-functional requirements, such as availability or security. Additionally, such software systems are developed with several teams of developers, architects and designers. This means, the chosen development process must be able to scale up to accommodate this scenario (Ambler 2009).

## *2.2 Scaled Agile Approaches*

To accommodate multi-team software development in the agile world, several different approaches have been developed to scale scrum for multiple teams, e.g. Larman and Vodde (2014), Schwaber (2018), and Sutherland (2019). While the proposals differ in some ways, they share two important ideas. (1) A small number of people is responsible for decisions regarding the project content and priorities. For example, the NEXUS approach proposes to set up a nexus integration team. This is an overarching team accountable for ensuring a "Done" integrated increment after every sprint. This team also includes the single Product Owner for all the scrum teams (Schwaber 2018). Similarly, LeSS prescribes a single Scrum Master for one product developed by several Scrum Teams (Larman and Vodde 2014). Scrum@Scale on the other hand proposes a team of product owners with a Chief Product Owner and a team of Scrum Masters with a Scrum of Scrums Master (Sutherland 2019). (2) The different approaches also agree on keeping the meeting and communication overhead limited while exchanging information between all teams and ensuring a common goal. To this end, all three approaches propose meetings in which delegates from each Scrum team are present. Scrum@Scale only prescribes a Scaled Daily Scrum meeting (Sutherland 2019). LeSS prescribes scaled versions of the backlog refinement, the sprint planning, the retrospective and the review, with refinement, planning and retrospectives also happening on the team level (Larman and Vodde 2014). Nexus prescribes overall and team level daily scrums as well as overall and team level planning, and additionally prescribes overall reviews and retrospectives (Schwaber 2018).

All three approaches can be applied in developing large scale software projects with multiple teams. However, if such a project should start with a Design Thinking phase as presented in the integrated approaches (cmp. Sect. 2), it is necessary to investigate and understand the problems of a multitude of user groups, stakeholders, and their required features. A single Design Thinking team would need a great deal of time to create the necessary knowledge and to design an integrated solution concept. Being able to scale Design Thinking to multiple Design Thinking teams in such a project would save time and enable the creation of user-centered and innovative solutions for large software projects. To the best of our knowledge, so far no approaches to scale Design Thinking for multiple teams exists.

## 3 DT@Scale: Design Thinking at Scale Concept

In order to reach our goal of taking the first steps towards scaling Design Thinking for multiple teams and converging the different result towards implementation as one product, we first created a concept for scaling Design Thinking based on the following research questions:

RQ1: How can we scale the Design Thinking process to multiple teams and ensure sufficient communication between teams?

RQ2: How can we validate and develop the resulting concepts from several teams when aiming for an integrated product?

When developing the scaled Design Thinking concept, we mainly looked for guidance in existing approaches to scaling agile processes and to integrating Design Thinking and software development (cmp. Sect. 2). Additionally, we drew from our experience with various Design Thinking projects in industry and educational contexts.

In order to scale Design Thinking for multiple teams and implement the resulting concepts as one software product, we propose an initial Design Thinking phase that can be implemented with several teams. Following this phase we suggest a phase in which initial prototypes (proof of concepts or MVPs) are developed to answer open questions, ensure technical feasibility, and test the concepts with users. In a third phase, the different prototypes can be integrated into one product that is further developed using scaled agile approaches.

### *3.1 Scaled Design Thinking Phase*

During the scaled Design Thinking phase several self-organized Design Thinking teams work in parallel on a common challenge and create several solution concepts for the challenge at hand.

The teams share an overall challenge owner and a project lead, who is responsible for answering any questions regarding the challenge and providing access to interview partners and research materials. In cases where the project is commissioned by an external customer, this role could be filled by a customer representative who is responsible for the project on the customer-side. Additionally, an internal project lead should be appointed who is responsible for organizing the activities during this phase. In cases where the project is commissioned internally, both roles can be filled by the internal project lead. In both cases, the challenge should be decided with higher level management to ensure their general support. Participants for the Design Thinking teams should be selected according to their field of expertise and position in the company. We recommend building several diverse teams with software developers, architects, designers, user researchers and staff from sales and marketing. This ensures that all stakeholders inside the company have a part in the project and no one feels left out. Additionally, a diverse team ensures that the different viewpoints of sales, development, and design are respected when it comes to creating product concepts. In case special knowledge on certain technologies or domains is required for the chosen challenge, experts for this knowledge have to be part of every Design Thinking team. Additionally, each team should be guided by a coach to ensure that the Design Thinking process is properly implemented. Similar to a Scrum Master, the coach supports the team while they work and helps them with impediments, method knowledge, and facilitating team discussion and meetings.

We propose to structure activities during this phase through a series of 1- or 2-day workshops that allow the project lead to track progress in the different teams and provides the teams with an opportunity to exchange ideas and feedback. The series of workshops can either be planned ahead with a given time-frame or adapted as needed depending on the teams' progress. Figure 1 depicts an example for such a workshop series.

In order to prepare the workshop series and ensure that teams can quickly gain the knowledge required to address the challenge, the challenge owner, the project lead and the coaches collect and prepare initial research material about similar products and research in the field. Depending on the challenge, they recruit suitable customer contacts and other stakeholders as interview and test candidates or project partners for the project. Additionally, internal or external domain and technology

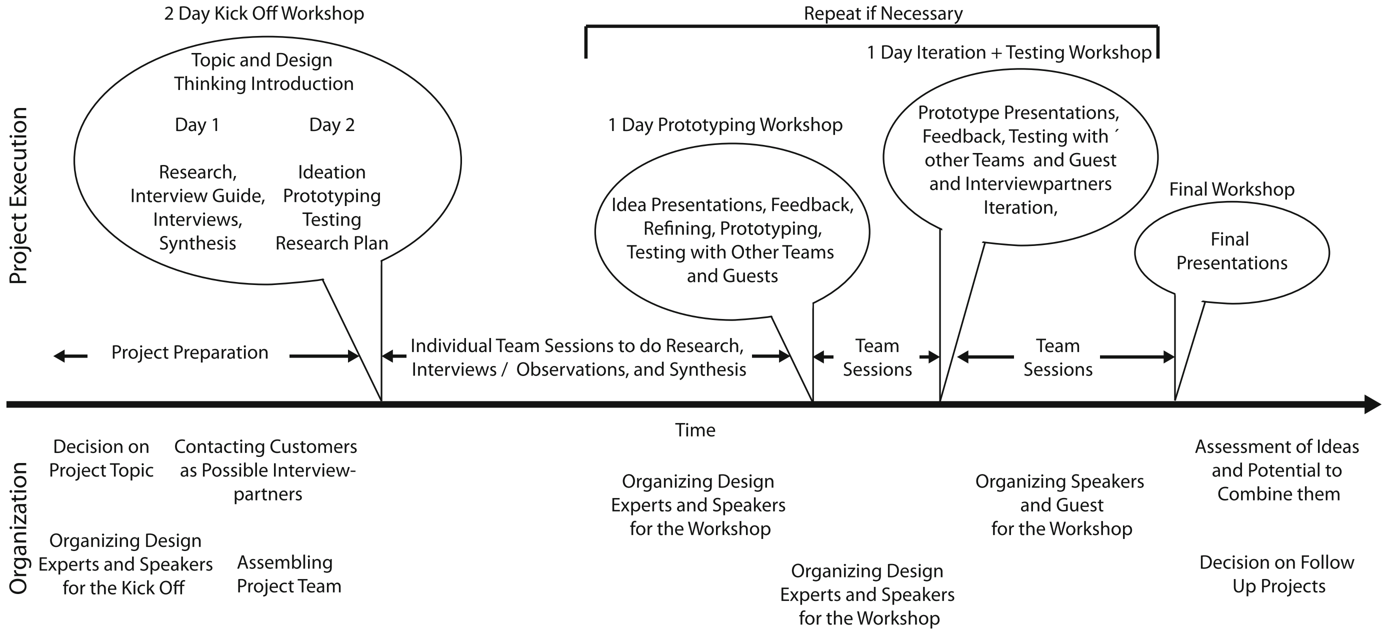


**Fig. 1** Example for a scaled Design Thinking workshop series

experts can be recruited as consultants and speakers for the workshops to support the teams with knowledge in their area of expertise. To avoid copyright problems and issues stemming from differing customer and expert partnership expectations, customer co-development agreements or similar contracts can be created and signed beforehand. Following this preparation, the series should start with an initial kick-off workshop to introduce the challenge for the teams and, if necessary, introduce Design Thinking. Internal or external domain and technology experts should be invited to share their knowledge with the project participants in presentations and discussions allowing them to quickly get into the topic. The Design Thinking coaches guide the participants through the workshop and provide input and help with Design Thinking techniques as necessary. Within this kick-off workshop, the teams can run through the Design Thinking process in a fast-forward fashion. Prepared research materials about similar products and research in the field ensure an easy and quick starting point for the teams. A few invited customers serve as the first interview contacts to gain insights and practice interviewing techniques. Afterwards, a first round of brainstorming and an exchange between the teams helps to share and spark new ideas. Quick and easy prototypes, e.g. sketches or clickable wire-frames, can be tested with the interview partners. After such a fast-forward Design Thinking iteration, each team creates a detailed research plan with the interview partners provided and possibly additional contacts. After the initial workshop the teams embark on their research phase: interviewing and observing customers and researching existing solutions and ideas. Each team should setup a synthesis workshop to share research results and define their point of view. Following the research phase and synthesis workshops, the teams come together in an ideation and prototyping workshop. This workshop introduces ideation, prototyping and testing techniques as well as ways to collect feedback. Additionally, it allows the teams to exchange their research findings, come up with initial ideas and share them with each other, and experience prototyping and initial testing situations with the other teams. Following this workshop, each team creates one or more prototypes and then validates their ideas and assumptions by testing their prototypes with end-users during the prototyping and testing phase. This phase should be concluded with team internal synthesis workshops to share test results. Following the research and test phase, alternating iteration workshops and team work phases can drive the further development of concepts as necessary. In an overall final workshop all teams present their findings and their final concept to the other teams concluding the workshop series and the scaled Design Thinking phase.

## *3.2 Prototype Development Phase*

During this phase one or several self-organized development teams create high-level prototypes of the solution concepts generated during the scaled Design Thinking workshop series. These prototypes ensure technical feasibility, viability, and desirability. They also help to clear up any assumptions, open questions, and conceptual issues. During this phase, concepts might be combined into a joined prototype. After this assessment key-users and key-stakeholders interviewed by the team should be recruited as project partners for the follow-up projects.

We propose structuring activities during this phase into an initial assessment of the concepts from the scaled Design Thinking phase and several smaller follow-up projects in which these ideas will be prototypically implemented.

For the assessment, management, the project lead, and the challenge owner discuss and assess the generated ideas, based on documentation created by the Design Thinking teams, low-fidelity prototypes, and presentations from the final workshop. They decide which ideas will be developed into higher level prototypes. They should consider which ideas have open technical or conceptual issues and think about combining concepts to a greater product vision. The assessment of ideas can follow different criteria, for example, budget, time, necessary effort, or existing knowledge within the teams. For each concept that should be implemented as a prototype, a follow-up project is set-up and one or more development teams are staffed for the project. These projects can follow standard agile or scaled agile development. For the staffing of teams we recommend following the unified project model and recruiting team members for the follow-up projects from the Design Thinking teams in which the concepts were created. Ensuring that part or all of the development team know how the concept was developed, helps prevent the "not invented here" syndrome and guarantees that the necessary knowledge to implement the concept is present within the team.

In case several follow-up projects are established in parallel, the project lead should establish and encourage communication between the different projects. Thereby enabling the teams to learn from each other and ensuring that the different projects will integrate with each other once it comes a larger development project starts.

## *3.3 Product Development Phase*

During this phase several development teams implement and deliver the final product, which merges insights and refined concepts from the different follow-up projects.

After the different concepts have been sufficiently validated and refined, management, the project lead, and the challenge owner once more asses the outcomes of the prototyping phase and decide which concepts will be integrated into the final product vision.

Afterwards, a number of development teams can be staffed to implement the product in a scaled agile development process. The team members should be recruited from the former Design Thinking and development teams to ensure knowledge transfer.

### 3.4 Conclusion

This section presents a general approach to scale Design Thinking to multiple teams and implement the ideas generated by these teams in follow-up projects converging to one project. The approach facilitates the use of Design Thinking for large scale software development projects. It can be combined with Scrum or scaled Scrum development processes or incorporated into other existing approaches that merge Design Thinking and agile software development such as Grossman-Kahn and Rosensweig (2012), Hildenbrand and Meyer (2012), Ximenes et al. (2015), Dobrigkeit et al. (2018), and Sohaib et al. (2018).

## 4 Case Study: Improving the Software Development Experience

To validate the DT@Scale concept, we ran a case study in an educational context. The case study included a Design Thinking seminar and a series of smaller and larger follow-up projects set up as either research or student development projects. For data analysis, we observed the seminars and projects and collected artifacts such as the documentation from the seminar and reports from the different projects. The case study allowed us to gain practical experience with a scaled Design Thinking approach and follow-up implementations.

### 4.1 General Setup and Concept Adaptations

The workshop series proposed in our scaled Design Thinking concept was implemented in the form of a Design Thinking seminar consisting of five phases: a preparation phase, a 2 day kick-off workshop, a research phase, a seminar week, and a documentation phase. Due to the educational context, some adaptations to the scaled Design Thinking concept had to be made.

As proposed in the DT@Scale concept (cf. Sect. 3), the kick-off workshop introduces the teams to Design Thinking and the topic of the seminar. During the following research phase each team ran through the "understand" and "observe" phases of the Design Thinking process and conducted desk research as well as ethnographic research. At the end of the research phase the teams met for an internal synthesis workshop. For our case study, we had to compress the rest of the proposed workshop series into the seminar week, in which the ideas were refined, prototyped and tested. At the end of the week each team presented a final prototype. In the educational context, we cannot guarantee that team members from the Design Thinking teams will be available for follow-up projects. Therefore, we included a documentation phase in which the Design Thinking teams document their process throughout the seminar and their ideas, including discarded ideas, open questions and possible implementation of their final prototype. They also create a video or interactive version of their final prototype.

For assessment of the ideas, we revisited these documentations as a starting point and collected interesting ideas from the final prototypes as well as ideas that came up during the seminar, but were discarded. We then classified the ideas in terms of knowledge required, effort to implement, risk of failure and open questions. With the help of this classification we assigned the ideas to different types of projects we can facilitate at our chair. The available project types are:

- seminar project on bachelor or master-level,
- bachelor project,
- master project, or
- student project outside of a seminar

Generally, projects that run as part of the curriculum in a seminar or bachelor/-master projects should not have a high risk of failure as students are graded on the outcome of the project. In contrast to seminar projects on the bachelor or master level, we distinguish between the "bachelor project" and "master project", which both have vastly different time frames. While the bachelor project is conducted by six students with a workload of about 160 days each, the master project is typically conducted by five students with only 34 working days per person. Projects that require a lot of previous knowledge are more suitable for master students, as these students have already acquired a bachelor degree and appropriate knowledge in software engineering. The implementation effort needs to fit the time available during the course. If the effort is too high or cannot be assessed, we start the projects as student projects outside of the curriculum rather than within a course.

## *4.2 Scaled Design Thinking Seminar*

The design challenge chosen for our seminar asked the following question: "Against the background of new, emerging technologies, how might we enable software developers to faster develop high quality software and how can we provide them with a better user experience?".

During the preparation phase we contacted startups and established software development companies in the Berlin and Brandenburg area to recruit interview partners, such as developers but also managers and employees from support or quality assessment. Additionally, we contacted employees from SAP and asked them to give a presentation on their development process in order to provide the students with insights on software development in a global company.

A total of seven student teams were enrolled in the seminar. For the kick-off workshop we presented the topic to the students and gave them an overview of respective research done at our chair. A contact from SAP presented the SAP development process and the software tools they use. Additionally, he introduced

**Table 2** Overview of problems and solution ideas at beginning of seminar week

| Problem | Solution ideas |
|---|---|
| Onboarding to a new project/code base | Map UI features to underlying code segments |
| Time spent with recurring task such as installing or updating software, writing boilerplate code, waiting for compilation before testing | Run and test code immediately while it is written, automatic proposal of boilerplate code snippets from a company wide database |
| Few or no access to customers and real customer data | Work on real customer data or a subset of such data, enable debugging on the customer system |
| Problems with knowledge sharing, e.g. outdated wiki/documentation | |
| Communication overhead, e.g. helping others interrupts workflow, hard to find the right contact person | Find experts for a piece of code by analyzing submissions of code and documentation, solving of tickets and bugs, emails written, ... |
| No time/not enough knowledge to write good tests | Collect information on the usage of code while software is running and use this information during debugging, testing |
| Finding old or unused code | Collect information on the usage of the code while software is running and use this information to detect unused code |

the students to an average day for an SAP developer. We invited further developers from the SAP Innovation Lab in Potsdam as interview partners during the kick-off workshop. Initial problems identified during the workshop included: meetings interrupting programming tasks, switching often between different software tools, and few or no contact to end users.

During the research phase, the students conducted interviews with the provided interview partners and personal contacts in the software industry. Afterwards, each team synthesized their findings into a point of view and came up with three initial ideas to solve the identified problem.

At the beginning of the seminar week each team presented its findings and ideas. Table 2 provides an overview of the problems software developers encountered as identified by the teams, and the initial ideas to solve these problems.

After presenting their ideas the teams received feedback from the teaching staff, the invited guests and the other students. Following the feedback sessions we gave a presentation on how to use feedback to refine ideas. A second presentation introduced technologies that could be useful when thinking about implementation details for the ideas. Afterwards, all teams were asked to choose and refine one of their ideas with the feedback and possible implementations in mind. The second day of the seminar week was devoted to prototyping and initial testings between teams. The students received a presentation on prototyping techniques and were given useful tips throughout the day from the teaching staff. The third day started out with a presentation on testing methods. The afternoon was reserved for testing with interview partners. On the fourth day the students iterated their ideas and prototypes, based on the feedback received through the user testing. The afternoon was reserved for another round of user testing. The last day of the week was used to prepare and hold the final presentations which concluded the seminar. Table 3 provides an overview of the final prototypes presented by the seven teams.

After the seminar students wrote a 20-page documentation that was used by us to collect and assess their ideas and decide on possible follow-up projects.

## *4.3 Follow-Up Projects*

Table 4 provides an overview of the projects we set up following our scaled Design Thinking seminar. While there are plenty of details for each project, the following sections focus on the actual progress in the projects. Apart from that, the surrounding conditions that allow comparing and relating the projects to each other are briefly mentioned.

### 4.3.1 Seminar Project: Immediate Feedback

**Findings/Need** The cycle of writing, compiling and testing software is very time consuming and often requires context switches. This is especially true when writing database queries because these are often tested in a database console outside of the development environment. Thus, they not only require a context but also a tool switch.

**Aim** To demonstrate the technical feasibility and the value of immediate feedback in the development environment.

**Setting**

Required skill level: Master
Number of students: 3
Time frame: 4 h per week each student, 5 month seminar
Method: Team-driven development, feedback sessions with advisor, user testing with the final prototype

**Progress** The seminar was focused on building a prototype that was integrated in a programming environment and used immediate feedback for a database-related scenario. The team mostly consisted of Ruby developers. Therefore, they decided to build a plugin for the Redcar editor[6] and tackle the problem of writing ORM code, an object oriented way of writing database queries. The first issue was to write a parser that could detect and extract working ORM queries in a Ruby code file, especially ORM queries that are built within conditional branches and over multiple lines of code. The second issue that had to be addressed was integrating

[6] http://redcareditor.com/.

**Table 3** Overview of the final ideas and prototypes from our scaled Design Thinking seminar

| Prototype | Idea and concept |
|---|---|
| Extrapolating storage engine | A storage engine that scales the available data-set according to a scale factor allows application developers to test their application with growing data-sets. This approach saves them from having to prepare CSV files for the different required data volumes and having to load them into the database. Thus, it speeds up the performance testing for database volumes of different sizes |
| WebIDE | This prototype is an online IDE that provides developers with everything they need to develop simple applications, while releasing them from having to set up the development environment. Furthermore this approach merges the development and the actual application environment enabling developers to react faster to customer feedback |
| E2EViz—End-to-end profiler | E2EViz is a tool for real-time performance analysis based on end-to-end visualization of execution traces. This tool helps performance engineers to quickly locate performance leaks when profiling a production systems |
| Real time performance estimation | This prototype enables developers to faster develop high quality software by providing instant performance feedback for every database query they implement. It lets the developers concentrate on their code while observing query run times on the fly—consequently avoiding the implementation of slow queries |
| Providing data context during development | This prototype also provides instant data and performance feedback on database queries. In addition to the former prototype, it provides the developer with information on different contexts where the query is used, e.g. different views and reports using the query. Thereby, the prototype enables developers to be aware of different contexts and estimate performance and the data returned by the query |
| Code badger | This project is an IDE Extension that enables developers to find and use existing knowledge on pieces of code. The extension collects information from documentation, commits, tests and discussions and provides the information as well as people who are associated with the code. Furthermore, the extension enables the developer to comment on the code or start a discussion with an expert |
| Explorative-testing-plugin | This plugin enables developers to explore the available data sets and proposes suitable test cases while they are writing code, thus minimizing the context switch between implementation and testing |

**Table 4** Overview of projects following scaled Design Thinking seminar

| Project name | Type of project | Team size | Time frame | Outcome | Follow-up |
|---|---|---|---|---|---|
| Immediate feedback (P1) | Seminar project | 3 | 4 h/week, 5 months | Functional prototype with minor technical issues; results from developer testing; technical documentation | Findings and ideas integrated in P4 |
| Data generator (P2) | Student project | 3 | 9 h/week, 3 months | Functioning prototype; results from user testing; technical documentation | Handover to software company for production; used in P4 |
| Developer needs (P3) | Student project | 2–3 | 9 h/week, 9 months | Documented interviews and synopsis; implementation ideas; functioning prototype; technical documentation | Findings served as input for P4 |
| Development experience (P4) | Bachelor project | 6 | 10 h/week, 6 months + 32 h/week, 6 months | Functioning prototype; bachelor theses documenting the work | |

the parser into the editor and extracting the ORM queries while code is written in the editor. Here the team had some problems as the editor did not allow multiple threads and the parser sometimes blocked the writing process. However, the team decided to overlook this technical issue as it was mainly a problem of the editor selected, which could be exchanged later for another editor. The final issue to solve before user testing was querying a database with the extracted query and showing the results inside the editor. Finally, the team tested its prototype with several Ruby developers to evaluate its usefulness.

**Outcome** technical prototype, user feedback from testing with developers, technical documentation.

### 4.3.2 Student Project: Data Generator

**Findings/Need** Developers tend to test their software too late. Additionally, the amount of test entries is usually far too small.

**Aim** Providing a tool for developers that allows them to easily generate appropriate test data for their applications that reflects real world data characteristics.

**Setting**

Required skill level: mixed: master for algorithms and architecture, bachelor for user interface, tests, bug fixes, etc.
Number of Students: 3
Timeframe: 9 h per week each student, 3 month "epics", variable sprints. Total runtime from April 2013 until end of April 2014
Method: team driven development, usage driven addition of new features, sporadic external user tests

**Progress** The data generator project started with a clear mission statement and a focus on tool development. The first goal was to develop a useable prototype that is integrated into the Eclipse development environment. After the first 3 months, it was decided that we wanted to aim for a more responsive user interface that presents the user with direct previews of the currently generated results. Therefore, the front-end technology was exchanged. And a dynamic web interface was developed to replace the Eclipse plugin. The back-end part was kept stable and was further enhanced with more complex functionalities like assistive configuration, datatype inference, and advanced distribution functions. Subsequent to this second epic, it was decided that the back-end technology should be exchanged to better comply with the database environment. The students were confident to transfer the learned principles to a new technology, given the fact that we could reuse the front end completely. Having the opportunity to test different technologies, the functionality was ported to SQLScript as well as XSJS. The project and the implemented prototypes were shown to interested internal and external parties on different occasions. The project received interest and approval. A cooperation with the SAP Innovation Center Potsdam was established. By that time, the developed prototype satisfied most of the requirements our research group had for internal usage. It became clear that it would not be reasonable to go the remaining way to guarantee reliable product quality in the university context. We agreed to completely hand over the project to SAP and take on the role of a stakeholder in the sense of a customer. Consequently, the last 3 months were spent on precise interface descriptions, documentation and code as well as knowledge transfer.

**Outcome** Three prototypes, feedback, technical documentation.

### 4.3.3 Student Project: What Information Does a Developer Need?

**Findings/Need** Developers have to spend remarkable amounts of time searching for additional information. They would, however, prefer to stay in their “coding flow” and encounter fewer interruptions.

**Aim** Outline the most pressing information need and develop a prototypical solution to solve this drawback.

**Setting**

Required skill level: bachelor, training was done as part of the project
Number of Students: 2–3
Time frame: 9 h per week each student, 3 month “epics”, total runtime of about 9 months (Mai 2013–Jan 2014).
Method: Interviews, user observations, clustering and idea building during the first sprint. From second sprint on, coding in monthly sprints.

**Progress** The first part of the project was all about user studies and information retrieval. The students received some training on user testing and observation, after which they conducted a total of ten interviews. Additionally, paper research was conducted. The overall approach was mostly “standard” Design Thinking. The gathered information from observations and interviews was clustered and condensed into a total of five ideas after 3 months. Selecting the idea to pursue was also driven by the requirement to implement it within 3 months. The second part was mostly “standard” software engineering, meaning technology and tool tests in the first 2–3 weeks. Afterwards some unstable prototypes were followed by more stable ones. In the third part, the software was tested with some of the initial interview partners and additional small feature requests were incorporated. A documentation phase marked the completion of the project. The students wrote a technical documentation as well as a short user manual and created a logo for their project. The results are presented in our public wiki. The last action, before the students were assigned to other projects, was open general and personal feedback from all supervisors.

**Outcome** Ten documented interviews, synopsis, five implementation ideas, documented working prototype.

### 4.3.4 Bachelor Project: Data and Performance Aware Development

**General Remarks** This project combines and interweaves ideas and learnings that originated from the Design Thinking sessions of the seminar as well as from the mentioned projects that were run beforehand.

**Findings/Need** Development of complex applications often results in slow and unmaintainable code. These downsides are caused by lack of knowledge about the behavior of the application under realistic circumstances, running on real data reflecting actual business characteristics. Even if this data is available in principle, it is usually not incorporated into actual development because it is too difficult to integrate and handle as data sizes in enterprise computing might be extreme.

**Aim** Prototyping an integrated development environment that sharpens data awareness by combining explorative visualization with immediate feedback.

**Setting**

Required skill level: bachelor, training was done as part of the project
Number of Students: 6
Timeframe: 10 h per week per student within the first 6 months, afterwards 32 h per week and student in the second 6 months

**Progress/Experience Report** First half: We started with a hands-on coding task, having the students implement a simple and tiny web-shop with the technologies and frameworks typically used for enterprise software development. The task had a deadline of 2 weeks, forcing students to work under time-pressure while getting familiar with the tools. This way, we simulated real conditions that usually lead to bad code and slow applications. Just before the students had their slot to show their web shop to the teaching team, we increased the data volume in the database by a factor of 10. The effect was, as intended, slow response time and a partly broken user interface. The students were partly irritated by this “unfair interference” but calmed down when we assured them that they solved their given task to our full expectation and were asked to reflect about their experiences. Based on the insights gained, the students picked constant data visualization and runtime estimation as their main goals to work on. The following weeks were mostly spent on interviewing and shadowing developers to validate the relevance of their aims and assumptions. Right after the consolidation of the insights, the team received tasks that covered three major parts, focusing on different aspects of the intended solution. The first part focused on bridging the gap between the language to communicate with the database (i.e. SQL) and the language to express imperative program logic (i.e. JavaScript). The second part required predicting runtimes and result sizes of database queries based on small samples and machine learning approaches. Finally, the third part was to provide automatically generated test cases and to visualize the results. It was noticeable that from that point on the team formed three sub-teams of two, each working on one of the aforementioned parts. While the sub-teams were not separated in any way, they drifted slightly apart concerning project understanding and working style.

Second half: The second half was all about solving the remaining, algorithmically hard problems and bringing the parts together. The sub-teams grew together again with the rising pressure of deadlines and presentations. The most important learning in regard to the team and project progress was that increased workload might actually help to solve social team issues, if the surrounding conditions fit and the situation is monitored and navigated. In our case, the increased stress pulled the team together and increased productivity as well as satisfaction in the end. With regard to the technical outcome, the developed web-IDE joins the languages SQL and JavaScript seamlessly into one editor and provides users with helpful information about the underlying data. Thus, the prototype fulfills the expressed needs and expectations.

**Outcome** A working prototype, a poster explaining the features and benefits, a presentation and six bachelor theses.

## 5 Discussion

We deem our case study to be successful overall. The thorough preparation of the workshop and the seminar, including the provision of initial research material and the organization of experts and interview partners as contacts for the team, was the key to successful team work in the limited time available for the seminar. The frequent presentations of the teams during the workshop and the seminar week ensured that everyone knew what the other teams were working on and encouraged feedback and discussions between the teams, which in turn encouraged the teams to build on each other's ideas. No two teams came up with the same idea, even though they shared interview partners and talked to the same user groups. Furthermore, most of the prototypes presented at the end of the seminar week had the potential to be combined into a larger software system. The documentation and interactive prototypes submitted by each team after the seminar, provided a good starting point for student teams working in one of the follow-up projects. They conveyed the general idea to students new to the topic and provided an overview of the team's process that helped the new students to understand why the idea emerged.

Figure 2 depicts the flow of ideas through projects until the time of writing for this case study. As can be seen, some ideas needed refinement or technical or conceptual validation. Therefore, we started smaller student projects. The bachelor project is a bigger project combining several ideas from the seminar and the follow-up projects.

After assessing the ideas and outlining actual projects and tasks to be carried out, we ran the projects and noticed a constant change in the focus of the projects. The progress in one project uncovered additional problems and thereby spawned new ideas in another. A constant exchange between the developing student teams

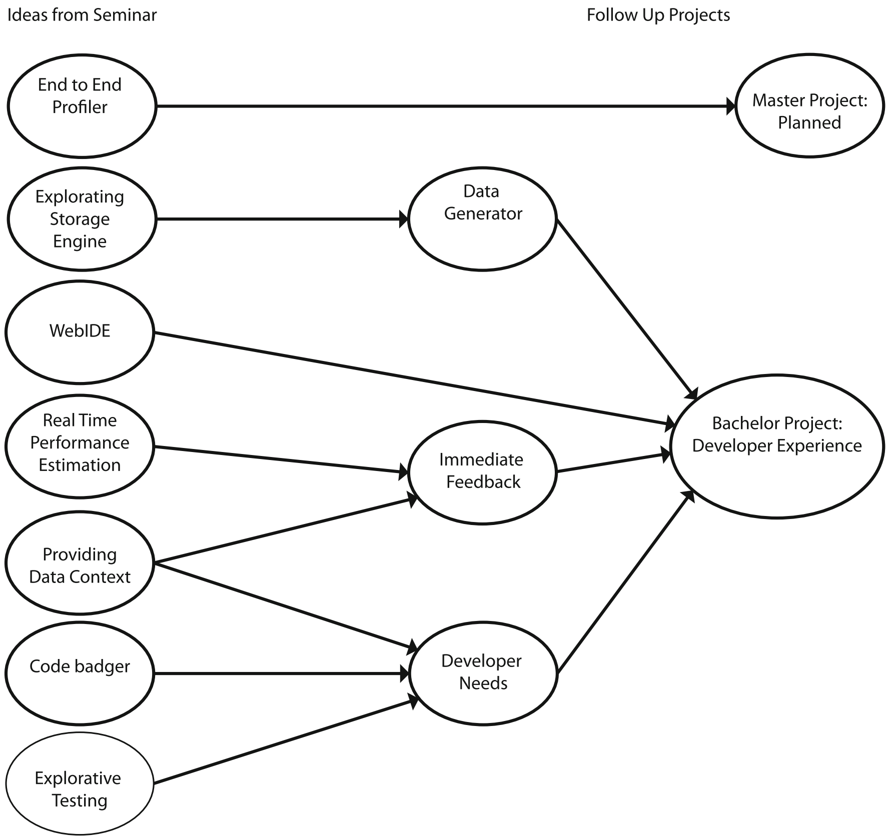


**Fig. 2** Connections of ideas and projects for case study

helped to build on each other's ideas. Thus, it was not only important for Design Thinking activities but proved to be equally important during software development. For example, the bachelor project used the data generator developed in another project to simulate challenging data characteristics. On the other hand, the team developing the data generator integrated a simplified version of their frontend into the bachelor's project web-IDE. On both occasions, potential features were wished for, additional use cases were uncovered, and valuable feedback was gained. Despite the fact that each team had a different focus and background, they shared the mutual aim to advance their prototypes. They knew that they were not competing against each other but profited from each other, an important condition for fostering idea and knowledge sharing between teams.

### 5.1 Benefits and Challenges

We believe the presented approach is suitable for companies to scale Design Thinking for multiple Design Thinking teams in a project and to kick-start projects with multiple view points and concepts. While we believe our approach provides various benefits some challenges remain.

As discussed in Sect. 2, most approaches that integrate Design Thinking in software companies run smaller scale projects e.g., for specific customers or products like smart phone applications. One reason could be that the number of features and different users and stakeholders are too much to be investigated by a design team of four to six people. Additionally, the authors know of no existing concept for scaling Design Thinking for more or larger design teams in such projects. The approach presented in this chapter aims to fill this gap by allowing several design teams to investigate all user groups and their required features for a large-scale software project.

Similarly to other Design Thinking initiatives in companies e.g., running a Design Thinking phase in the beginning of a project, our concept provides a fast way to get into a new topic and learn a lot about the end user and other stakeholders of a project. With the ability to scale the Design Thinking phase, more project members can take part in this experience. Additionally, integrating a large part of the project team into the concept generation process of a product prevents the "not invented here" syndrome and lets all participants feel represented in the concept.

Apart from these positive aspects we see three main problems that might arise with our concept. The first problem we see is that Design Thinking efforts do not guarantee the creation of a product concept that fits the company's strategy and abilities e.g., user research might show that the users do not need software to solve their problem. This problem exists with other Design Thinking approaches as well. However, running the user research with multiple teams provides an opportunity to find another problem that better fits within the company's strategy. The second problem can be that the different design teams come up with very similar concepts, therefore not allowing for a larger project vision. This could be prevented by letting each design team investigate the needs of a different user group. For example, in the case of creating a new business software, one team investigates controlling, another team investigates sales personnel, another team board members, and so on. A similar problem arises when the different design teams come up with a set of concepts so diverse that they cannot be combined into a larger project vision. In such a case, ideas should be combined to form several project visions, and single concepts that do not combine with any other idea can still be kick-started as small innovation projects.

## 6 Summary and Outlook

In this study, we take the first steps towards scaling Design Thinking to multiple teams. To that end, we created the DT@Scale concept based on existing approaches that to scale Scrum, existing approaches that integrate Design Thinking and software engineering and our experience. The concept proposes a Design Thinking workshop series that can employ multiple teams in parallel working on one shared design challenge. The workshop series is followed by an idea assessment and follow-up projects that converge the ideas into a single coherent product vision.

We evaluated the DT@Scale concept with a case study in an educational environment. The workshop series was implemented as a Design Thinking seminar. The ideas from the seminar were implemented in follow-up projects in and outside the university curriculum.

For our case study the scaling of Design Thinking to multiple teams fulfilled our expectations. The seven Design Thinking teams came up with solution concepts that were prototypically implemented in three follow-up projects and converged into one final project. Thorough preparation of Design Thinking activities and frequent exchange between the teams during the Design Thinking seminar as well as during the follow-up projects were the key to this success and ensured that ideas would not be repeated and instead complemented each other. Our results suggest that working on one project with multiple Design Thinking teams for a complex challenge is a promising way to kick-start large-scale software projects. However, we could only validate our concept in an educational setting. For future work, we suggest implementing DT@Scale in a company setting, in order to gain insights on its applicability to the industry.

This study contributes to academic research by developing and validating a concept to scale Design Thinking for multiple teams and implement the different results into one software product. Moreover, it contributes to the industry by providing insights to practitioners on how to scale Design Thinking implementation to multiple teams.

## References

Ambler, S. W. (2009). The agile scaling model (ASM): adapting agile methods for complex environments. *Environments*. IBM.

Beckman, S. L., & Barry, M. (2007). Innovation as a learning process: Embedding design thinking. In *California management review, 50*(1), 25–56.

Jensen, M. B., Lozano, F., & Steinert, M. (2016). The origins of design thinking and the relevance in software innovations. In P. Abrahamsson, A. Jedlitschka, A. Nguyen Duc, M. Felderer, S. Amasaki, & T. Mikkonen (Eds.), *Product-focused software process improvement* (Vol. 10027, pp. 675–678). Cham: Springer International Publishing.

Brenner, W., Uebernickel, F., Wulf, J., Zelt, S., Györy, A. A. B., Heym, M., et al. (2012). *Strategies for application management services*. University of St. Gallen.

Chartron, J., Steinhoff, F., & Paulssen, M. (2011). User driven innovation@ telekom laboratories-das innovationsforum. *Ideenmanagement-Vorschlagswesen in Wirtschaft und Verwaltung, 37*(1), 14.

Dobrigkeit, F., & de Paula, D. (2019). Design thinking in practice: understanding manifestations of design thinking in software engineering. In *Proceedings of the 2019 27th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering – ESEC/FSE 2019* (pp. 1059–1069). New York, NY: ACM Press.

Dobrigkeit, F., de Paula, D., & Uflacker, M. (2018). InnoDev – A software development methodology integrating design thinking, scrum and lean startup. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking – Research looking further: Design thinking beyond solution-fixation. Understanding innovation* (pp. 199–228). Cham: Springer.

Dobrigkeit, F., Pajak, P., de Paula, D., & Uflacker, M. (2020). DT@IT toolbox: Design thinking tools to support everyday software development. In *Design thinking research investigating design team performance. Understanding innovation* (pp. 201–227). Cham: Springer.

Glomann, L. (2018). Introducing human-centered agile workflow (hcaw) – an agile conception and development process model. In *Advances in usability and user experience* (Vol. 607, pp. 646–655). Cham: Springer International Publishing.

Grossman-Kahn, B., & Rosensweig, R. (2012). Skip the silver bullet: Driving innovation through small bets and diverse practices. In *Innovation through Design: Proceedings of the DMI 2012 International Research Conference*. ISBN 978-0-615-66453-8 (electronic)

Gurusamy, K., Srinivasaraghavan, N., & Adikari, S. (2016). An integrated framework for design thinking and agile methods for digital transformation. In A. Marcus (Ed.), *Design, user experience, and usability: Design thinking and methods* (Vol. 9746, pp. 34–42). Cham: Springer International Publishing.

Hildenbrand, T., & Meyer, J. (2012). Intertwining lean and design thinking: Software product development from empathy to shipment. In A. Maedche, A. Botzenhardt, & L. Neer (Eds.), *Software for people: Fundamentals, trends and best practices. Management for Professionals* (pp. 217–237). Berlin: Springer.

Holloway, M. (2009). How tangible is your strategy? How design thinking can turn your strategy into reality. *Journal of Business Strategy, 30*(2/3), 50–56.

Larman, C., & Vodde, B. (2014). *Large-scale scrum: More with LeSS*. Upper Saddle River: Addison-Wesley.

Lindberg, T., Köppen, E., Rauth, I., & Meinel, C. (2012). On the perception, adoption and implementation of design thinking in the it industry. In *Design thinking research* (pp. 229–240). Berlin: Springer.

Lucena, P., Braz, A., Chicoria, A., & Tizzei, L. (2016). IBM design thinking software development framework. In *Brazilian workshop on agile methods* (pp. 98–109). Cham: Springer.

Nussbaum, B. (2004). The power of design. *Business Week, 17*(5), 2004.

Pedersen, T. Ø. (2016). UX Toolbox for Software Developers (Doctoral dissertation, Ph. D. thesis).

Schwaber, K. (2018). Nexus guide – the definitive guide to scaling scrum with nexus: The rules of the game. https://www.scrum.org/resources/nexusguide

Sohaib, O., Solanki, H., Dhaliwa, N., Hussain, W., & Asif, M. (2018). Integrating design thinking into extreme programming. *Journal of Ambient Intelligence and Humanized Computing, 10*, 2485–2492.

Sutherland, J. (2019). The scrum@scale guide – the definitive guide to scrum@scale: Scaling that works. von Scrum Inc. https://www.scrumatscale.com/wpcontent/uploads/Scrum@Scale-Guide.pdf

Thomke, S., & Feinberg, B. (2010). Design thinking and innovation at apple. *Harvard Business School*, 9-609-066, March 2010.

Ximenes, B. H., Alves, I. N., & Araújo, C. C. (2015). Software project management combining agile, lean startup and design thinking. In A. Marcus (Ed.), *Design, user experience, and usability: Design discourse* (Vol. 9186, pp. 356–367). Cham: Springer International Publishing.

# Design Guidelines for Early Childhood Computer Science Education Tools

**Griffin Dietz, Jenny Han, Hyowon Gweon, and James A. Landay**

**Abstract** The current literature on developing tools for early childhood computer science education focuses primarily on the *content* of the lessons and how to embed that content into educational technologies. However, in considering "CS For All" it is critical to understand how the environment and approach surrounding the technology itself can best serve both students and educators in learning this material. This chapter presents results from a grounded-theory analysis of classroom observations and in-depth semi-structured interviews with both students and educators. We contribute to an understanding of how intentional design—via eight specific design considerations—can lead to more accessible, approachable, and engaging technologies.

**Keywords** Computer science education · Education technology · Early childhood · Design guidelines

## 1 Introduction

In recent years, we've seen a global push to teach computer science to children of all ages. At the early elementary school level (ages 5–8), in particular, this effort is largely driven by three main objectives: to teach children computational thinking and computational literacy, to build skills and foster preparedness for a child's later educational career, and to broaden future participation in a field that lacks diverse representation (Guzdial 2015; Wing 2006; Brennan and Resnick 2012).

Critically, early school-age children already have the cognitive capacities to understand many abstract computing concepts and practices, as evidenced by their ability to engage in abstract reasoning and learning (Gopnik 2012; Schulz 2012). For instance, preschool-age children construct novel hypotheses from observations

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via inductive generalization and design novel experiments to test these hypotheses in a manner that resembles the debugging process (Cook et al. 2011; Legare 2012). In line with the objectives of algorithmic efficiency and optimization, prior work has shown that even infants expect rational agents to act in ways that minimize cost (Gergely et al. 1995; Scott and Baillargeon 2013), and they infer the reward an agent assigns to a goal based on the cost incurred to achieve it (Liu et al. 2017). Finally, evidence suggests the rapid development of planning abilities between ages 4 and 6, including an increase in the number of steps children can plan ahead to solve a problem (Klahr and Robinson 1981; Gardner and Rogoff 1990). These skills are critical to decomposition and abstraction. Indeed, a direct study of children's capacities for problem decomposition demonstrates that the ability to evaluate extant decomposition plans emerges around age 4, and that children's abilities to generate these plans themselves continues to develop in the years following (Dietz et al. 2019). Collectively, these early-emerging capacities to generate and test hypotheses, reason about efficiency, engage in advance planning, and successfully decompose complex problems suggest that the basic aspects of computational thinking are in place by the time students begin formal schooling.

Today, the technologies that exist to teach or learn computer science and computational thinking in early school years often fall into one of two categories: block-based programming languages or programmable robots.

Block-based languages remove the barrier of programming syntax by leveraging function blocks that fit together only when syntactically correct. Children are then able to focus on the content and structure of their program without worrying about whether the program will run. Critically, though, Scratch (Resnick et al. 2009) and Blockly (Fraser et al. 2013), arguably the most prominent block-based languages, still incorporate written text and therefore may not effectively reach the early elementary audience. At this point in their schooling, children are still building foundations in literacy. Consequently, some languages following the block-based paradigm replace text with symbols in order to reach a younger audience (Flannery et al. 2013; Hu et al. 2015). These languages succeed in allowing preliterate children to create programs by piecing visual (and sometimes tangible) blocks together to represent different coding structures. However, these languages often require a more experienced teacher to encourage best practices or to guide the student toward building more complex programs (Meerbaum-Salant et al. 2011). Furthermore, the visual nature can make it hard to represent abstract commands, so many such tools center around spatial navigation tasks (e.g., moving a character through a maze).

Programmable robots, too, often center around spatial navigation and sequencing tasks. For instance, Bee-Bots (Terrapin Thinking Tools 2008) and Kibo (Sullivan et al. 2015) specifically use small robots to teach navigational sequencing to children as young as four. The physicality of these devices can be compelling to students. Unfortunately, though, this specialized hardware can be expensive, and purchasing a full set for a classroom—or even one for home use—is financially infeasible for many schools and parents.

Block-based programming and programmable robots share many common features. They are often visuospatial, particularly useful in introducing concepts like sequencing and looping, and effective in removing the barriers of syntax. However, in a push for "CS For All" these approaches may not effectively reach all students, whether due to cost, interest, or design. CS continues to face problems with diversity and access, especially in early school years where CS education disproportionately reaches wealthy urban students (Wang 2017). Therefore, we must believe that the existing technologies are not exhaustive of potential opportunities; the space of possibilities remains a frontier for exploration. What would technology look like that diverges from these common paradigms?

As we look to future solutions, it is critical to consider: (1) what goals and objectives do students and educators have in learning or teaching computer science, (2) what direct challenges to these objectives (in both formal and informal settings) are they currently facing, and (3) how are users adapting the existing tools and creating new materials to circumvent these challenges and meet these objectives? In understanding the needs of the users of these tools, we can make informed design decisions regarding the goals to design for, the challenges to those goals, and the approaches that best achieve them.

In this chapter we report on a needfinding process consisting of interviews with students and educators and observations in informal computer science classrooms. We identify three high-level design goals within our data, along with eight specific design considerations for technology creators to consider to achieve these goals. We then discuss how these design considerations fit into the current landscape of education research and technology-based solutions and propose directions future designers might go to design computing education tools that achieve these objectives.

## 2 Method

To understand the goals, challenges, and approaches of computer science educators and learners, we conducted interviews and classroom observations.

### *2.1 Participants*

Seven educators (six male) were recruited via email between December 2018 and March 2019. They live and work in California, New York, Massachusetts, or Mexico. To achieve diversity of experience, we recruited educators who work in a variety of settings, as illustrated in Table 1. Interviews were conducted remotely via video-conferencing software.

We additionally recruited four child participants for these interviews, ages 6–12 (one male; see Table 2). All children have at least 2 years of programming experience, and began programming during their early school years. Two of these interviews were conducted in person and two were conducted remotely. All

**Table 1** Backgrounds and roles of educators who participated in interviews

| ID | Low-income community | Outside U.S. | Teacher educator | Classroom teacher | Curriculum development |
|---|---|---|---|---|---|
| E1 | | | | X | |
| E2 | X | | X | | X |
| E3 | | | X | | X |
| E4 | | | | | X |
| E5 | X | | | X | |
| E6 | | | | X | |
| E7 | | X | | X | |

**Table 2** Child participant ages, number of years spent programming, and locations where they have learned computer science material

| ID | Age | Years programming experience | At school | After-school program | At home |
|---|---|---|---|---|---|
| S1 | 12 | 5 | X | X | X |
| S2 | 10 | 2 | X | | X |
| S3 | 9 | 3 | | X | X |
| S4 | 6 | 2 | X | | X |

interview participants (both educators and students) received nominal compensation in return for their time.

Finally we conducted two classroom observations in informal education settings (after-school programs). One observation was in a class of 4–9 year old students in a program that provides free classes to underrepresented and low-income students. The other was a paid after-school program for 9–12 year old students.

## 2.2 Interview Procedure

The interviews were conducted to understand the objectives, challenges, and approaches of educators and learners. According to the interview protocol, the researcher explained the high level goals of the study, gave an overview of the procedure, explained the data collection and use policies, and collected voluntary, informed consent from the participant (and parent, where applicable).

The interviews followed a semi-structured format. It began with questions relating to experiences teaching or learning computer science and typical activities. It then explored the specific challenges and motivations for such teaching and learning. Finally, it ended with questions about user needs and what these participants felt was missing from their current practice. Throughout the interview, the interviewer took notes on participant responses and asked targeted follow up questions. The interviews were transcribed after the session for later analysis.

### 2.3 Observation Procedure

For classroom observations, the class facilitator introduced the researcher and explained their presence. The researcher then sat in the back of the classroom and took notes on classroom behaviors, class activities, and notable student and instructor comments and interactions. During both classroom observations, students approached the researchers for help on their program because the primary instructor was already busy assisting another student. In these situations, the researcher assisted the student and then took more targeted observational notes about this direct interaction.

### 2.4 Data and Analysis

Educator interviews ranged in duration from 34 to 63 min ($M = 48.14$) and student interview durations ranged from 10 to 29 min ($M = 19.25$). Observed classes lasted 45 min for the younger students and 2 h for the older students. The entire data set yielded transcriptions for 7 h and 16 min of audio data plus observation notes from 2 h and 45 min of class time.

Analysis of this collected data followed the qualitative coding process. In line with the emergent coding methods outlined by Strauss and Corbin (1998), researchers identified patterns within and between participant responses. By combining the coding of educator interviews, student interviews, and classroom observations, we were able to continue refining the coding categories, in accordance with the iterative Grounded Theory procedure.

## 3 Findings

Through our analysis process, we identified three primary design considerations that should influence the creation of computational learning technologies: accessibility, approachability, and engagement.

### 3.1 Accessible

To begin with, students face issues with accessibility, in terms of availability of technology, general literacy, and computational literacy. While some young learners have technology readily available at home and parents or educators who support computational learning, others are not afforded the same opportunities. Although computing education is increasingly widespread, access to it is not well distributed:

> We really don't have that many schools [teaching technology]. There are probably schools that have done it [since] a long time ago, but maybe 90% of the schools don't do it.—*E7*

In this excerpt, we see the frustrations of an educator that sees unequal access to a computing education. While some schools have long had a computing curriculum, the majority of them still do not, meaning most students still do not have the opportunity to learn this content through their formal education.

At home, though, access to technology is not equitably distributed either. As we observed when visiting classrooms, some students' only opportunity to interact with a computer was during the weekly session, while others brought their own laptop with them from home to their class. In large part, this inequity results from the cost of technology itself:

> Just for funding reasons, we've only provided one set of Beebots or one set of Makey Makeys to a site, so the teachers have to share those materials. That can be a bit of a challenge on the student side because the students don't get to fully realize the project they want to create or they don't get as much time with the Beebots.—*E2*

Specialized hardware, in particular, can present prohibitive cost to schools and school districts. A single device is expensive, and this effect only increases with the need to support a whole class. Furthermore, even when there are enough devices for each child, the need to put this hardware away to ready it for the next group prevents teachers and students from taking on multi-session projects; students are unable to pick back up from where they left off. The cost of technology can be prohibitive to parents as well, and this lack of access can contribute further to inaccessibility by directly impacting computational literacy.

Additionally, despite the fact that students today are growing up in a technology rich world, many of them still face challenges with navigating on devices:

> The hardest part of programming, so, I actually have a very big trouble of typing. Like if I am on my computer and I'm looking at the screen and I want to do J-A-K-I-A-J, I don't know where—I don't really know where things are.—*S4*

This 6-year-old participant explained that the hardest part of learning to program was the need to type. She does not know where the letters on the keyboard are, which makes typing an arduous process. Later on she explains that her dad sometimes helps her with programming by typing and reading for her when she gets tired, but not all children will have the same degree of parental support at home.

Finally, even if children can reliably access computer science learning technologies, they may not have the literacy skills to use them, which can also exacerbate computational literacy challenges if navigation relies on textual labels. When designing for children in early elementary school it is important to consider their still developing academic abilities. Most notably, our youngest students are still building foundations in literacy and may not reliably be able to read and write. Five of the educators cited challenges due to this literacy requirement:

> [For] the age group I work with, a lot of them are non-readers. So there's nothing really—there's really no curriculum out there for non-readers.—*E5*

In designing a computational learning system it is critical to consider students at the level they are at elsewhere in their education. Children have the cognitive capacities to engage in computational thinking (Dietz et al. 2019), but if they lack accessible tools to learn these concepts, the concepts remain out of reach. For students who are non-readers or tentative readers, text-filled tools present a huge barrier to entry.

To surmount these accessibility challenges, educators have started using publicly available free online software (e.g., Scratch and Twine) and creating communities to share teaching resources. Regarding literacy challenges, children discussed learning from videos, rather than from text, and educators creatively incorporate voice recognition, physicality, and unplugged activities into lessons so children do not need to read or type in order to engage:

> I try to combine [Twine] with some voice recognition stuff where I have younger kids talk into a Google Doc, 'cause then they can just tell stories. And then we can help them get it into Twine and turn it into these adventures.—*E1*

Students and educators alike are still finding clever ways to circumvent the accessibility limitations in the existing tools and curriculum, which can be both hard to obtain and hard to use for the youngest students. Despite the rise of computer science education, the cost of technology means that access to that education remains inequitable. In the classroom, lack of access and experience manifests as challenges with computational literacy, making interface navigation difficult for our youngest learners. This problem is further exacerbated by still-developing literacy; non-readers, especially, have a very hard time using and navigating many of the existing text-based CS education tools. Moving forward designers of early childhood computer science learning technologies need to pay close attention to accessibility to ensure that children are able to access and utilize the technologies being built. To make computer science learning tools accessible, designers should:

1. Use Widely Accessible Hardware
2. Limit Literacy

## *3.2 Approachable*

Even if technology and computer science learning tools are accessible, though, many educators and students are reticent to use them unless they are also approachable. To begin with, technology teachers today often do not come from a programming background, and can be wary about teaching material that they themselves are not confident with:

> "With CS is [sic] I think there's a lot of self-doubt and there's some mindset issues of educators feeling like, 'Oh I'm not good at math or I'm not good at science [and] therefore I'm going to translate a lot of these insecurities into teaching CS.'"—*E3*

Educators who are learning computer science for the first time in order to teach it to their students may bring in their own insecurities and doubts. These doubts can derive from stereotypes, biases, or personal mindset. If educators doubt themselves and their own ability to teach the material, they may not teach it effectively, may pass their insecurities on to their students, or might even choose not to learn computer science in the first place.

To make computer science both more approachable and more accessible, educators and curriculum developers have taken an interdisciplinary approach:

> That's where we're seeing the strongest push on the integration piece: where it's like you can teach CS alongside the writing that you're doing, you can use CS to reinforce the math instruction that you're already doing.—*E2*

E2 explains here that, especially in schools that do not have a computer science specialist, an interdisciplinary approach to computer science learning can be very effective. Educators may doubt their ability to teach computer science directly or worry that there is not enough time to teach a peripheral subject that is not included in standardized testing, but by incorporating computer science alongside regular classroom subjects, like reading or math, teachers are more confident in teaching the material and are more willing to take the time to do so. The interdisciplinary aspects help educators overcome their self-doubt.

However, this self-doubt is not limited to educators; learners can similarly face both biases and self-doubt that can make computer science seem daunting:

> I've been working in this field for a while and, some kids, they developed this 'no to technology' mindset. And I don't know what age it starts but I feel like working with the really young minds, they don't really have that mindset at all. They have this can-do mentality, and it's really cool to be around.—*E5*

E5 has worked with students of varying ages and has noticed that older students can begin to develop negative perceptions about what they can and cannot do with technology. This mindset can become a barrier to approaching the content. However, one of the most effective ways to counter rising self-doubt in children is to introduce them to technology early on, before these insecurities can take root. Exposure to technology and computer science at a young age means that children can engage with these ideas while they are still developing their sense of identity. Technology proficiency can be a part of that identity.

In particular, when children see that they can connect technology to their own interests, they feel empowered to approach the material and can overcome their self-doubt:

> We've found that puzzles only speak to certain groups of students, but creative projects, where students can connect it to their interests and themselves has [sic] so much more power and helps students see themselves as someone who can use computer science, someone who could be interested in computer science.—*E2*

E2 speaks of the power of personal projects in teaching computer science. Whereas many approaches might leverage programming puzzles, these puzzles may not be approachable and interesting to every student. However, when students are given the opportunity to inject their own interests into their programs and take ownership over their projects, they see how they can be interested in computer science. This ownership and personal aspect makes computer science more approachable to reticent students and helps to foster long-term interest.

Another way to encourage computer science participation is to leverage peer support and social learning:

> There's a lot of students developing this mindset of 'technology is not for them' and I tried to counter that through...just having the joy of collaborating with others and making projects and prototypes together.—*E5*

When students doubt their own ability to complete a project, working with others can address some of this reticence. This collaborative, social aspect provides a built in support system; students are able to lean on each other. Even though children feel they may not be able to complete a program on their own, they can work together with other students to succeed. Educators rely on this social aspect by teaching their students about the satisfaction of working together toward a common goal. Students echoed this desire for social and collaborative tools and projects, explaining that the opportunity to work together with their friends can make computer science more appealing.

Ultimately, computer science learning tools need to be approachable, on top of just being accessible. Even if students and educators can access these technologies, they need to be confident enough in themselves and their potential in order to use them. As we've shown here, designers can build approachable technologies by leveraging interdisciplinary topics, allowing children to connect projects with personal interests, and supporting collaboration. Therefore, in order to make computer science learning tools approachable, designers should strive to:

3. Leverage Interdisciplinary Topics
4. Make It Personal
5. Support Collaboration

### *3.3 Engaging*

Even if students have access to computer science learning tools and the confidence to approach them, they still need sustained engagement in order to learn from them. The most immediate goal of educators outside direct content teaching is to engage their students, and students themselves want to use engaging tools.

However, engagement can be particularly challenging in the early school years because of children's short attention spans:

> Developmentally, they don't sit for very long and listen to too much. You've got to really get things introduced and move fast and get things—get the activities going with that age group.—*E6*

Here E6 describes the unique challenges of working with his youngest students (as young as 4). These children have short attention spans and trouble sitting still, so educators need to introduce the lesson and get them engaged very quickly. In at-home settings, engagement may need to happen even faster yet, as students will not have the structure of a lesson plan and the motivation of an instructor to keep them focused. Therefore, computer science learning technologies should draw students right in and teach them as they go, rather than having a long introductory preamble.

Once students dive into a project, experiences of success and accomplishment with technology are crucial to encouraging sustained engagement with the material. Frustration can be a large barrier and too much of it can cause children to give up. However, overcoming frustration is not always possible without assistance. In particular, all four of the students noted a need for learning tools to have built in scaffolding and support:

> So maybe, like, as you're playing the game, you could add tips to how you do something.—*S2*

Here S2 was describing a game she would make if she were teaching other kids programming and specifically mentioned the scaffolding and support systems she would embed into it. That is, it should include built-in tips and hints for when a learner was stuck. Notably, at-home learners, in particular, may not always have someone to go to when they get stuck, so it is important that the tools they are using can help them to overcome challenges as they arise.

Finally, to effectively facilitate engagement and encourage long-term interest, computer science education needs to be fun. To achieve this goal, educators and students often pulled heavily on creativity and physicality:

> I'm excited about bringing it into the physical space. Being able to perform computational thinking and computing in ways that don't feel like programming, doing it by drawing or sketching.—*E4*

> We also find that the creative projects are just where students get to be more self-expressive, they get to create things that then they're proud of, they get to create things that they're invested in actually working on. So, yeah, it just fosters that all those positive feelings around computer science." —*E2*

Students engage more enthusiastically with the material when it's presented in novel and exciting ways. Across the interviews, we saw how computer science could be tied to things like dance, animation, design, music, performance, drawing, and storytelling in ways that get kids up and moving or thinking about problems in new and creative ways. This creativity and physicality can foster excitement, self-expression, and pride in ways that traditional programming projects may not.

Even if students and educators can access and approach computer science, engagement remains crucial to fostering sustained interest. Computer science learning technologies should overcome student's short attention spans and rising frustration, and engage students in novel and exciting ways. Designers who hope to make engaging learning tools should:

6. Jump Right In
7. Provide Explicit Scaffolding
8. Let Kids Be Creative or Physical (or Both)

## 4 Discussion

In the above section, we identified eight design considerations that align with the high level goals of accessibility, approachability, and engagement. Given children's existing capacities to engage with computational thinking and abstract reasoning (Dietz et al. 2019; Gopnik 2012; Schulz 2012; Klahr and Robinson 1981) and the increasing need to learn this material to successfully operate in the modern technological world (Wing 2006; Guzdial 2015), there is huge potential for building impactful learning tools for early computer science education, especially if we carefully consider these eight criteria. Here we detail how prior research and existing technologies align with these design considerations and the ways future technologies might support them.

### *4.1 Use Widely Accessible Hardware*

There is currently a large financial barrier to CS education, with lower income and minorities students, reporting less access to CS learning opportunities in the U.S. than wealthy, white students (Wang 2017). As of 2016, 55% of principals and 57% of school superintendents said there was not enough money to train or hire CS educators for their schools, so we cannot rely on all students getting access to CS education in their formal classrooms (Google Inc. and Gallup Inc. 2016). Furthermore, specialized CS education technology itself can be quite expensive. Therefore, designers might consider how to create financially accessible informal CS education tools by leveraging technology that users already have access to, for example, smartphones. Specifically, 84% of American households have smartphones, and minority and lower income Americans disproportionately rely on smartphones as their only means to connect to the internet (Pew Research Center 2017, 2019).

## 4.2 Limit Literacy

When designing for children in early elementary school it is important to consider their still developing academic abilities. Most notably, our youngest students are capable of engaging with computational thinking (Dietz et al. 2019), but are still building foundations in literacy. That is, these students are still learning to read, rather than reading to learn (Fiester 2010). Languages like Scratch Jr. (Flannery et al. 2013) and tools like Kibo (Sullivan et al. 2015) have done an admirable job of removing the need to read from learning computer science, although they do still rely on left-to-right ordering and basic numeracy. Moving forward, technologies that teach computer science can follow a similarly visual trend or adopt alternative ways to reduce literacy requirements, for example, by leveraging voice interaction.

## 4.3 Leverage Interdisciplinary Topics

Interdisciplinary approaches are an effective means to introduce computer science, especially in early education where schools may lack computer science specialists (Goldschmidt et al. 2011). This interdisciplinarity can make computer science more approachable for students and educators alike. Already educators have taken existing tools, like Scratch, and woven them effectively into math and science education for the older elementary grades (Goldschmidt et al. 2011; Lopez and Hernandez 2015). Similarly, we see success with STEAM methods, or incorporating arts education into the traditional STEM disciplines (Land 2013). Prior work has shown that these interdisciplinary creative activities can lower the barrier of entry to STEM learning (Land 2013). Ultimately, designers can make computer science education more approachable by connecting it to activities that students are already excited about or familiar with, such as storytelling or science.

## 4.4 Make It Personal

Personally meaningful projects are another effective mechanism by which to engage students. People are driven to see their ideas realized in the real world (Schwartz et al. 2016), and indeed, this is a principle underlying the design of many of the most successful CS education tools today (e.g., Scratch (Resnick et al. 2009)). Designers can support this sense of ownership by giving learners freedom in what they create. That is, rather than imposing a problem to solve, instead teach a structure by which to solve it (Klahr and Carver 1988) and let students choose how to apply that structure in a way that resonates with their interests.

### *4.5 Support Collaboration*

The promise of collaboration, support, and social engagement can make learning computer science less daunting. Collaborating around computing is a core part of the K12 CS framework that drives much of the current computer science curriculum in the United States (K-12 Computer Science Framework Steering Committee 2016). Connecting with other people is also one of the computational thinking perspectives embedded in Brennan and Resnick (2012) computational thinking definition. Existing mouse- and keyboard-based tools can limit collaboration because they constrain input to a single student, but one tool that is particularly conducive to collaboration is Kibo because it allows multiple children to interact with and manipulate the blocks at a time (Sullivan et al. 2015). Designers can create learning tools that support collaboration by explicitly supporting turn-taking or allowing more than one child to use the system at a time; physical, multitouch, or voice interfaces, for example, can all inherently support this objective of collaboration.

### *4.6 Jump Right In*

Children have short attention spans, which can make lengthy instructions ineffective. Not only is it hard for children to focus for a long time, it is also hard to remember a long set of directions. "Low floors, wide walls, high ceilings" is a common mantra among computer science educators and technology creators, deriving from the work and writing of Seymour Papert (Papert 1980; Resnick et al. 2009). Computing education tools should be easy to jump into (low floors), support a range of activities and use-cases (wide walls), and scale up as students grow and learn (high ceilings). Students should be able to receive a minimal introduction, and then learn as they go. To a designer, this means creating tools that children can jump right into without listening to lengthy directions or following explicit tutorials.

### *4.7 Provide Explicit Scaffolding*

Even if children jump right in, though, they will still sometimes need help and direction. Frustration is a huge barrier to computing engagement, but students who learn computing outside of a formal classroom may lack access to, or knowledge of, help resources. Rather than providing a large amount of up-front instruction, help should be given "just in time" (Schwartz et al. 2016). With shorter instructions given at the right moment, children receive the guidance they need when they need it without forgetting critical information (Schwartz and Bransford 1998). In addition, excess instruction can limit children's exploration and discovery; by avoiding premature help, we allow room for students' exploratory learning (Bonawitz et al.

2011). Together, this research suggests to designers that scaffolding and help should be built into a learning activity, rather than provided in advance via instruction from educators or system tutorials.

### *4.8 Let Kids Be Creative or Physical (or Both)*

Finally, to create engaging learning experiences, computing education tools should leverage creative or physical activities, an objective that can weave in very closely with that of being interdisciplinary. Research into STEAM has shown that creative activities can make STEM learning more engaging to students, and expressing oneself is a core computational thinking perspective (Land 2013; Brennan and Resnick 2012). That is, children learning computer science should also learn that computing is a powerful tool for self-expression (Brennan and Resnick 2012). Some existing tools explicitly foster connections to creative activities such as music (Gorson et al. 2017), and in our interviews we saw educators connecting technology to art, dance, or storytelling as well. Designers moving forward can foster creativity by connecting computer science to these more creative activities.

Meanwhile, approaches leveraging physical movement have also been successful in engaging students. Unplugged approaches have gotten kids up and moving in order to learn things like binary counting and sequencing (Goldschmidt et al. 2011; Bell et al. 2009), and technologies like the Bee-Bot have children imagining or acting out the direct embodiment of a programmable agent (Terrapin Thinking Tools 2008). Designers can encourage students to get up and move by using physical technologies or cleverly incorporating motion into a game, for example, by using accelerometers or cameras built into existing accessible hardware.

## 5 Conclusion

As the importance of early computer science education continues to grow, it is critical to consider the existing educational ecosystem: what challenges do teachers and learners currently face and how are they adapting existing tools and creating new ones to meet their pedagogical goals? In this chapter we identify three high-level design objectives for creating computer science learning technologies, split into eight specific design considerations. We then tie these design considerations back into the literature, exploring how education research and existing tools align with these goals and proposing how designers of future technologies might achieve these design objectives in new ways.

## References


Bell, T., Alexander, J., Freeman, I., & Grimley, M. (2009). Computer science unplugged: School students doing real computing without computers. *The New Zealand Journal of Applied Computing and Information Technology, 13*(1), 20–29.

Brennan K., & Resnick, M. (2012). New frameworks for studying and assessing the development of computational thinking. In: *Proceedings of the 2012 Annual Meeting of the American Educational Research Association, Vancouver* (Vol. 1, p. 25).

Bonawitz, E., Shafto, P., Gweon, H., Goodman, N. D., Spelke, E., & Schulz, L. (2011). The double-edged sword of pedagogy: Instruction limits spontaneous exploration and discovery. *Cognition, 120*(3), 322–330.

Cook, C., Goodman, N. D., & Schulz, L. E. (2011). Where science starts: Spontaneous experiments in preschoolers' exploratory play. *Cognition, 120*(3), 341–349.

Dietz, G., Landay, J., & Gweon, H. (2019). Building blocks of computational thinking: Young children's developing capacities for problem decomposition. In *Proceedings of the 41st Annual Meeting of the Cognitive Science Society*.

Fiester, L. (2010). *Early warning! Why reading by the end of third grade matters*. Baltimore: Annie E Casey Foundation.

Flannery, L. P., Silverman, B., Kazakoff, E. R., Bers, M. U., Bontá, P., Resnick, M. (2013). Designing scratchjr: support for early childhood learning through computer programming. In *Proceedings of the 12th International Conference on Interaction Design and Children* (pp. 1–10). New York: ACM.

Fraser, N., et al. (2013). *Blockly: A visual programming editor*. Google, Inc. https://developers.google.com/blockly

Gardner, W., & Rogoff, B. (1990). Children's deliberateness of planning according to task circumstances. *Developmental Psychology, 26*(3), 480.

Gergely, G., Nádasdy, Z., Csibra, G., & Bíró, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*(2), 165–193.

Goldschmidt, D., MacDonald, I., O'Rourke, J., & Milonovich, B. (2011). An interdisciplinary approach to injecting computer science into the K-12 classroom. *Journal of Computing Sciences in Colleges, 26*(6), 78–85.

Google Inc, & Gallup Inc. (2016). Trends in the state of computer science in US K-12 schools. Technical report.

Gopnik, A. (2012). Scientific thinking in young children: Theoretical advances, empirical research, and policy implications. *Science, 337*(6102), 1623–1627.

Gorson, J., Patel, N., Beheshti, E., Magerko, B., & Horn, M. (2017). Tunepad: Computational thinking through sound composition. In: *Proceedings of the 2017 Conference on Interaction Design and Children* (pp. 484–489). ACM.

Guzdial, M. (2015). *Learner-centered design of computing education: Research on computing for everyone*. San Rafael: Morgan & Claypool Publishers.

Hu, F., Zekelman, A., Horn, M., & Judd, F. (2015). Strawbies: explorations in tangible programming. In *Proceedings of the 14th International Conference on Interaction Design and Children* (pp. 410–413). New York: ACM.

K-12 Computer Science Framework Steering Committee. (2016). K-12 computer science framework. https://k12cs.org/

Klahr, D., & Carver, S. M. (1988). Cognitive objectives in a LOGO debugging curriculum: Instruction, learning, and transfer. *Cognitive Psychology, 20*(3), 362–404.

Klahr, D., & Robinson, M. (1981). Formal assessment of problem-solving and planning processes in preschool children. *Cognitive Psychology, 13*(1), 113–148.

Land, M. H. (2013). Full steam ahead: The benefits of integrating the arts into stem. *Procedia Computer Science, 20*, 547–552.

Legare, C. H. (2012). Exploring explanation: Explaining inconsistent evidence informs exploratory, hypothesis-testing behavior in young children. *Child Development, 83*(1), 173–185.

Liu, S., Ullman, T. D., Tenenbaum J. B., & Spelke, E. S. (2017). Ten-month-old infants infer the value of goals from the costs of actions. *Science, 358*(6366), 1038–1041.

Lopez, V., & Hernandez, M. I. (2015). Scratch as a computational modelling tool for teaching physics. *Physics Education, 50*(3), 310.

Meerbaum-Salant, O., Armoni, M., & Ben-Ari, M. (2011). Habits of programming in scratch. In *Proceedings of the 16th Annual Joint Conference on Innovation and Technology in Computer Science Education* (pp. 168–172). ACM.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books, Inc.

Pew Research Center. (2017). A third of US households have three or more smartphones. https://www.pewresearch.org/fact-tank/2017/05/25/a-third-of-americans-live-in-a-household-with-three-or-more-smartphones/

Pew Research Center. (2019). Mobile fact sheet. https://www.pewresearch.org/internet/fact-sheet/mobile/

Resnick, M., Maloney, J., Monroy-Hernández, A., Rusk, N., Eastmond, E., Brennan, K., et al. (2009). Scratch: Programming for all. *Communications of the ACM, 52*(11), 60–67.

Schulz, L. (2012). The origins of inquiry: Inductive inference and exploration in early childhood. *Trends in Cognitive Sciences, 16*(7), 382–389.

Schwartz, D. L., & Bransford, J. D. (1998). A time for telling. *Cognition and Instruction, 16*(4), 475–5223.

Schwartz, D. L., Tsang, J. M., & Blair, K. P. (2016). *The ABCs of how we learn: 26 scientifically proven approaches, how they work, and when to use them*. WW Norton & Company.

Scott, R. M., & Baillargeon, R. (2013). Do infants really expect agents to act efficiently? a critical test of the rationality principle. *Psychological Science, 24*(4), 466–474.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research techniques*. Thousand Oaks, CA. Sage Publications.

Sullivan, A., Elkin, M., & Bers, M. U. (2015). Kibo robot demo: engaging young children in programming and engineering. In *Proceedings of the 14th International Conference on Interaction Design and Children* (pp. 418–421). ACM.

Terrapin Thinking Tools. (2008). Bee-bot. http://www.terrapinlogo.com/

Wang, J. (2017). Is the US education system ready for CS for all? *Communications of the ACM, 60*(8), 26–28.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM, 49*(3), 33–35.

# Towards a Theory of Factors that Influence Text Comprehension of Code Documents

**Patrick Rein, Marcel Taeumel, and Robert Hirschfeld**

**Abstract** The design of domain-specific software systems can benefit from participatory design practices making domain experts and programmers equal, collaborating partners. The source code of such a system might be a viable communication artifact to mediate the perspectives of the two groups. However, source code written in a general-purpose programming language is often considered too difficult to comprehend for untrained readers. At the same time, it is yet unclear what makes general-purpose programming languages difficult to understand. Based on our previous study and related work from programming pedagogy and cognitive psychology, we develop an initial theory of factors that might influence the comprehensibility of source code documents by untrained readers. This theory covers factors stemming from the features of source code, factors related to the visual appearance of source code, and factors concerned with aspects independent of code documents. This chapter discusses and illustrates these potential factors and points out initial hypotheses about how these factors can influence comprehensibility.

## 1 Motivation: Code Documents for Participatory Design

Software can generate value in many domains whose experts are not necessarily programmers themselves. Thus, the evolution of software in domain-specific projects leads to a collaboration of domain experts and programmers. This is particularly important for software systems which are highly domain-specific, for example payroll accounting systems, or geographic information systems. *Participatory design* can serve as a framework for the collaboration between domain experts and programmers as it regards them as equal partners in the design of the software system (Asaro 2000).

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Participatory design emphasizes mutuality, reciprocity, and mutual learning. In the described situation of domain-specific software development, experts can learn technical possibilities and constraints from programmers with regard to the software to be created. Programmers can learn from the domain experts the inner workings of the domain, its vocabulary, and its constraints. Eventually, such a collaboration of groups from both areas of expertise can yield the creation of something more valuable than the sum of its individual contributions (Asaro 2000; Muller 1108; Rein et al. 2020).

To facilitate the participatory design process, teams use various practices such as playing out situations in dramas, collaborative game design, and mock-ups. Part of the purpose of these practices is the creation of concrete artifacts representing a shared language between the different groups participating in the design process. These artifacts should improve the mutual understanding of each others perspectives and needs, while creating a sense of shared ownership of the language (Muller 1108; Ehn 1988).

We argue that the source code of a software system has the potential to serve as a useful concrete artifact representing a shared language in a team of programmers and domain experts (Rein et al. 2020). First of all, source code explicitly expresses all domain knowledge relevant for the behavior of the system. Further, source code can be open to different interpretations. For domain experts it can serve as a written out formal model of domain knowledge. The exact execution semantics of the code might not matter much, as long as the meaning of the domain knowledge is sufficiently clear. At the same time, for programmers source code serves as a static description of the dynamic behavior of a computer. It describes the mapping from domain knowledge to technical infrastructure such as user interface components, or hardware input and output. Bringing these two perspectives together is a major challenge for software development, therefore source code, which combines these two perspectives, is an interesting artifact for participatory design.

## *1.1 The Challenges of Code as a Communication Artifact*

Formal descriptions of the behavior of software systems have previously been proposed and have been used in participatory design in software development teams (Kensing and Munk-Madsen 1993; Barrett and Oborn 2010; Evans 2004; Luebbe and Weske 2012). However, multidisciplinary teams use descriptions containing specialized representations, such as diagrams or domain-specific languages (DSL) instead of the actual source code. This makes the described behavior more accessible to the domain experts. At the same time, these specialized representations require extra effort as they increase the distance between the domain experts and the actual system description in source code. This distance has to be bridged either by developers mapping these descriptions to actual code or by additional infrastructure and tools which have to be maintained (for example a DSL compiler and a corresponding debugger). In contrast to that, the actual source code of the system is always available. Further, changes to the source code are directly executable and no additional infrastructure has to be maintained.

> How can program source code be used as a frequent communication artifact when exploring (or discussing) domain-specific terms and rules, which can also be expressed as natural-language text?

While source code written in a general-purpose programming language is readily available as a communication artifact, it is currently often regarded as difficult to understand for non-trained readers. Many of the mentioned formalism designed to be accessible for non-programming readers are motivated by this assumption. In a previous study, we investigated whether this assumption holds for object-oriented programs in a domain with simple rules (Rein et al. 2020).

The results of our text comprehension study showed that inexperienced readers performed worse on a process description expressed in object-oriented code than they performed on the English text variant. At the same time, the effect size in our experiment was rather small. As this was only a first study on the topic, final conclusions cannot be drawn. However the small effect size is still surprising as one would expect a formal document format such as source code to be generally difficult for inexperienced readers to read. Based on previous work, we again see that the mere fact that code documents are written in a language with formal semantics does not directly result in incomprehensible documents (Nardi 1993). Other features of code seem to influence the comprehensibility of source code. Thus, our refined research question is:

> Which features of code documents make them more "difficult" to understand than English texts for readers with little to no programming experience?

A detailed understanding of what actually makes code "difficult" to understand could help designers of future languages in targeting non-programming readers to make conscious design choices for or against language features. Existing observations of difficulties faced by novice programmers are not sufficient in this regard, as novice programmers aim to learn to program while our target group might not necessarily intend to do so.

## 1.2 Overview of the Theory and a First Example

In order to investigate the obstacles to understanding code documents written in general-purpose programming languages, we describe an initial set of factors that potentially influence how well readers can comprehend the content of these documents. Thereby, we aim to create a theory of which features of source code, used to express dynamic processes, are difficult for readers with no programming background to understand.

We argue that existing theories on program comprehension do not apply as they are mostly concerned with the comprehension process of trained programmers (Von Mayrhauser and Vans 1995). Further, even theories from programming pedagogy can only be applied to a limited extent, as they mostly deal with learners specifically trying to learn how to program (Robins et al. 2003). In contrast, we investigate situations in which readers have no prior experience and in which readers do not intend to learn programming. Further, we take inspiration from cognitive psychology research results on the process of reading (Rayner et al. 2012). Our theory, however, focuses on the results of that process and does not try to contribute to the existing theories of the cognitive processes happening during text or program comprehension.

When untrained readers encounter a source code document, they face content presented in an unfamiliar form (for an example see Listing 1). In order to try to understand the content, they have to overcome several "obstacles" at different levels: from strange formatting, to alien vocabulary, and unfamiliar semantics.

The underlying challenge is the representation of domain knowledge through programming languages. For untrained readers, the document is, in fact, written in an unknown language. The language might include English vocabulary, but the grammar and semantics of the language are different from the grammar and the semantics of natural languages. We, argue that this can be somewhat mitigated by programming languages as long as the grammar and semantics are similar to the grammar and semantics of natural languages. Readers can then use their knowledge of natural languages to try to understand the source code. However, even with a completely familiar grammar and semantics, source code remains a means for expressing technical knowledge. Thus, the domain knowledge might be encoded in technical descriptions or the description of domain knowledge might be mingled with technical vocabulary. Both make it more difficult for readers to find relevant domain knowledge. We describe these factors, all resulting directly from the features of source code, in Sect. 2.

While the described features are inherent to source code, untrained readers might not notice them at first but will first notice that source code also looks different from natural language text. Due to its inner structure, source code is formatted and styled differently. For example, indentation is often used to visualize the underlying structure of phrases in programming languages. This can result in source code documents in which no two consecutive lines have the same indentation. We describe the factors concerning the visual appearance of source code in Sect. 3.

Finally, the comprehensibility of a document is not a property of the document itself but of a particular document and a particular reader. The background and attitude of readers with regard to formal languages might influence the comprehensibility. For example, readers familiar with complex sets of production rules, for example chemical reaction formulas, might have less difficulty when trying to understand a program written in a rule-based logic programming language. We discuss factors that are independent off a particular code document in Sect. 4.

The resulting list of factors is by no means complete but serves as a starting point to generate initial hypotheses to test. We expect that new factors will come up during testing the initial hypotheses and that some of the initial factors will turn out to be irrelevant. Our initial list of factors is informed by related work on program comprehension, programming pedagogy, results of cognitive psychology research on reading, and the qualitative results of our previous study.

Before explaining each group, we will give an overview of how these groups relate to each other. We will also introduce a running example, which we will use to illustrate the different levels of factors whenever suitable. The example shows how a step in a conference registration process is described in source code of the programming language Smalltalk (Goldberg et al. 1983).

## *1.3 Running Example*

The following example is one step in the registration process of a commercially used conference registration system one of the authors worked on. Both excerpts are from the material we used in the experiments to test some of the initial hypotheses (Rein et al. 2020).

The English text version of the process step reads as following:

> Fifth, the participant will select the workshop they want to attend. Therefore, the system first determines all workshops available for the participant to attend. A workshop is available if it has capacity left and if the workshop is open for the participant type of the participant. [...] The system asks the user to select a workshop from the set of available workshops.

This text describes the interactions between a user, called "the participant," and the registration system. The workshop registration step is only one of several steps in the registration process. The longer text from which this excerpt is taken also defines the relevant concepts such as participants, the conference, and why the workshop registration matters to the overall process. The ellipsis in the middle of the excerpt includes rules describing what defines whether a workshop has capacity left and whether a workshop is open for particular types of participants. These rules are omitted as they are also omitted in the source code excerpt below. This does not mean that the description in source code does not express these rules, but that they are not expressed in the excerpt used.

**Listing 1** The example process step expressed in the Smalltalk programming language. The process step is expressed in a method called processStepFiveSelectWorkshop

```
1 ConferenceRegistrationProcess >>processStepFiveSelectWorkshop
2
3  | availableWorkshops |
4  availableWorkshops := self allWorkshops select: [:workshop |
5    workshop hasCapacityLeft and: [
6      workshop canBeAttendedBy: participant]].
7
8  participant setSelectedWorkshopTo: (
9    self askUserToChooseWorkshopFrom: availableWorkshops).
```

Now, compare the textual description above to the following excerpt in Listing 1 describing the same process step in the Smalltalk programming language (Goldberg et al. 1983).

We will briefly outline what some of the elements mean and how they map to the description in the English text. The first line tells us that we are looking at the class ConferenceRegistrationProcess and at the method processStepFiveSelectWorkshop . For the discussion of factors, it is sufficient to know that classes are collections of methods and methods include code. Further, when explaining the code, we will sometimes refer to *statements*. As a heuristic, statements in programming languages are what sentences are in natural languages. Line 4 to 6 are a statement that describes the rules defining which workshops are available. To get the list of all available workshops, we go through allWorkshops and select each one that hasCapacityLeft and canBeAttendedBy the participant . Finally, we say that we set the selected workshop property of the participant to the result of asking the user to choose a workshop from the availableWorkshops.

## 2 Factors Resulting from the Features of Source Code

By its very nature, source code is expressed in a formally defined language, such as the Smalltalk programming language (Goldberg et al. 1983). This alone might already explain why source code is difficult to comprehend to untrained readers: source code is written in a language they do not know. The meaning of a source code document depends largely on the semantics of the programming language, which is unknown to untrained readers, thus preventing them from comprehending the document. However, as our initial experiment has shown, even readers completely unfamiliar with programming can still comprehend large parts of a source code documents. So, missing knowledge about the underlying semantics of the programming language does not make source code completely incomprehensible but only hampers comprehension *to some degree*.

Further, our past experiment implies that other features of source code are also relevant. In a debriefing questionnaire, we asked for specific difficulties readers encountered. Besides general expressions of uncertainty with regard to the meaning of the document, participants mentioned specific aspects such as particular syntactic elements, as well as technical vocabulary such as “nil”.

Therefore, we shall take a closer look at features of source code documents that might influence comprehensibility. We identified four potential sources of difficulty: *discoverability of grammar*, *familiarity of semantics*, *decomposition versus linearization*, and *representation of domain knowledge*.

## *2.1 Discoverability of Grammar*

The grammar of a programming language, just like the grammar of a natural language, determines which sequences of characters are valid phrases in the language and what role a word plays in a phrase. We argue that the *discoverability* of grammatical rules could potentially influence the comprehensibility of source code documents for untrained readers. In detail, we argue that the discoverability is determined by the *familiarity* or *explicitness* of symbols denoting special grammatical structures in code.

For programming languages, the strict adherence to the grammar is important, as the grammar is later used to determine how the code should be executed. The grammar of natural languages has a similar role. Research on the process of reading shows that one part of understanding the meaning of a natural language sentence is to associate individual words with their grammatical roles, such as subject and verb (Rayner et al. 2012). Assuming that untrained readers try to apply a similar process of reading to source code, readers would also try to use a grammar to assign roles to words in source code. However, the grammar of programming languages might be completely unfamiliar to them.

In addition to the above, the role of words or phrases in programming languages is often denoted by special symbols. These symbols can be whole words or special characters, among them punctuation characters. In our example above, the bars (“| ... |”) mark the beginning and the end of a list of temporary variables, in our case a list with only one variable called “availableWorkshops”. The usage of special words and symbols in programming language grammars can be located along a spectrum ranging from using only explicit words to using unfamiliar special characters.

The implicit meaning of special characters in general might make the grammar less discoverable. Thus, some programming languages avoid punctuation characters and use words instead, for example the language AppleScript (Cook 2007). We expect such *explicit* representations of the syntax to be more discoverable and in turn easier to comprehend than implicit representations. In Listing 2, we can see the difference between the two approaches by replacing some punctuation characters with explicit descriptions of what parts of the code mean:

**Listing 2** A variant of the example method rewritten according to a grammar that makes the grammatical roles of elements more explicit

```
ConferenceRegistrationProcess >>processStepFiveSelectWorkshop

 temporary variables: availableWorkshops.
 set availableWorkshops to self allWorkshops select: do
   arguments: workshop
   workshop hasCapacityLeft and: [
     workshop canBeAttendedBy: participant]
 end.

 participant setSelectedWorkshopTo: (
   self askUserToChooseWorkshopFrom: availableWorkshops).
```

Somewhere between these two extremes is another option: to use punctuation characters from natural language. These punctuation characters are used to denote something similar to what they indicate in natural language. The programming language Smalltalk uses special characters in this way, as do many other programming languages. In our example above, we can see that the period is used to separate statements just as the period separates sentences from one another in natural language. We assume that this improves accessibility because untrained readers simply employ their familiar understanding of punctuation characters. In contrast, if we use unfamiliar special characters or common punctuation characters in unfamiliar ways, the grammar would become less discoverable and consequently the document less comprehensible. In replacing known characters with unusual ones, we can expect the document to become less comprehensible for untrained readers. This can be seen in Listing 3.

**Listing 3** A variant of the example method rewritten according to a grammar that uses unfamiliar characters to denote grammatical roles

```
ConferenceRegistrationProcess >>processStepFiveSelectWorkshop

 / availableWorkshops /
 <availableWorkshops <- self:allWorkshops:select ->[:workshop /
   workshop:hasCapacityLeft:and->[
     workshop:canBeAttendedBy->participant]]>

 <participant:setSelectedWorkshopTo->(
   self:askUserToChooseWorkshopFrom->availableWorkshops)>
```

## 2.2 Familiarity of Semantics

The meaning of a statement in a programming language is formally defined by what happens in the computer when that statement is executed. So, in order to fully understand what a given statement in a programming language means, one needs to know the complete set of evaluation rules for that language. These evaluation rules are called the semantics of the programming language. We assume that two dimensions could influence text comprehension for untrained readers: *similarity of semantics to common sense*, and *number and combinations of evaluation rules used*.

The first aspect is again grounded in the process of reading (Rayner et al. 2012). In order to understand a sentence, readers of natural text first assign grammatical roles to words, then combine words into phrases structures, and finally combine these phrase structures into sentence structures[1] (Rayner et al. 2012). The grammar of the language and the lexical information for each word provide the information on the relation between the words in the sentence. These relations are then interpreted through the readers knowledge about the world.

For source code documents, untrained readers do not have any knowledge of the evaluation rules and thereby about the actual relations between words in the document. In order to still be able to understand the meaning of statements in the document, they might heuristically use their natural language grammar and lexical information. This in turn would mean that evaluation rules which are similar to common sense should make a document more accessible. Statements which make use of evaluation rules that are close to common sense could then be understood in the same way as natural language text. For example, for native English speakers, time should flow from top to bottom through the document, or names that have been defined at some point should be available from then on.

The following example snippet illustrates the spectrum between what might be regarded as common sense and what is special to programming language semantics.

```
availableWorkshops := self allWorkshops select: [:workshop |
   workshop isAvailable].
lastWorkshop := workshop.
```

In this snippet, the execution of statements happens from top to bottom, so time flows in the reading direction. After executing the first statement, the variable availableWorkshops contains all workshops which are currently available. We can use the variable availableWorkshops from now on. At the same time, the usage of the variable workshop in the assignment to lastWorkshop is not possible, as the name “workshop” is only valid within the block denoted by square brackets

[1] This is a simplified depiction of the full version of one of the theories on the process of reading. This part of the theory is sufficient for our argument.

("[ ... ]"). However, for an untrained reader the name was used beforehand in this snippet, so it seems plausible to assume that it could be used further down. Consistently interpreting the scopes in which a name is valid is a task which can also be challenging for programmers when they do not know the programming language (Wilson et al. 2017).

Beyond the familiarity of the used evaluation rules, the number and combinations of rules used in a document might also influence the text comprehension.

### *2.3 Decomposed Versus Linearized*

The way source code documents are structured is fundamentally different from how most natural language texts are structured. Natural language text is mostly written to be read *linearly*. In contrast, source code is decomposed into many small elements which are referenced from many different locations within the source code, similar to the way an encyclopedia is structured. We argue that this fundamental difference is a main obstacle for untrained readers who are used to consuming text in a linear fashion, from the beginning of the text to the end. In order to understand code, it has to be read by jumping from one element of the source code to another.

Code is decomposed to improve the maintainability of source code. The goal is to try to avoid any duplication so that every relevant domain concept is only expressed once within the document. At the same time, the code can also become less accessible for untrained readers. This is also indicated by related work on programming pedagogy[2] (Robins et al. 2003).

For example, to answer any questions about concrete scenarios based on our original example method, readers would need to first look up further information. The method processStepFiveSelectWorkshop describes the general steps to get the available workshops, but intentionally leaves out several details. To answer questions on whether one specific participant would be able to select a specific workshop, readers would need to know how canBeAttendedBy: is actually defined. To learn about its definition, they would have to scan the document and look for the definition of canBeAttendedBy: and read that definition.

Assuming that a linear version of our example would be more accessible, we could directly include the definitions of all other relevant methods directly within our example method. The resulting code might look similar to Listing 4.

---

[2]For example, a survey on studies on how to teach and learn programming found that object-oriented programming was difficult for novices because the program text was distributed across many small elements (Robins et al. 2003).

**Listing 4** A linearized variant of the example method that includes the definitions of relevant other methods

```
1  ConferenceRegistrationProcess >>processStepFiveSelectWorkshop
2
3   | availableWorkshops |
4   availableWorkshops := self allWorkshops select: [:workshop |
5     workshop isUniversityWorkshop ifTrue: [capacity := 15].
6     workshop isCompanyWorkshop ifTrue: [capacity := 20].
7     workshopHasCapacityLeft := workshop attendance < capacity.
8     workshopCanBeAttendedByParticipant := workshop
          isCompanyWorkshop or: [
9       workshop isUniversityWorkshop and: [participant
            isLocalStudent]].
10    workshopHasCapacityLeft and: [
          workshopCanBeAttendedByParticipant]].
11
12  participant setSelectedWorkshopTo: (
13    self askUserToChooseWorkshopFrom: availableWorkshops).
```

Now, when answering questions about which participant can attend which workshop, readers do not have to refer to other methods. The phrases `workshop hasCapacityLeft` and `workshop canBeAttendedBy: participant` have been expanded with their definitions (see line 5 to 7 and line 8 to 9).

## 2.4 *Representation of Domain Knowledge*

Code always expresses the domain knowledge of the application domain in some way. At the same time, source code is also primarily a means to describe the behavior of a technical machine. Thus, source code necessarily intertwines the two aspects. We argue that two dimensions of this relationship have an influence on the comprehensibility of code: *how explicit the domain knowledge is expressed* and *the relative proportion of technical and domain vocabulary* in the document.

The first dimension influences comprehension as it determines how much the source code expresses logic of the domain versus how much it expresses the underlying operations of the computer. To create a software system, programmers inevitably have to map the domain knowledge to underlying operations of the execution environment at some point. At the same time, programming languages allow programmers to abstract from these underlying operations, for example by putting them in a separate method and giving the method a name which reflects the domain logic expressed through these underlying operations. We can then use this method wherever that domain logic is needed. Readers encountering the method name can understand what happens in terms of the domain and do not have to know which primitive operations are executed in the computer.

Listing 5 illustrates how a version of our example method would look with a somewhat less explicit description of the rules to determine which workshops are available. First of all, the explicit method hasCapacityLeft was removed as the method name describes knowledge of the domain. Second, the code expressing that we select specific workshops was replaced by a loop which iterates over the offsets in a primitive collection of numbers (line 5). The offset, called workshopIndex is used to look up the type of the workshop with that number in the mapping called workshopTypes. The type of the workshop itself is represented as a number which we compare to some known numbers (line 7 and 10).

**Listing 5** A variant of the example method which represents domain knowledge through underlying data structures and operations, thereby making the expression of domain knowledge less explicit

```
1  ConferenceRegistrationProcess >>processStepFiveSelectWorkshop
2
3   | workshopsAvailable isCapacityLeft |
4   workshopsAvailable := Array new: self typesOfWorkshops size.
5   self workshopTypes indexDo: [:workshopIndex |
6     isCapacityLeft := false.
7     (self workshopTypes at: workshopIndex) = 1 ifTrue: [
8       isCapacityLeft := (self
9         workshopAttendances at: workshopIndex) < 15].
10    (self workshopTypes at: workshopIndex) = 2 ifTrue: [
11      isCapacityLeft := (self
12        workshopAttendances at: workshopIndex) < 20].
13    (isCapacityLeft and: [self workshop: workshopIndex
          canBeAttendedBy: self participant]) ifTrue: [
14        workshopsAvailable at: workshopIndex put: 1].
15
16  participant setSelectedWorkshopTo: (
17    self askUserToChooseWorkshopFrom: workshopsAvailable).
```

The overall structure looks similar to Listing 4. However, while Listing 4 still has method names which reflect knowledge about the name, such as isUniversityWorkshop, the code in Listing 5 no longer contains any method names with this vocabulary..

However, making much of the domain knowledge explicit and hiding all underlying operations might not be a guarantee for creating comprehensible source code. The domain logic could still be mixed with logic concerned with technical infrastructure, for example maintaining data structure or handling in- and output mechanisms such as user interface interactions. We assume that the more technical logic and vocabulary is intermixed with the domain logic, the less comprehensible the source code becomes. One argument for this is that the domain logic becomes less dense. Non-technical readers have to filter the technical details as noise to get to the actual domain knowledge in the document.

For example, Listing 6 shows how our example method would look if more technical logic were introduced. The most prominent part is visible at the bottom. The method askUserToChooseWorkshopFrom was removed and replaced with explicit handling of the user interface interactions (lines 10 to 17). The fact that the user is asked to choose a workshop is still expressed in these lines. However, the relevant words and phrases are intermixed with technical code, such as the unwrapping and converting of the result of the user interaction (lines 14 and 15).

**Listing 6** A variant of the example method, which includes a mixture of domain vocabulary and technical vocabulary dealing with user interactions

```
1  ConferenceRegistrationProcess >>processSelectWorkshop
2
3   | availableWorkshops uiRequestResult chosenWorkshopIndex |
4   availableWorkshops := OrderedCollection new.
5   self allWorkshops do: [:workshop |
6     (workshop hasCapacityLeft and: [
7       workshop canBeAttendedBy: participant]) ifTrue: [
8         availableWorkshops add: workshop]].
9
10  uiRequestResult := UIManager default
11    chooseFrom: availableWorkshops
12    values: availableWorkshops
13    title: 'Please choose a workshop'.
14  chosenWorkshopIndex := (uiRequestResult at: #index)
15                          withBlanksTrimmed asNumber.
16  participant selectedWorkshop: (availableWorkshops
17    at: chosenWorkshopIndex).
```

As can be seen from a comparison of Listings 5 and 6, the two dimensions of how domain knowledge is represented are not completely orthogonal. When domain knowledge is encoded implicitly in technical data structures, the source code will necessarily contain the operations to work with these technical data structures and thereby *add noise* to the representation of domain knowledge.

## 3 Factors Related to Visual Appearance

As illustrated in the previous section, code is more structured than natural language text. Understanding the described behavior of the system fully, requires a complete understanding of the respective structure. Furthermore, the decomposed form of code, forces readers to often jump between sections in the code document. Thus, programmers often use visual cues to help them navigate the documents or recognize the structure of a statement more easily. In the following we will look at two aspects which determine the visual appearance of code documents, namely the *layout of the document* and the *formatting and styling*.

## 3.1 Document Layout

While, typically, source code is semantically decomposed into small elements, source code documents are still layouted just as natural language text is. Natural language documents linearly show one paragraph after another and source code shows one semantic unit after another, such as a class, method, function, or procedure. For example, the structure of the document containing our example method may look like Listing 7 (the content of the methods is omitted).

**Listing 7** A shortened version of the source code document in which the example method is included, illustrating how the elements within a document might be ordered. The content of the methods is omitted

```
Object subclass: #ConferenceRegistration
  instanceVariableNames: 'participant'
ConferenceRegistration startRegistration [...]
ConferenceRegistration processStepOnePersonalDetails [...]
ConferenceRegistration processStepTwoEventType [...]
ConferenceRegistration processStepThreeParticipantType [...]
ConferenceRegistration processStepFourBookings [...]
ConferenceRegistration processStepFiveSelectWorkshop [...]
ConferenceRegistration limitOfWorkshopParticipants [...]
ConferenceRegistration limitOfParticipants [...]
ConferenceRegistration numberOfRegisteredParticipants [...]
ConferenceRegistration numberOfRegisteredBachelorStudents [...]
```

We argue that the *ordering of the semantic elements within a document*, might influence the comprehensibility for untrained readers.

For experienced programmers, an alphabetic ordering of the elements, or a grouping of methods according to a unifying topic, might ease navigation while jumping between methods. However, for untrained readers an ordering that corresponds to the likely navigation on the first reading might be more helpful. For example, the first method should be the most high-level method. All methods used by this high-level method should be listed below that high-level method. After these methods, all methods used by them are listed, and so on. Note, that this assumes that readers employ a top-down strategy when encountering the source code for the first time (Von Mayrhauser and Vans 1995). A reverse order might be used for the assumption that readers employ a bottom-up strategy (Von Mayrhauser and Vans 1995).

## 3.2 Formatting and Styling

The question as to how source code should be formatted has been discussed in the software engineering community for more than 40 years (Miara et al. 1983). We are more interested in only the distinguishing features of the code, independent of its presentation. However, as research on code presentation shows that some features can impact comprehension levels and speed, we would briefly like to discuss some of the common features: *syntax highlighting*, *indentation*, and *identifier styles*.

Syntax highlighting is a technique to enrich the visual information of source code. To highlight syntax elements, colors and text emphasis are added to parts of the source code that have special meaning. For example, a section of our original example might look like Listing 8 with some syntax highlighting added to emphasize the methods being sent.

**Listing 8** A rendering of an excerpt from the example method with syntax highlighting emphasizing the names of methods used in the statement

```
availableWorkshops := self allWorkshops select: [:workshop |
   workshop hasCapacityLeft and: [
      workshop canBeAttendedBy: participant]].
```

Several empirical studies have investigated the effects of syntax highlighting. One study found that for reading source code in text books, syntax highlighting does not affect comprehension levels or speed (Beelders and Plessis 2016). Another study found that for novices trying to solve program comprehension tasks, based on small examples, syntax highlighting does significantly change the comprehension level (Hannebauer et al. 2018). While this does not imply that syntax highlighting does not help professional programmers or novices in writing code, it hints that the impact of syntax highlighting might be less important for our research question on factors influencing the comprehensibility of source code documents.

Another common question of code presentation is indentation. In all previous listings we have used the indentation of lines to show which statements belong together. For example, all lines within the example method were indented by one space and every statement within the square brackets of the first line was indented by at least three spaces. Indentation is said to improve the visual perception of such groups of statements. Without indentation it is more difficult to recognize these groups quickly. For example, the excerpt of Listing 8 would look like Listing 9 without indentation and coloring:

**Listing 9** A rendering of an excerpt from the example method without indentation

```
1 availableWorkshops := self allWorkshops select: [:workshop |
2 workshop hasCapacityLeft and: [
3 workshop canBeAttendedBy: participant]].
```

In this version it is less obvious that the second and third line contribute to the list of available workshops in comparison to the original version. Correspondingly, one of the few studies on the topic found that indentation does indeed influence program comprehension (Miara et al. 1983). The effect on comprehension levels was rather small. For novices the effect was stronger than for professional participants. Further, participants reported a higher subjective difficulty of comprehending the source code when indentation was missing. Whether the impact of indentation on the comprehension levels of untrained readers is positive or negative remains unclear. While indentation might help discovering the hidden semantics of source code, it could also hinder the reading process by making the code visually more difficult to read linearly.

The final consideration with regard to formatting is the way names used in code are generated. Two major styles can be distinguished in contemporary programming languages: camel case and underscores. The following listing shows an example for each of the two styles:

```
canBeAttendedBy: "camel case"
can_be_attended_by: "underscores"
```

Program comprehension research shows that for experienced programmers and novices alike, there is no difference in correctness between the two styles (Sharif and Maletic 2010; Binkley et al. 2013). However, a one eye-tracking study found that the style using underscore results in some speed up (Sharif and Maletic 2010). The effect was larger for novices than it was for experienced programmers, indicating that with increased experience the influence weakens. While a similar effect might occur with untrained readers, we are mostly interested in comprehension levels not speed.

## 4 Factors Independent Off the Document

With this project, we aim to improve the code documents in order to improve comprehensibility. Thus, the factors presented so far focus on features of code documents directly. However, we also include factors beyond the features of code documents in our initial theory in order to inform future experiment setups. The first set of factors are concerned with the *readers* themselves. For example, beyond the basic reading and comprehension skill of readers, their past experience with any kind of formalism might influence how well they can deal with source code. The second set of factors captures the influence from the *application domain*. For example, a complex domain might make it even more difficult for readers to deal with the unknown format of source code.

### *4.1 Reader*

While reading source code is different from reading natural language text, we suspect the general reading comprehension skill impacts how well a particular reader can comprehend the domain knowledge of a source code document.

The general comprehension skill level of readers is probably also influenced by whether they are native speakers of the language the code document is written in. While this seems like an obvious statement at first, it is important to keep in mind when considering source code. Most source code is written in English. Moreover, most programming languages use English words as keywords. Past studies have shown that this factor impacts comprehension by novice programmers (Guo 2018).

While we focus on untrained readers, a reader's past experience with document formats other than natural language text might influence how well the person can comprehend the code document. We assume that if readers have an educational background in a domain which makes heavy use of formal models, such as mathematics or systems theory, they might struggle less with the hidden semantics of the unknown programming language.

Beyond general and specific comprehension skills, the overall perception of the readers own assessment of their ability to understand a particular document format might influence the level of comprehension (Ashcraft 2002; Zhang et al. 2013).

## *4.2 Domain*

Finally, for a given source code document, the level of comprehension a reader can achieve also depends on the domain described in the document. Two aspects of the domain might influence the comprehension level: the complexity of the domain and the familiarity with the domain.

The complexity of the content of a document influences how difficult it is for a reader to understand the document. Thus, more complex domain logic will make any kind of document harder to understand. However, complex domain logic might interact with the difficulty of comprehending the unknown format of source code for untrained readers. A more complex domain might in code result in more complex dynamic behavior, which on top of all the aforementioned challenges adds the requirement of being able to simulate that behavior in the readers mind. While this might influence future experiments, it can, in general, also not be solved, as the complexity of the domain is what we mainly want to express (Brooks Jr 1995). Reducing this complexity will subtract from what we initially wanted to express.

Finally, the familiarity with the domain has been shown to influence the program comprehension strategies used by professional programmers (Shaft and Vessey 1995). Programmers familiar with the application domain employ a top-down strategy to program comprehension, going from the high-level, domain-specific parts of the code to the more technical ones. Programmers who were not familiar with the application domain employed a bottom-up strategy, presumably going from what they know—this means from the low-level technical parts to the high-level, domain-specific parts. The study did not investigate whether the familiarity of the domain influenced comprehension levels. Nevertheless, we would argue that, for untrained readers, the difficulty of understanding an unfamiliar domain might interact with the difficulty of understanding the unusual format of source code and result in a decrease in overall comprehension.

## 5 Conclusion

Being able to read general-purpose source code, enables participatory design on the level of the fundamental definitions of the domain logic of a system. Enabling participatory design on this level is relevant in a variety of settings. For example, general software development can benefit when teams working on applications in domains with complex rules, or citizens might be able to participate in discussing how public administration processes are defined in open-source software. However, so far, the approach of language designers has been to provide representations of domain logic that were designed to be accessible to readers unfamiliar with source code. However, these representations require additional effort to keep them consistent with the actual source code. Consequently, we posed the research question of how to make general-purpose source code accessible to untrained readers.

This chapter did not answer this question, but instead described an initial theory of what might influence how well a reader can comprehend a source code document. In particular, we listed features of source code which might pose a challenge—namely the discoverability of the grammar, the familiarity of the semantics, whether code was presented in a decomposed or a linear form, and how explicit the domain knowledge was encoded. This theory is an initial proposal used to generate first hypotheses to be tested in experiments.

A more profound version of a theory would describe why untrained readers struggle with comprehending source code. Therefore helping future language and tool designers. General-purpose programming language designers can take the described obstacles into consideration and domain-specific language designers could even try to avoid these obstacles altogether.

## References

Asaro, P. M. (2000). Transforming society by transforming technology: the science and politics of participatory design. *Accounting, Management and Information Technologies, 10*(4), 257–290.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science, 11*(5), 181–185.

Barrett, M., & Oborn, E. (2010). Boundary object use in cross-cultural software development teams. *Human Relations, 63*(8), 1199–1221.

Beelders, T., & Plessis, J. P. (2016). Syntax highlighting as an influencing factor when reading and comprehending source code. *Journal of Eye Movement Research, 9*, 2207–2219.

Binkley, D., Davis, M., Lawrie, D., Maletic, J.I., Morrell, C., Sharif, B. (2013). The impact of identifier style on effort and comprehension. *Empirical Software Engineering, 18*(2), 219–276. https://doi.org/10.1007/s10664-012-9201-4

Brooks Jr, F. P. (1995). The mythical man-month. Addison-Wesley Longman Publishing Co., Inc., USA ISBN: 0201835959

Cook, W. R. (2007). Applescript. In *Proceedings of the Third ACM SIGPLAN Conference on History of Programming Languages, HOPL III* (pp. 1–1–1–21). , New York, NY: ACM. https://doi.org/10.1145/1238844.1238845

Ehn, P. (1988). *Work-oriented design of computer artifacts*. Ph.D. thesis, Arbetslivscentrum.

Evans, E. (2004). *Domain-driven design: Tackling complexity in the heart of software*. Addison-Wesley Professional.

Goldberg, A., & Robson, D. (1983). *Smalltalk-80: The language and its implementation*. Boston, MA: Addison-Wesley Longman.

Guo, P. J. (2018). Non-native English speakers learning computer programming: Barriers, desires, and design opportunities. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (p. 396). New York: ACM.

Hannebauer, C., Hesenius, M., & Gruhn, V. (2018). Does syntax highlighting help programming novices? *Empirical Software Engineering, 23*(5), 2795–2828. https://doi.org/10.1007/s10664-017-9579-0

Kensing, F., & Munk-Madsen, A. (1993). Pd: Structure in the toolbox. *Communications of the ACM, 36*(6), 78–85. http://doi.acm.org/10.1145/153571.163278

Luebbe, A., & Weske, M. (2012). *When research meets practice: Tangible business process modeling at work* (pp. 211–229). Berlin: Springer. https://doi.org/10.1007/978-3-642-31991-4_12

Miara, R. J., Musselman, J. A., Navarro, J. A., & Shneiderman, B. (1983). Program indentation and comprehensibility. *Communications of the ACM, 26*(11), 861–867.

Muller, M. J. (2007). Participatory design: the third space in HCI. In *The human-computer interaction handbook* (pp. 1087–1108). Boca Raton: CRC Press.

Nardi, B. (1993). *A small matter of programming: perspectives on end user computing*. Cambridge, MA: MIT Press.

Rayner, K., Pollatsek, A., & Ashby Jr., C. (2012). *Psychology of reading*. Hove: Psychology Press. https://doi.org/10.4324/9780203155158

Rein, P., Taeumel, M., & Hirschfeld, R. (2020). *Towards empirical evidence on the comprehensibility of natural language versus programming language* (pp. 111–131). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-28960-7_7

Robins, A., Rountree, J., & Rountree, N. (2003). Learning and teaching programming: A review and discussion. *Computer Science Education, 13*(2), 137–172. https://doi.org/10.1076/csed.13.2.137.14200

Shaft, T. M., & Vessey, I. (1995). The relevance of application domain knowledge: The case of computer program comprehension. *Information Systems Research, 6*(3), 286–299.

Sharif, B., & Maletic, J. I. (2010). An eye tracking study on camelcase and under_score identifier styles. In *2010 IEEE 18th International Conference on Program Comprehension* (pp. 196–205). Piscataway: IEEE.

Von Mayrhauser, A., & Vans, A. M. (1995). Program comprehension during software maintenance and evolution. *Computer, 28*(8), 44–55.

Wilson, P., Pombrio, J., & Krishnamurthi, S. (2017). Can we crowdsource language design? In *Proceedings of the Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software (Onward!)* 2017. New York: ACM Press. https://doi.org/10.1145/3133850.3133863

Zhang, S., Schmader, T., & Hall, W. M. (2013). L'eggo my ego: Reducing the gender gap in math by unlinking the self from performance. *Self and Identity, 12*(4), 400–412.

# Presenting and Exploring Challenges in Human-Robot Interaction Design Through Bodystorming

**Parastoo Abtahi, Neha Sharma, James A. Landay, and Sean Follmer**

**Abstract** In the coming era of ubiquitous robotics we envision the need for the effortless design of contextually-aware interactions with robots. Ubiquitous robots create a number of challenges for designers. Firstly, due to their dynamic nature, prototyping requires skillful programming and is often time consuming. Moreover, these devices are often context-aware and their behavior is affected by people, objects, and their environment. Existing tools for human-robot interaction designers require programming expertise, do not leverage design methodologies such as iterative design, and do not support in-situ user testing. We propose that bodystorming can be used as an effective method in this process, to communicate needfinding results and to explore the design of situated interactions with robots. As a case study, we first conduct a series of interviews and observe the workflow of human-robot interaction designers to better understand the challenges they face. We summarize the insights gathered from our needfinding, including challenges around data capture and information overload. We then describe how we used a mystery-game-style role-playing activity in an interactive workshop to communicate our findings, induce empathy, and initiate an effective ideation phase. Finally, we summarize the learnings from this workshop and how such bodystorming techniques can be used to communicate needfinding results at early stages of the human-robot interaction design process.

## 1 Introduction

Recent advances in robotics and the reduction in price of hardware components have led to the development of many commercial and open-source robotic platforms. We envision a future in which robots are present in our homes, workplaces, and public spaces, collaborating with us and augmenting our capabilities. While much

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of robotics currently focuses on accomplishing simple mechanical tasks, such as assembly or cleaning, we see a future of ubiquitous robots that interact with us in a variety of contexts, augment our capabilities, and collaborate with us in accomplishing complex tasks. These robots do not repeatedly perform one task, but rather tackle open-ended tasks, are situated seamlessly in our environment, and are contextually-aware (sense and manipulate the world), adapting to different circumstances and responding to users accordingly.

These robots can range from a simple household vacuum robot to a humanoid robot with many moving parts. In this chapter, we focus on mobile autonomous social robots. These robots are *mobile*, meaning that they move around and navigate dynamic environments. They are *autonomous* in that they are programmed to accomplish tasks independently, without the need for a human operator or a remote tele-operator. Moreover, they are programmed to accomplish tasks that are complex and not necessarily pre-determined or repetitive. What we mean by *social* is not that these robots are merely designed to engage in social interactions, but that they co-exist with us and consequently need means of interpreting our intentions and actions, as well as means of communicating with us. Note that these robots need not be humanoid, meaning they may not have an appearance similar to a human, and can take on a variety of physical forms. We chose to focus on mobile autonomous social robots, as these characteristics closely describe the ubiquitous robots that we envision in our environments in the future.

This coming era of ubiquitous robotics highlights the need for designers to explore novel applications and experiment with various contextually-aware Human-Robot Interactions (HRIs). Rapid prototyping and iteration are crucial stages of the design process for learning more about the design, communicating ideas, and eliciting user feedback. Despite these advantages, various factors make prototyping with robotic platforms challenging:

1. *Complexity:* robotic systems are complex, and prototyping interactions with a robot requires skillful programming and is often time consuming.
2. *Opacity:* autonomous robots have an underlying representation of the world and operate based on complex sensing and learning algorithms. This information is often invisible to designers or presented in a form that is decoupled from the context of the human-robot interaction, which makes sensemaking difficult.
3. *Interdependency:* in a robotic system many interdependent parameters determine the resulting robot behavior. As a result, designers are unable to engage in an iterative design process and effectively explore the large space of possible outcomes.
4. *Uncertainty:* finally, given the situatedness of interactions and the uncertainty of human behavior, even expert programmers are challenged with the task of predicting how the robot affects and is affected by people and the environment.

Due to these challenges, designers are unable to effectively engage in traditional design processes, such as rapid prototyping, situated user testing, and iteration; methodologies that are critical for testing assumptions, evaluating designs, and communicating ideas. As a result, designers often resort to simulation environments;

however, simulation cannot fully capture hardware defects, the influence of physical objects and the environment, user interactions, and the context of those interactions. Additionally, at the early stages of the design process, these factors make it difficult for designers to communicate HRI needfinding results in a contextual manner, which highlights the need for a new design methodology for tackling this challenge.

We propose that bodystorming can be used as an effective tool at early stages of the design process to communicate needfinding results, by allowing participants to have an embodied experience, situated in the context of the human-robot interaction. In order to explore this design method, we present a case study exploration of needfinding for HRI design using this approach. We first conduct a series of interviews and observations to gather more information about the challenges designers face in the context of human-robot interaction design. More specifically, our goal is to better understand the breakdown of traditional design processes when designing interactive robotic systems. We summarize the insights gathered from our needfinding, including challenges around information overload, data capture, and analysis.

We then describe how we ran a workshop where we used a mystery-game-style role-playing activity and two hypothetical scenarios to communicate our findings. Finally, we describe our learnings from the workshop and how such bodystorming techniques can be used at early stages of the human-robot interaction design process to effectively communicate needfinding results, gain a shared understanding of the problem space, induce empathy for stakeholders, and initiate an effective ideation phase.

## 2 Background

Methodologies such as iterative design, Wizard of Oz (WoZ) prototyping, and user testing are invaluable for designing products and interactions. However, it is unclear how these methodologies can be utilized effectively in the design of emerging, intelligent systems that are often complex and situated. In the context of human-robot interaction design, most current tools target expert robot programmers and do not leverage these design methodologies.

The Wizard of Oz (WoZ) technique, for example, is invaluable as it enables rapid prototyping of ideas during the users' interaction with the system (Kelley 1983). Recently, a Wizard of Oz prototyping tool was developed for automotive settings; WoZ Way is a tool that allows designers to observe and interact with drivers during their commute and to prototype in-car interface behavior in real-time (Martelaro and Ju 2017). Our work identifies a similar need for tools that better support iterative and rapid prototyping in the context of situated human-robot interactions.

Previous work has explored rapid exploration of designs and rapid programming of robotic systems through physical manipulation. Bosu is a design tool that has the ability to record and playback motion for soft materials (Parkes and Ishii 2010). Topobo is an assembly system with kinetic memory; the ability to record and play back physical motion (Raffle et al. 2004). These tools are suitable for programming robots that perform repetitive tasks. Others have built tools that use a graphical user-interface to enable the designer to explore more open-ended and context-aware human-robot interactions (Kooijmans et al. 2006; Sauppé and Mutlu 2014). In this chapter, we summarize the insights we have gathered from observing and interviewing human-robot interaction designers and researchers that can inform the design of such tools.

To communicate our findings and initiate an effective ideation phase, we utilize the bodystorming technique through a mystery-game-style role-playing activity. Bodystorming has been used in the past as a means of generating on-site innovation, by conducting design sessions situated in the real environment (Schleicher et al. 2010) or a replicated environment (Oulasvirta et al. 2003) where the product will ultimately be used. Others have highlighted the use of bodystorming as a form of role-playing activity where designers can improvise and communicate their ideas by acting out different scenarios; what has been called informance design (Burns et al. 1994) or embodied design (Oulasvirta et al. 2003). Such bodystorming techniques have been used in a variety of applications, including the design of mobile learning experiences (Smith 2014) or movement-based interaction design (Segura et al. 2016). For robotics applications, researchers have explored bodystorming as a way of designing affect features for social robots (Yim and Shaw 2009) or to program robot interactions (Porfirio et al. 2019). In this work, we explore how designers of robotic systems can use bodystorming to communicate design insights at an earlier stage in the design process. We use bodystorming to communicate what we learned through needfinding, to develop a shared understanding of the challenges human-robot interaction designers face, and to induce empathy for all stakeholders.

## 3 Case Study: Needfinding for HRI Design

To showcase how bodystorming can be used to effectively communicate needfinding results in a situated manner, we begin by describing a needfinding case study regarding understanding current workflow and challenges in human-robot interaction design.

Designers face many challenges when exploring and testing situated interactions with robots, primarily due to the complexity of the robots, the dynamic environments that they operate in, and the unpredictability of people they interact with. To gather more information about these challenges and better understand the nuances, we conducted a series of semi-structured interviews with nine individuals, including robot programmers, human-robot interaction designers, and robotics researchers, working at universities, research institutes, large corporations, or startup companies.

In this section we provide a high-level summary of our findings while preserving anonymity of participants. It should be noted that our interviewees highlighted many challenges that are not discussed in this chapter. For example, at the system level, we found that researchers often integrate different hardware and software components, and many difficulties arise from the lack of a unified ecosystem in which these components can coexist. Others mentioned programming challenges related to current Integrated Development Environments (IDEs), debugging workflows, and error messages for robot programming. We focus specifically on the breakdown of traditional design processes, more specifically, factors that make rapid prototyping, user testing, and iteration challenging in the context of human-robot interaction design, as highlighted by our interviewees:

1. *Need for context switching:* designers often use a desktop or laptop computer to monitor the status of the system in real-time, fix potential problems, modify parameters of the design space, and record user study data. The mobile autonomous robot however, is situated in the environment. As a result, the programming medium is decoupled from the context of the human-robot interaction, as shown in Fig. 1. This disconnect forces designers to attend to the robot in the real-world and the design/debugging interface simultaneously. One interaction designer highlighted that user testings are often conducted in highly dynamic environments, and due to this need for context switching, at times, they miss people's reactions to the actions performed by the robot or the context of the human-robot interaction more generally. Moreover, a researcher noted that this split-attention may have dangerous consequences, and to ensure safety, they often conduct user testings in pairs, with one researcher carrying a mechanical shutdown button that is used to intervene in case of an emergency.
2. *Frame of reference:* robotic systems consist of multiple hardware components, each with a 3D coordinate frame. For example, the robot base coordinates differ from the sensor frame or the gripper frame. These 3D coordinates are also distinct from the world frame. Programmers often use the *tf* package in the Robot Operating System (ROS) to keep track of these coordinate frames over time and the relationships between them. When designing situated interactions with robots it is necessary to take on the perspective of either the robot or the human

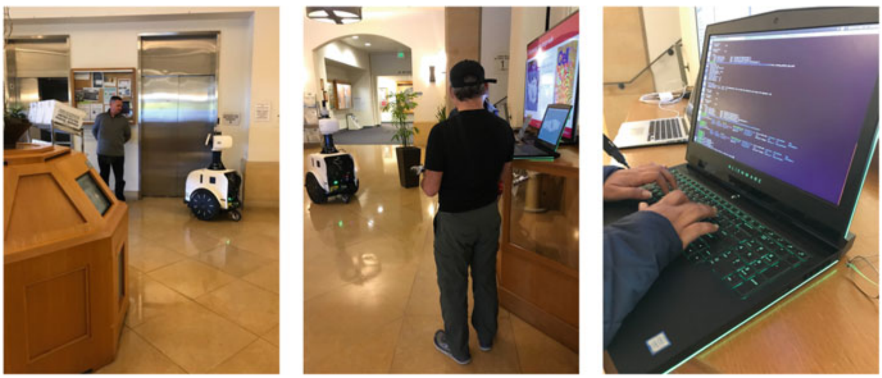

**Fig. 1** Researchers testing an autonomous mobile social robot, the JackRabbot, in a dynamic indoor environment, at Stanford University

interacting with it. For example, one designer mentioned that deciding what an appropriate distance is between the user and the robot might be different if you take a third-person view of the interaction, or to determine the speed at which the robot should approach a user it might be necessary to consider the interaction from the user's frame of reference. When prototyping and iterating on human-robot interactions, these frames of reference pose a challenge for designers in terms of sensemaking and perspective taking.

3. *Difficulty in data capture:* when conducting user testings it is necessary to capture relevant information to reflect on the testing session, analyze the data, and communicate the findings with others. In traditional design processes, designers utilize techniques such as video and audio recordings; however, in the context of human-robot interaction design, the complexity of the robotic systems makes data capture more challenging. As one researcher highlighted, in some cases, depending on the complexity of the robot, the overhead of capturing data is so large that it is infeasible to record the sensor data alone for a test session longer than a few minutes. Moreover, the dynamic nature of the testing environment makes data capture even more challenging. Autonomous mobile robots are often context-aware and integrated within our physical environment. People, objects, and the properties of the environment will affect their behavior and their performance, and for a holistic analysis, it is often necessary to capture additional data from these external sources.
4. *Information overload:* even when all relevant data is captured, the complexity, interdependency, and large amount of data makes sensemaking difficult. Designers grapple with the challenge of information overload when monitoring robotic systems in real-time or when performing post-hoc analysis of captured data. RViz is a 3D visualization tool for ROS, shown in Fig. 2, that is commonly used by robot programmers and designers to visualize real-time or captured spatial-temporal data. Designers often navigate the overwhelming amount of information by hiding most sources of data and inspecting smaller sub-components, one at a time. However, as one robot programmer highlighted, when debugging an undesirable behavior without a clear intuition about the source of the problem, it remains unclear what to direct one's attention to and how to investigate the problem.

At a high-level, we have identified the need for tools that better support the use of critical design methodologies in the context of human-robot interaction design. We highlighted factors that make it challenging for HRI designers to utilize such techniques, including the complexity, opacity, and interdependency of autonomous, mobile robotic systems, as well as the uncertainty associated with the dynamic environments they operate in and the people they interact with. Our needfinding sheds light on additional challenges including the need for context switching, perspective taking through multiple frames of reference, difficulties in data capture, and information overload when sensemaking. Human-robot interaction design tools can facilitate the use of traditional design techniques by helping designers overcome these challenges.

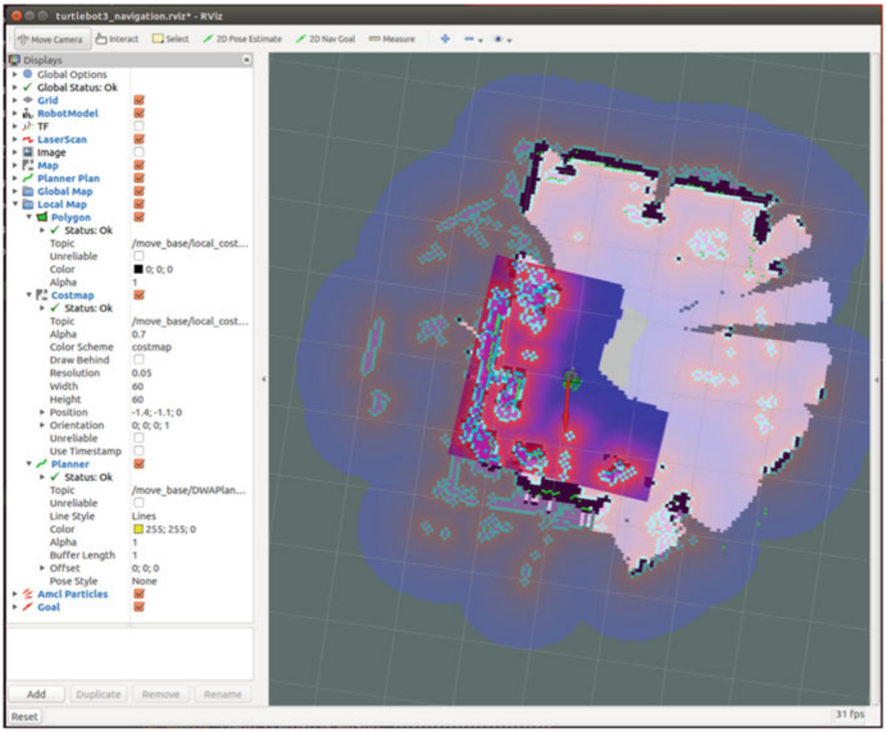


**Fig. 2** RViz: the state-of-the-art 3D visualization tool used for the Robot Operating System

## 4 Designing Methods for Sharing HRI Needfinding Results

Needfinding has been explored as an effective tool to guide robotics research and development (Pantofaru and Takayama 2011). Once completed, it is necessary to communicate the findings, as not all stakeholders or designers are involved in the needfinding stage. However, needfinding results are commonly presented from a third-person perspective, and while this approach is time efficient, it has short-comings when used for human-robot interaction design. Firstly, robots are often contextually-aware and interactions with them are situated in dynamic environments. When using traditional ways of communicating findings, the context and the nuances of the situated interactions may be lost. Moreover, receiving the information through a third-person perspective does not allow others, or even those who were involved in the needfinding stage, to experience the scenario first-hand and gain the tacit knowledge needed for effective framing and ideation.

Bodystorming and role-playing allow designers to have first-person, embodied experiences, situated in the context of the problem. Such techniques have been used in the design process for evaluating prototypes and communicating ideas (Oulasvirta et al. 2003). We propose that advantages of bodystorming can also be leveraged at earlier stages of the design process, to communicate needfinding results. For this application however, an effective bodystorming activity needs a different set of mechanics. More specifically, when evaluating prototypes, the designers are participants in the activity and through the performance they learn how the prototype is used in context and are able to use improvisation as a form of ideation. For communicating needfinding results however, the goal is to allow participants to experience the problem first-hand without explicitly stating what the problem is. This hidden information requires an additional component in the activity: a mystery. A role-playing "game" in which participants are asked to solve an unknown, provides an opportunity to challenge the player in similar ways that the stakeholders in the problem space are being challenged. In this section, we describe how we used bodystorming to communicate our needfinding results in more detail.

We designed a mystery-game-style role-playing activity and ran a workshop to:

1. communicate the insights gathered from our needfinding,
2. induce empathy for stakeholders and initiate a more effective ideation phase, and
3. study how such bodystorming techniques could be utilized early on for rapid prototyping of ideas in the context of human-robot interaction design.

We chose an existing autonomous robot, Relay, made by the company Savioke, which is used in a variety of contexts including healthcare. We created two hypothetical scenarios in which Relay is used for hospitality in a hotel. In the first scenario, Relay was tasked to guide a hotel guest from the lobby to their room. In this scenario, we wanted to explore how a designer might experiment with different parameters in the design space, including the speed at which the robot should move when guiding guests to their hotel room. In the second scenario, Relay needed to deliver a towel to the guest's hotel room. In this scenario, we wanted to highlight the challenge of detecting a faulty sensor, an occluded camera, and how a designer might inspect the system to find the source of the undesirable behavior and resolve the problem.

For each scenario, eight people volunteered and took on specific roles, such as the robot, the designer, or the hotel guest. Each person received a role tag, and inside each tag there were two secret instruction notes, a green note for Round 0 and a yellow note for Round 1, as shown in Fig. 3. Participants were asked to read the instructions on their notes without sharing that information with others. Round 0 was designed to walk users through the hypothetical scenario to familiarize all participants with the task and their role in it. Round 1 was the repetition of the same scenario; however, in this round the yellow instruction notes introduce a mystery, only known to the person taking on the role of Relay. The mystery then needs to be resolved by the designer with the help of other participants.

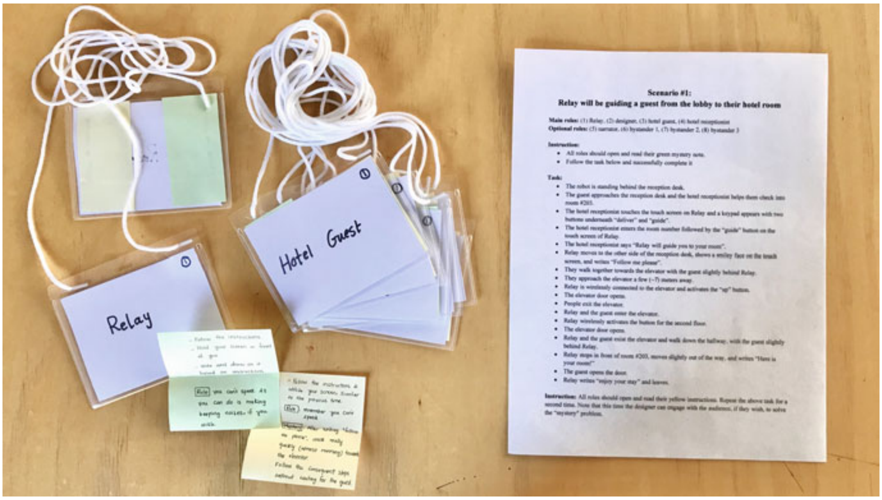


**Fig. 3** The mystery-game-style role-playing activity materials. Left: individual role tags with the green and yellow instruction notes inside each tag. Right: scenario description read by the narrator

**Fig. 4** The mystery-game-style role-playing activity designed to communicate needfinding insights, induce empathy, inspire ideation, and explore rapid prototyping through bodystorming

Once the activity started, the facilitators did not participate or intervene in any way. The narrator's role was to read the scenario description out-loud and to guide everyone throughout the role-playing activity. A small whiteboard was used as the touchscreen on the Relay robot, as seen on the left in Fig. 4. The first scenario and the instructions for each role are described below.

### Scenario 1: Relay Will Be Guiding a Guest from the Lobby to Their Hotel Room

| | |
|---|---|
| Main roles | Relay, designer, hotel guest, hotel receptionist |
| Optional roles | Narrator, bystander1, bystander2, bystander3 |
| Instructions | All roles should open and read their green instruction note |
| Description | The robot is standing behind the reception desk |
| | The guest approaches the reception desk and the hotel receptionist helps them check into room #203 |
| | The hotel receptionist touches the touch screen on Relay and a keypad appears with two buttons underneath “deliver” and “guide” |
| | The hotel receptionist enters the room number followed by the “guide” button on the touch screen of Relay |
| | The hotel receptionist says “Relay will guide you to your room” |
| | Relay moves to the other side of the reception desk, shows a smiley face on the touch screen, and writes “Follow me please” |
| | Relay and the guest walk together towards the elevator with the guest slightly behind Relay |
| | Relay and the guest approach the elevator a few ( 7) meters away |
| | Relay is wirelessly connected to the elevator and activates the “up” button |
| | The elevator door opens |
| | People exit the elevator |
| | Relay and the guest enter the elevator |
| | Relay wirelessly activates the button for the second floor |
| | The elevator door opens |
| | Relay and the guest exist the elevator and walk down the hallway, with the guest slightly behind Relay |
| | Relay stops in front of room #203, moves slightly out of the way, and writes “Here is your room!” |
| | The guest opens the door |
| | Relay writes “enjoy your stay” and leaves |
| Followup instructions | Repeat the above task a second time. All roles should open and read their yellow instruction notes. Note that this time the designer can engage with the audience, if they wish, to solve the “mystery” problem |

## Scenario 1 (Round 0): Green Mystery Information Notes

| | |
|---|---|
| Relay | Follow the instructions. Hold your screen in front of you. Based on the instructions write or draw on your screen. Rule: Remember you cannot speak. All you can do is make beeping noises if you wish |
| Designer | Stand a certain distance away from Relay. Follow and observe the interactions without interfering |
| Guest | Follow the instructions |
| Receptionist | Follow the instructions |
| Narrator | Read the instructions for everyone out-loud |
| Bystander1 | You keep taking photos and videos of the robot in the lobby |
| Bystander2 | You exit the elevator before Relay and the hotel guest enter |
| Bystander3 | You are waiting for the elevator on the second floor |

## Scenario 1 (Round 1): Yellow Mystery Information Notes

| | |
|---|---|
| Relay | Follow the instructions and utilize your screen, similar to the previous round. Rule: Remember you still cannot speak. Mystery: After “follow me please”, walk really quickly (almost running) towards the elevator. Follow the consequent steps in the instructions without waiting |
| Designer | Once again, stand a few meters away from Relay and observe without interfering. Watch as the hotel guest follows Relay to the elevator! Do you notice a problem this time? Mystery: You have the power to manipulate robot parameters and time. Whenever you want, stop time by asking everyone to freeze. Then you can reverse time, go back to a certain point in time, and replay. Think about what parameters you can modify in your design and how you can do that to fix the problem. Use your imagination |
| Guest | Follow the instructions again, but this time you are an older person walking with a cane. When following the robot walk really slowly, and remember the pace at which you walk because you may have to replicate it later |
| Receptionist | Follow the instructions |
| Narrator | Read the instructions for everyone out-loud |
| Bystander1 | You are again standing in the lobby taking videos of the robot. When the robot moves quickly towards the elevator, turn around and keep recording, while “accidentally” blocking the hotel guest’s view of the robot |
| Bystander2 | You exit the elevator before Relay enters. You find a flyer in-front of the elevator, you stop and read it while blocking the hotel guest from getting to the elevator before the door closes again |
| Bystander3 | You are waiting for the elevator on the second floor |

This scenario was inspired by the experience of a designer we interviewed. Through the activity we shared what we had learned from the interviews and showcased how testing a pre-programmed robot in the real-world can help designers test assumptions they have made and identify potential problems with their designs. The role-playing portion of the activity enabled participants to take the perspective of different stakeholders and gain empathy, particularly for the designer. The participant who was the designer was able to “pause time” by asking everyone to freeze, replay the scenario, and test different values for the speed of the robot. Through the mystery component of the activity, participants recognized the need for data capture during user testings and the challenge that the dynamic environment poses when iterating on parameters in the design space. The bodystorming overall resulted in a shared understanding of a subset of challenges designers face when testing situated human-robot interactions and led to an effective ideation phase. For example, one participant suggested choosing the design parameter (in this case the speed of the robot) as a function of a sensor data input (the speed of the user), instead of selecting a constant value.

We continued the workshop with a second scenario that was designed to provide a similar experience for participants. However, this time we focused on fault detection and debugging, instead of exploring the parameters of the design space. Through our needfinding, we found that to prototype an interaction, designers often program the robot, and when the robot behavior is not as expected they are often challenged with the task of debugging. More specifically, the complexity, opacity, and interdependency of robots make the task of debugging situated robotic systems difficult. In the second scenario, we designed a hypothetical fault detection task to communicate these findings. The instructions for each role are described below.

### Scenario 2: Relay Will Be Delivering a Towel to a Guest's Hotel Room

| | |
|---|---|
| Main roles | Relay, designer, hotel receptionist, bystander1 |
| Optional roles | Narrator, hotel guest, bystander2, bystander3 |
| Instructions | All roles should open and read their green instruction note |
| Description | The robot is standing behind the reception desk |
| | The guest calls reception and asks for an extra towel to be sent out to room #203 |
| | The hotel receptionist opens the lid on top of Relay and places a towel in it. Closes the lid and enters the room number on the touch screen |
| | The hotel receptionist enters the room number followed by "deliver" on the touch screen of Relay |
| | Relay moves towards the elevator |
| | Relay is wirelessly connected to the elevator and activates the "up" button |
| | The elevator door opens. People exit the elevator. Relay enters the elevator |
| | Relay wirelessly activates the button for the second floor |
| | The elevator door opens. Relay exists the elevator and moves down the hallway |
| | Relay stops in front of room #203 and calls the phone inside the room |
| | Hotel guest picks up the phone and an automate message plays "Relay is outside of your door with a delivery" |
| | Guest opens the door |
| | Relay writes "Hello! Here is your delivery" on the screen, and the lid automatically opens |
| | The guest picks up the towel and Relay writes "Did you get everything you requested?" |
| | The guest presses the "all set" button on the touch screen |
| | Relay writes "excellent", closes the lid, and goes back |
| Followup instructions | Repeat the above task a second time. All roles should open and read their yellow instruction notes. Note that this time the designer can engage with the audience, if they wish, to solve the "mystery" problem |

### Scenario 2 (Round 0): Green Mystery Information Notes

| | |
|---|---|
| Relay | Follow the instructions. Hold your screen in front of you. Based on the instructions write or draw on your screen. Rule: remember you cannot speak. All you can do is make beeping noises, if you wish |
| Designer | Stand a few meters away from Relay. Follow and observe the interactions without interfering with what is happening |
| Guest | Follow the instructions |
| Receptionist | Follow the instructions |
| Narrator | Read the instructions for everyone out-loud |
| Bystander1 | You enter the elevator with Relay while holding a big bag |
| Bystander2 | You exit the elevator before Relay and the hotel guest enter |
| Bystander3 | You are waiting for the elevator on the second floor |

### Scenario 2 (Round 1): Yellow Mystery Information Notes

| | |
|---|---|
| Relay | Follow the instructions and utilize your screen similar to the previous time. Instead of stopping in front of room #203, keep going until the end of the hall and stop there. Rule: remember you cannot speak. Mystery: The mystery is that when the person in the elevator accidentally touched their bag to you, a sticker stuck to your camera and partially covered it. Now you cannot really see through your camera and therefore your localization algorithm cannot locate where you are in the lobby. Even though you are an “intelligent” robot you actually do not understand that your camera has been occluded. So if the designer asks, you cannot share this mystery with them. All you know is that your localization algorithm is not sure where you are in the hotel hallway, and it thinks that you are further back in the hallway with probability 0.2! If the designer asks what your camera is seeing you can draw this image: [black square] |
| Designer | Again stand a few meters away from Relay and observe without interfering. Do you notice a problem this time? Mystery: You have the power to manipulate robot parameters and time. whenever you want, stop time by asking everyone to freeze. Then you can reverse time, go back to a certain point in time, and replay. Think about what components you can inspect, what questions you can ask, and what you can do to fix the problem. Use your imagination |
| Guest | Follow the instructions |
| Receptionist | Follow the instructions |
| Narrator | Read the instructions for everyone out-loud |
| Bystander1 | You enter the elevator with Relay while holding your big bag in your hand. You accidentally touch the robot with your bag as you try to put it down |
| Bystander2 | You exit the elevator before Relay and the hotel guest enter |
| Bystander3 | You are waiting for the elevator on the second floor. When Relay comes out very carefully walk around Relay and enter the elevator |

Similarly, this scenario was inspired by the experience of an HRI researcher we interviewed. In this activity we showcased the challenges programmers and designers face in the debugging process when the robot behavior is not as expected. Specifically, through the mystery component of the activity, participants found it challenging to identify why the robot was not stopping in front of room #203. The first step was to realize that the localization algorithm was the source of the problem and to ask the robot where it thought it was located. Once they found that the robot was unable to localize itself correctly, they then needed to identify the source of the problem at the sensor-level. This required the designer to have some technical knowledge about how the simultaneous localization and mapping algorithms work and what information they rely on. The designer then had to inspect all relevant sensor inputs to ultimately realize that the camera view was occluded.

At a high-level participants recognized the importance of asking good questions in the debugging process and forming relevant hypotheses about why the robot is not behaving as expected. In this process, they empathized with the designer and gained a better understanding of the difficulties they face when debugging such a complex and situated system. More specifically, participants recognized that due to the complexity of the robot and the context in which it operates in, the search space is rather large, and this information overload makes identifying the source of the problem challenging. Similar to the previous scenario, the shared understanding that resulted from this bodystorming activity led to an effective ideation phase. For example, one participant suggested monitoring all sensor data and automatically detecting sudden and dramatic changes in the input stream to help the designer narrow down the search space. Another participant suggested recreating the user testing scenario in virtual reality with the use of the captured data, to provide context for designers as they engage in a more indepth debugging analysis.

Through bodystorming, we were able to rapidly communicate our needfinding results regarding the challenges that prevent designers from effectively utilizing design methodologies, such as rapid prototyping and user testing, in the human-robot interaction design process. Participants gained relevant tacit knowledge about the problem at hand and were able to empathize with various stakeholders involved. Bodystorming was also an effective medium through which participants were able to rapidly create early prototypes of human-robot interactions situated in the context, and at a meta-level, ideate on tools that can assist human-robot interaction designers in their design process.

## 5 Bodystorming for Sharing Needfinding Results

We propose that bodystorming can be an effective tool for communicating needfinding results during the early stages of the human-robot interaction design process. Such bodystorming activities allow participants to have an embodied experience, situated in the context of the problem, that can induce empathy and provide a shared understanding of the problem space. In this section, we summarize our findings from the workshop and provide high-level instructions on how bodystorming activities can be created to communicate needfinding results in the context of human-robot interaction design.

First **create a list of objectives** for the activity. What are the key findings you want to communicate? What are the pain points or challenges you identified? In our workshop, we wanted to present the challenges designers face when prototyping situated human-robot interactions, such as complexity, opacity, and interdependency of robots, uncertainty of human behavior, need for context switching, having multiple frames of reference, difficulties in data capture, and information overload when sensemaking.

Based on the experiences that your users have had and examples that they shared with you, **create hypothetical, but concrete, scenarios** that capture variety of user experiences. Include details about the context and the stakeholders involved in the scenario description. How many people or robots are involved in this scenario? What are their roles? Then map the objectives to the hypothetical scenarios you created, based on which scenario can best describe the finding you want to communicate. Note that one scenario may map to multiple objectives.

**Evaluate your resources** and the context of the bodystorming activity. How many people will be participating? How much time do you have? Do you have any information about the participants' background and expertise? It is unlikely that you will be able to achieve all of the objectives in one activity. Prioritize your objectives and select a subset based on the resources you identified. In our workshop, we chose to focus primarily on the challenge of data capture in the first scenario and information overload in the second scenario.

**Write a description for each scenario** to be read out-loud by a narrator in order to guide all participants in their roles. Compile a list of roles involved in the scenario, in addition to a narrator, and write instructions that may not be explicitly stated in the scenario description read out by the narrator (green notes for Round 0). Include any rules that each role should follow. For example, in our activity, the participant playing the role of the robot could not speak. Based on the number of participants, adjust the roles by adding auxiliary roles or removing less critical ones.

For each selected scenario, identify **how the objective can be achieved by adding a mystery element** to the activity. What game mechanics are necessary? What information should be hidden from the main role? Which roles should carry out the mystery? In our workshop, the robot had additional information that the designer did not, and the designer was asked to solve the mystery-game. Write instructions that may not be explicitly stated in the scenario description (yellow notes for Round 1). Include more information about the mystery for roles that are involved and include information about what techniques the main role can utilize to solve the mystery. Think about what additional game mechanics are needed to achieve the scenario objective that may not be possible in the real world. In our example, the designer could pause time, reverse time, or go back to a certain point in time to reply the scenario.

Create copies of the individual role instructions for Round 0 and Round 1 (green and yellow notes). Make role tags and attach the individual instructions to each tag.

Create a copy of the scenario description for the narrator. Pilot the activity to ensure that it can be completed without the facilitator participating or intervening, and to test your assumptions before running the bodystorming activity.

While bodystorming was an effective technique for communicating needfinding results, we found a few challenges that should be addressed in future works. Firstly, the scenarios and instructions used in our workshop were carefully designed to provide sufficient structure to the activity without over-constraining the participants' actions and decisions. This was a challenging task and future work should study different ways designers can achieve this balance such that participants can freely explore the problem and solution space, while ensuring that the pre-determined objectives of the activity are accomplished. Moreover, this technique, in its current form, may not be suitable for large-scale needfinding efforts and future work should study how to leverage the advantages of bodystorming in a larger scale. Lastly, at a high-level, there are many opportunities for further exploration of new design tools or methodologies that can help human-robot interaction designers tackle the challenges that arise from the complexity and situatedness of ubiquitous and contextually-aware robotic systems.

## 6 Conclusion

In this chapter, we discuss factors that make the design of human-robot interactions difficult, including the complexity, opacity, interdependency, and uncertainty of situated robotic systems. We then summarize insights we gathered through interviews and observations, highlighting additional challenges human-robot interaction designers face, including the need for context switching between the real-world environment where the robot is situated and the 2D computer interface, the difficulty of perspective taking given the 3D nature of interactions and the existence of many frames of reference, the overhead of data capture, and information overload when interpreting the captured data. These findings shed light on why designers are often unable to adopt important design methodologies such as rapid prototyping, user testing, and iteration in the context of situated interactions with robots. Finally, we propose that bodystorming can be an effective tool in the early stages of the human-robot interaction design process as a means of presenting needfinding results. We describe how we designed such mystery-game-style role-playing activity to communicate our findings, enable perspective taking to induce empathy, and encourage situated, rapid prototyping for human-robot interaction design.

## References

Burns, C., Dishman, E., Verplank, W., & Lassiter, B. (1994). Actors, hairdos & videotape – informance design. In *Conference Companion on Human Factors in Computing Systems* (pp. 119–120).

Kelley, J. F. (1983). An empirical methodology for writing user-friendly natural language computer applications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 193–196).

Kooijmans, T., Kanda, T., Bartneck, C., Ishiguro, H., & Hagita, N. (2006). Interaction debugging: an integral approach to analyze human-robot interaction. In *Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction* (pp. 64–71).

Martelaro, N., & Ju, W. (2017). WoZ way: Enabling real-time remote interaction prototyping & observation in on-road vehicles. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing* (pp. 169–182).

Oulasvirta, A., Kurvinen, E., & Kankainen, T. (2003). Understanding contexts by being there: case studies in bodystorming. *Personal and Ubiquitous Computing, 7*(2), 125–134.

Pantofaru, C., & Takayama, L. (2011). Need finding: A tool for directing robotics research and development. In *RSS 2011 Workshop on Perspectives and Contributions to Robotics from the Human Sciences*.

Parkes, A., & Ishii, H. (2010). Bosu: A physical programmable design tool for transformability with soft mechanics. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems. DIS '10* (pp. 189–198). Aarhus: ACM. . ISBN: 978-1-4503-0103-9. https://doi.org/10.1145/1858171.1858205http://doi.acm.org/10.1145/1858171.1858205

Porfirio, D., Fisher, E., Sauppé, A., Albarghouthi, A., & Mutlu, B. (2019). Bodystorming human-robot interactions. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (pp. 479–491).

Raffle, H. S., Parkes, A. J., & Ishii, H. (2004). Topobo: A constructive assembly system with kinetic memory. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '04* (pp. 647–654). Vienna: ACM. ISBN: 1-58113-702-8. https://doi.org/10.1145/985692.985774

Sauppé, A., & Mutlu, B. (2014). Design patterns for exploring and prototyping human-robot interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1439–1448). New York: ACM.

Schleicher, D., Jones, P., & Kachur, O. (2010). Bodystorming as embodied designing. *Interactions, 17*(6), 47–51.

Segura, E. M., Vidal, L. T., & Rostami, A. (2016). Bodystorming for movement-based interaction design. Human Technology, 12(2), 193–251.

Smith, B. K. (2014). Bodystorming mobile learning experiences. *TechTrends, 58*(1), 71–76.

Yim, J.-D., & Shaw, C. D. (2009). Designing CALLY, a cell-phone robot. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems* (pp. 2659–2662).

# Part IV
# Outlook: Emerging of Neurodesign

# NeuroDesign: From Neuroscience Research to Design Thinking Practice

**Jan Auernhammer, Neeraj Sonalkar, and Manish Saggar**

**Abstract** There is an increasing use of neuroscience research methods to understand the neural basis of design activity. The use of Neuroscience research tools such as fMRI, EEG and fNIRS presents a new and insightful approach to potentially understand the neurocognitive processes underlying design thinking at the level of individual designers as well as teams. However, the results from neuroscience research while insightful are rarely directly applied to design practice. In this chapter, we explore this gap between neuroscience research and design practice and explore how the emerging field of NeuroDesign might bridge this gap. Delving into the epistemology of design practice and the promise of neuroscience, we present the understanding and practice of learning as a key bridge between the two fields. We explore the broader implication of learning in the framing of NeuroDesign and present a research agenda for further studies in the field.

## 1 Introduction

NeuroDesign is an emerging field of study that lies at the intersection of neuroscience research and design thinking practice. Consequently, a fundamental challenge in NeuroDesign is to effectively and efficiently apply the information gained by studying brain functioning to the development and teaching of improved design thinking practices. Neuroscience based approaches (e.g., fMRI) could provide information not only about whether a particular design-thinking-based approach works, but also how (or why) it does. Knowing the underlying neural mechanisms

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involved in a particular design thinking approach could provide valuable insights for developing new and effective pedagogical and practical methods. Further, advances in neuroimaging at the single participant level (a.k.a. Precision neuroscience; Saggar and Uddin 2019) could be immensely useful in tailoring design thinking practices to each individual.

In order to realize this promise, the studies that are undertaken in the field of NeuroDesign need to go beyond the paradigm of the current studies on neuroscience of creativity and design thinking and include elements that will orient the findings to practical use in day to day design thinking application. In this chapter, we outline specific gaps that need to be addressed and potential avenues for exploration to move the field of NeuroDesign towards the application of neuroscience-driven design thinking in the real world.

## 2 Neuroscience Experiments to Research Design Thinking

Neuroscientific research examines brain functioning through highly controlled lab experiments in which participants perform a pre-defined set of cognitive tasks. This allows us to investigate activation of specific brain regions by examining changes in brain activity/connectivity. Measuring such changes in activation/connectivity can putatively inform about which brain regions are active when performing certain cognitive tasks. For recent examples of finding neural correlates of design thinking based practices, see Saggar et al. (2015) for assessing neural correlates of figural creativity or Shealy et al. (2018) for examining neural correlates of brainstorming. Neuroimaging paradigms could provide valuable insights about the underlying neurocognitive process of thinking in design. Understanding and observing neurocognitive processes of designers has a great potential to inform design practices. However, there are several disciplinary gaps between applying neuroscience-derived insights into design thinking practice.

## 3 Disciplinary Gaps Between Neuroscience and Design

Neuroscience and Design Thinking have differing purposes. Neuroscience aims to understand the brain functioning that enables specific modes of thinking and behaving. Design Thinking aims to apply these specific modes of thinking and behaving to an external objective such as profit, beauty, utility or even justice. This difference in purpose creates several gaps. These differences are outlined in Table 1.

**Table 1** Shows the difference in the nature of Neuroscience and Design Thinking

| | Neuroscience | Design thinking |
|---|---|---|
| Purpose | Understanding thinking (in design, i.e. creativity) | Enabling and utilizing thinking in design (e.g. creativity) |
| Question | Hypothesis testing | Design challenge |
| Condition for answer | Falsifiable | Satisfactory |
| Reasoning | Deductive | Abductive |
| Predominant thinking | Analysis | Synthesis |
| Experimentation mode | Controlled experiment | Prototyping to reach real-world conditions |
| Practical considerations | Scientific terminology<br>Costs of brain imaging<br>Scientific methods | Design terminology<br>Costs for materials<br>Design methods |

## *3.1 Question Gap*

Neuroscience is situated within the empirical science paradigm of hypothesis testing and theory formation. It seeks to understand and model how the human brain functions when performing various cognitive, creative, affective, social as well as unconscious activities. It asks deep reasoning questions about how our neural mechanisms influence who we are and how we behave. Designers, on the other hand are situated within the constructivist and pragmatic paradigm. They ask generative—what if—questions that seek to both answer and shape how the world ought to be. A neuroscientist aims to understand the complex nature and dynamics of our brain, while a designer would consider ways to apply this thinking for an external purpose.

For example, McKim (1980) outlined how to think visually to create beauty, utility and ultimately profit. Similar, Adams (2001) described practices of how to overcome blocks to creative thinking. The effects in thinking developed through creative exercises can be observed by neuroscientists (Saggar et al. 2015).

## *3.2 Culture Gap*

Another gap is the culture gap of what each discipline values and how this value is manifest through everyday practice. The two cultures phenomenon has been expressed by Snow (1993) between science and writing. Neuroscience focuses on empirical proof through hypothesis testing and well designed and controlled experiments utilizing tightly defined cognitive tasks. The result of a neuroscience study is considered scientific when it is accompanied by empirical evidence that can be replicated or falsified by others. In contrast, design outcomes aim to create a satisfactory condition to the challenge at hand. This can be accomplished through many different solutions without a single right answer. The search for a satisfactory solution is pursued through abductive reasoning which is not necessarily empirically grounded or even explicitly communicable. There is an artistry in design which clashes culturally with the technical rationality of neuroscience.

### *3.3 Reasoning and Thinking Gap*

The nature of reasoning in the design thinking discipline differs from that in the neuroscience discipline. Neuroscience follows a deductive and inductive reasoning that allows for new knowledge to be created based on a strong foundation of what is already known. Design follows an abductive reasoning pattern that seeks to create variations that are an amalgamation of both concept and knowledge, and seeks to test, iterate and refine on these variations through real-world and informed trial-and-error. The gap between neuroscience and design is that too much focus on deductive reasoning and analytical thinking in design will not result in a novel satisfactory solution, while abductive reasoning and synthesis in neuroscience will not result in an answer that contributes to the body of scientific knowledge.

### *3.4 Approach Gap*

The approach gap consists of how knowledge is produced in both disciplines. As mentioned above, neuroscientific experiments require tightly controlled lab settings. In contrast, thinking in design includes experimenting of failing fast, prototyping and leaping or learning forward. These are different learning approaches. This gap becomes apparent when researching design thinking through neuroscience. Thinking of the designer incorporates real-world experience and insights and flexibility and fluency in thinking and approach. Therefore, when researching design thinking through neuroscience, trade-offs need to be made. Either the complexity of real-world practice needs to be reduced, in turn reducing ecological validity, or a higher degree of freedom in activities needs to be allowed which could putatively reduce the observability and scientific reproducibility to generate testable insights about the neural correlates of that design activity. These conflicting approaches present an important and challenging gap that needs to be bridged.

### *3.5 Practical Gaps*

The last gap is a practical gap incorporating costs, jargon and methodology. Experiments in neuroscience can involve costly procurement, operation and maintenance of brain imaging instruments. However, recent technological developments have decreased the cost making brain imaging more accessible (Gero 2019).

This could allow designers to utilize brain imaging techniques. However, it is important to understand both the language and methodology within a discipline to form a successful bridge between it and practice. When executing brain imaging study, designers need to understand the language used in the neurosciences to build on this large body of knowledge. Understanding the language will also help in understanding methodological approaches and how to collect, analyze and interpret data. This may be a steep learning curve for designers. However, without it, it will be difficult for designers to contribute and utilize the existing knowledge of neuroscientific studies to advance thinking in design. On the other side, neuroscientists need to understand the language and methodology of designers to generate value. If neuroscientists will simply persist in their methodology, they will provide explanation of design thinking, but will not contribute by creating knowledge that improves design thinking practice. To add value to thinking in design both sides need to understand the current technological limitations and methodological perspectives including the complexity involved in designing and developing meaningful solutions that serve the needs of people in real-world conditions. For this to happen, the practice of learning is key to bridging the gap between the two disciplines.

## 4 Practice of Learning to Bridge the Gap of Neuroscience and Design

Neuroscience and design thinking share a similar concern, which is to study, support and augment the ability of people to learn. For bridging the gap between the two (un)learning is essential. However, this kind of learning requires empathy for each other. Empathy to understand another field and culture requires one to detach from one's own worldview and to reframe the world from the other's point of view. The best way to understand one another is to experience the practice of the other. Embodied learning could be facilitated by doing or being involved in neuroscience research and design thinking practice. It is a process of socialization as described by Nonaka and Takeuchi (1995). For example, learning is best accomplished by practicing neuroscience in design thinking and utilize design thinking to creatively find new interesting questions and design neuroscientific experiments. This approach has been stated by Einstein and Infeld (1967) as making true advances in science. The first step is to offer each other a helping hand and start collaborating to bridge the neuro-and-design gaps. In this collaboration there are two modes of learning, a constructivist approach by practicing and reflecting, and a positivistic approach of scientific discovery.

### 4.1 Learning by Practicing

Neuroscientists can learn and develop their creative capability through participating in the creative thinking activities in design, while designers can learn and develop their scientific curiosity and analytical thinking through partnering with and practicing neuroscientific research. It allows each discipline not only to observe indirectly the thinking of people, but also it provides an environment to think about thinking, a reflexive practice of thinking about one's own design or neuroscience practice. This intersection allows the researcher and designer to develop their ambidextrous thinking as described by Faste (1994). In this sense, a neuro-designer is a creative scientist or a scientific creative who is able to bridge the gaps.

### 4.2 Learning from Research

Scientific research is an activity with the main focus of producing knowledge. Neuroscientific experiments can help to understand the underlying thinking in relation to specific practices. Insights on brain activation and structural developments can provide knowledge, which one can act upon to improve one's thinking. This by itself can help to develop practice of learning in science and design. To enable this learning in the intersection of neuro-and-design, we propose a framework that can help address the gaps between neuroscience and thinking in design.

## 5 A Framework to Address the Gaps

Neuroscience and design thinking have the potential to inspire and enable each other. The emerging intersection of neuro-and-design, NeuroDesign has the potential to bridge the gaps by understanding the neurocognitive processes in design thinking through scientific observation and improving the thinking in design through synthesis and informed intentional action. To enable this intersection several gaps outlined above need to be addressed through the practice of learning.

### 5.1 Bridging the Question Gap

The Question gap can be overcome by understanding the similarities of neuroscience and design thinking. Both start with an attitude of questioning and curiosity. Both the scientific problem finding or designer need finding require the gathering of information about the environment and the contextual frame. This has been described in science, arts and design (Getzels and Csikszentmihalyi 1976; Arnold

1959; Einstein and Infeld 1967). Creative thinking is at the core of this process of defining the research question, hypothesis or design challenge. The bridging of the Question gap could be achieved by creating a question formation toolbox that could be used by both design practitioners as well as neuroscientists to drive hypothesis generation.

### *5.2 Bridging the Culture Gap*

Overcoming the culture gap is probably one of the most difficult tasks. Culture has to do with shared beliefs and values (Schein and Schein 2016). Overcoming and accepting other beliefs and values that may challenge one's own value system requires letting go. A first step that may be helpful is to accept that different body of knowledge exists. The scientific body of knowledge is about how the universe "works". Design has a different body of knowledge as described by Vincenti (1993). The body of knowledge of design is constructive or productive knowledge. The knowledge of how to manipulate the world. Through designing, building and evaluating engineers and designers create knowledge about how the world could be. While these are two types of knowledge, they are not mutually exclusive. When designing and executing experiments designers produce something new while scientists can observe the process and outcome and empirically test it through interesting experiments. This allows us to examine the thinking in design neuroscience and utilizing the thinking in design through design practice to create real-world solutions that serve the needs of people.

### *5.3 Bridging the Reasoning and Thinking Gap*

The focus on deduction and in science and plausible reasoning in design can be overcome through developing the ability for both types of thinking. McKim (1980) and Faste (1994) expressed the ability of flexible thinking as ambidextrous thinking. It is important to know when each type of thinking is required and being able to flexibly move between the two. The meta-ability is to be able to change thinking modes by will (McKim 1980) thus allowing for individuals to work creatively and analytically when the task requires. There is a need to come up with novel and relevant experiments through creative study designs to advance theoretical knowledge as well as practice, and a need for thorough analysis to understand deeply observed concepts. Learning and developing these abilities will allow us to overcome the analysis and synthesis gap.

### 5.4 Bridging the Approach Gap

Experiments of neuroscience can be combined with design research approaches to examine both the neurocognitive process and context of these processes such as background of the person, chain of activities, outcomes such as products and environment of everyday practice. Through the combination of capturing these different variables, experiments can be designed in the neuro-design intersection that could contribute to both neuroscience and design disciplines. Other design practice aspects that could be examined include team interactions based neurocognitive process (Mayseless et al. 2019), and the context of cultural environments of design thinking practices.

### 5.5 Bridging the Practical Gap

The practical gap pertains to the gap in the actual practice of the two disciplines which could involve issues of cost, time, language and methods. The biggest challenge faced by both designers and neuroscientists is a lack of time to pursue the bridge to another discipline. Designers are on a tight schedule to deliver on their projects and do not necessarily have the time to learn new tools, language and methods from neuroscience. Similarly, neuroscientists are on a tight schedule or running research projects to take time to learn new methods and ways of thinking from design. If NeuroDesign is to become an interface between the two disciplines, it needs to somehow overcome these practical issues. One way is to create explicit programs that create space for collaboration between the two disciplines through grant making and funding of collaborative design projects. Another is to create a research and development agenda that seeks to create micro-tools or micro-activities that enable neuroscientists to practice design thinking and designers to adopt findings from neuroscience during the course of their daily routines. These tools or activities could act as a translator between the practitioners of the two disciplines.

## 6 Conclusion

Neuroscience and Design Thinking might seem unlikely collaborators but could form a potent partnership that could not only inform neuroscience studies but also radically improve design practice. We call this partnership, NeuroDesign. In this chapter we presented the gaps that NeuroDesign as a discipline will need to bridge between neuroscience and design practice and suggested a framework for closing these gaps. The term NeuroDesign is such a term that requires new meaning without overemphasizing the neuroscience analysis or the design thinking synthesis and develop a new intersection that can improve the thinking in design, the ability to design and develop better solutions for our world.

## References

Adams, J. L. (2001). *Conceptual blockbusting: A guide to better ideas* (4th ed.). Cambridge, MA: Perseus.

Arnold, J. E. (1959). Creativity in engineering. In P. Smith (Ed.), *Creativity, an examination of the creative process: A report on the third communications conference of the Art Directors Club of New York* (pp. 33–46). New York: Hastings House.

Einstein, A., & Infeld, L. (1967). *The evolution of physics*. London: Touchstone.

Faste, R. A. (1994). Ambidextrous thinking. In *Innovations in mechanical engineering curricula for the 1990s*. New York: American Society of Mechanical Engineers.

Gero, J. S. (2019). *From design cognition to design neurocognition*. Paper presented at the CogSci 2019.

Getzels, J. W., & Csikszentmihalyi, M. (1976). *The creative vision: A longitudinal study of problem finding in art*. New York: Wiley.

Mayseless, N., Hawthorne, G., & Reiss, A. L. (2019). Real-life creative problem solving in teams: fNIRS based hyperscanning study. *NeuroImage, 203*, 116161. https://doi.org/10.1016/j.neuroimage.2019.116161.

McKim, R. H. (1980). *Experiences in visual thinking*. Monterey: Brooks/Cole.

Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company how Japanese companies create the dynamics of innovation*. New York: Oxford University Press.

Saggar, M., & Uddin, L. Q. (2019). Pushing the boundaries of psychiatric neuroimaging to ground diagnosis in biology. *eNeuro, 6*, ENEURO.0384-19.2019.

Saggar, M., Quintin, E.-M., Kienitz, E., Bott, N. T., Sun, Z., Hong, W.-C., Chien, Y.-h., Liu, N., Dougherty, R. F., Royalty, A., Hawthorne, G., & Reiss, A. L. (2015). Pictionary-based fMRI paradigm to study the neural correlates of spontaneous improvisation and figural creativity. *Scientific Reports, 5*(1), 10894.

Schein, E. H., & Schein, P. A. (2016). *Organizational culture and leadership*. Hoboken, NJ: Wiley.

Shealy, T., Hu, M., & Gero, J. S. (2018). *Patterns of cortical activation when using concept generation techniques of brainstorming, morphological analysis, and TRIZ*. https://doi.org/10.1115/DETC2018-86272

Snow, C. P. (1993). *The two culture*. New York: Cambridge University Press.

Vincenti, W. G. (1993). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore: Johns Hopkins University Press.

# Neurodesign Live

**Julia P. A. von Thienen, Caroline Szymanski, Joaquin Santuber, Irene S. Plank, Shama Rahman, Theresa Weinstein, Babajide Owoyele, Matthias Bauer, and Christoph Meinel**

**Abstract** Neurodesign is a novel field of research, education and practice that emerges as a cross-disciplinary initiative. In 2019, the Hasso Plattner Institute (HPI) offered for the first time a neurodesign curriculum. The objective of neurodesign as we pursue it is to explore synergies at the intersection of (i) neuroscience, (ii) engineering and (iii) design thinking · creativity · collaboration · innovation. In this chapter, we share insights into the development of a curriculum that quickly became more comprehensive than we had anticipated for this initial implementation phase. Neurodesign evolves serendipitously driven by the passions of numerous protagonists who contribute their expertise, ideas and work results in a uniquely collaborative fashion. The chapter briefly summarizes input provided by neuroscientists and creative engineers from several countries and different continents, who contributed guest expert talks at the HPI to help build up a joint knowledge base. The major part of the chapter is a review of neurodesign projects that have emerged, often in collaboration with guest experts of the program. Overall, these projects indicate how intersections of neurodesign (i)–(ii)–(iii) open up cornucopias of opportunities. Especially the integration of engineering expertise has introduced many favourable dynamics. In terms of strategic reflections, this chapter shares "missions" we pursue in the development of neurodesign. These directions for further initiatives also commence a brief outlook on upcoming neurodesign developments.

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In October 2019, the Hasso Plattner Institute (HPI) started to teach and practice neurodesign. It was an "experiment" and we expected to start small. Out of passionate reactions of people who got involved, the movement quickly grew much bigger than we had anticipated in the beginning.

The bodily basis of design thinking had been a side-topic in research for a while. At the HPI d.confestival 2017, a podium discussion explored the topics of *Neurobiology and Design Thinking* (HPI 2017). A year later, along with an HPI-Stanford design thinking research meeting, a symposium addressed the topic of *Neuroscience and Physiological Perspectives on Design Thinking and Creativity* (HPI 2018). These were already collaborative events, with researchers from the HPI, Stanford and other academic partners such as the Marconi Institute for Creativity from the University of Bologna involved. Yet, these events span just a couple of hours each.

In parallel, at Stanford Allan Reiss, Manish Saggar and their research teams pioneered empirical investigations into the biological basis of design thinking creativity (e.g., Saggar et al. 2016; Xie et al. 2019). At the same time, studies into the history of design thinking revealed that extensive reflections on the (neuro-) psychological processes of creativity in engineering design informed the design thinking approach since its earliest beginnings (Clancey 2016, 2019; von Thienen et al. 2017, 2021).

The movement gained impetus when Larry Leifer, founder of the Center for Design Research at Stanford and head of the Design Thinking Research Program at his faculty, coined the term "neurodesign" as a headline for promising avenues in the development of design thinking. Larry was serious about the vision of design thinking as neurodesign. He found Jan Auernhammer as a passionate companion, who became Executive Director of the Leifer Neurodesign Research Program at Stanford and soon hosted a first neurodesign symposium aligned to a Stanford-HPI design thinking research meeting in March 2019.

Thrilled by this joint passion for an otherwise rare topic combination and emerging new perspectives, at the HPI Julia von Thienen and Christoph Meinel decided to bias to action and launch a neurodesign course in what was then the upcoming winter semester. Julia wrote an extensive manuscript for a neurodesign lecture she wanted to hold, with long abstracts for each planned session and literature references. To ensure that the topic selection, course messages and references would be up-to-date, she sent her manuscript to colleagues and friends with a background in the neuroscience of creativity or collaboration, to ask for additions as well as critique. Reactions were very different from what had been expected. Instead of commenting on manuscript details, colleagues rather expressed their high level of excitement about the topic and interest in getting actively involved.

Caroline Szymanski was the first to get on-board. With a PhD in the neuroscience of collaboration and many years of involvement at the HPI D-School, she was elated that two major passions in her life, which previously seemed to require all too disparate work, might find a fertile academic home. Julia and Caroline decided to rethink the lecture. Instead of a conventional format with a single teacher, the course should bring experts of pertinent topics together, so that everyone could contribute insights from his or her special field of expertise. All colleagues to whom we reached out immediately agreed to come—from various countries and even different continents—to discuss their topics in the neurodesign lecture, even though there would be no monetary remuneration for the engagement. Soon Julia and Caroline even had to denounce favourite topics they had planned to present in the lecture series themselves, because session slots were needed for other colleagues who were ready to come.

As another HPI colleague, Joaquin Santuber quickly became engaged. He had co-taught courses on design thinking in digital engineering together with Jonathan Edelman at the HPI, where they had made favourable teaching experiences with the use of physiological sensors to augment design. In joint discussions, pedagogical and methodological aspects of neurodesign soon came into focus. What is it that HPI students can learn and contribute in this novel field of neurodesign? Why would this particular student audience be interested in the topic? HPI students are digital engineers. At the HPI—akin to Stanford—, design thinking education is embedded in engineering education. Thus, for us it makes sense to explore and develop neurodesign as a field at the intersection of three domains: engineering, neuroscience and design thinking (Fig. 1).

Notably, the field of neuroscience is extremely rich in (digital) engineering tasks, so that engineering skills are in very high demand at neuroscience labs. Conversely, physiological measures and research methodology common in neuroscience and related fields can be very practical tools for engineering projects as well. For instance, usability studies of engineers can benefit from physiological data captured during the tests. Thus, physiological research methods can facilitate successful design thinking in engineering. Conversely, engineering skills can facilitate the neuroscientific-physiological understanding of design thinking, creativity, collaboration, innovation, design, or any other topic neuroscientists may turn to. Yet, all this hinges on engineers thoroughly understanding neuroscientific methods.

Against this background, we soon decided to offer two neurodesign courses, not only one. Next to the lecture, there should also be a more hands-on seminar

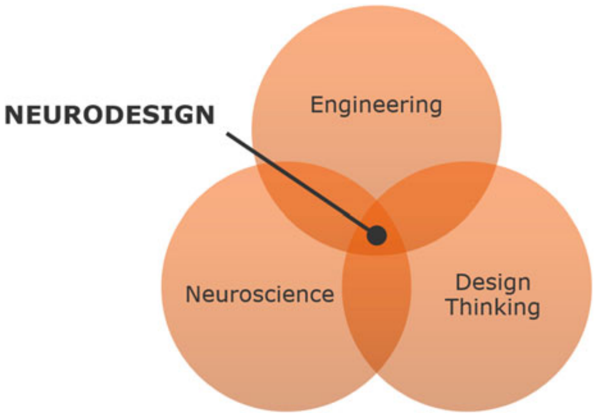


**Fig. 1** Neurodesign fosters explorations and contributions in three domains—especially at the intersections of fields: (i) engineering, (ii) neuroscience and (iii) design thinking · creativity · collaboration · innovation

where students could learn neuroscientific and related research methodology. The seminar should cover topics of study planning, the analysis of EEG and fMRI data and practical work with peripheral physiological sensors.

In terms of teaching experiences, Julia had a record of teaching study design and other methodological topics for social-science students. Joaquin had been conducting research with, and had taught the use of, physiological sensors in engineering design. To complement them, Irene Sophia Plank joined in from the Berlin School of Mind and Brain at Humboldt-Universität zu Berlin, to contribute her expertise in EEG and fMRI methodology by co-teaching the seminar.

Would there be only engineering students in the courses? Neurodesign was envisioned as a melting pot for ideas and expertises. Opportunities in neurodesign hinge on the integration of different academic disciplines. A limitation of audience backgrounds to engineering seemed to make no sense. We reached out to the Psychology Department of Potsdam University. Within a few days, Ralf Engbert and Martin Fischer—in charge of the master program “Cognitive Science—Embodied Cognition” replied with a concrete vision of how knowledge exchange in the form of teaching could happen across university faculties. They agreed to open up the HPI neurodesign courses to their students. Possibly, in subsequent semesters there could even be courses at both faculties, at the Digital Engineering and the Psychology Department, where our students could meet, work together and earn credit points for their studies.

Thus, two courses on neurodesign—the lecture and the seminar—commenced in October 2019, which were open to students from differing backgrounds. The courses were taught by a multidisciplinary teaching team who collaboratively improvised ahead based on what seemed to work well and what seemed to be needed from one week to the next.

Once again, the reception of topics went a way beyond anything we lecturers had anticipated. Suffice it to say that the passion of participants initiated a wealth of projects apart from grading, which students and staff pursued to a large extent in their leisure time. One example is a workshop on the sonification of EEG data, which neurodesign guest lecturer Chris Chafe offered at the Technical University of Berlin (TU) several weeks after his talk at the HPI. Here, students and staff from various courses and chairs at the HPI, some of Chris’ students from the TU and the University of Arts (UdK), neurodesign guest lecturers affiliated with Humboldt-Universität zu Berlin and some colleagues from other institutions came together (Fig. 2). We exchanged data, experimented with sonification approaches and agreed on projects conducted in loosely collaborating cross-institutional teams.

A second example of projects emerging from the passion of students concerns neuroscientific lab assessments. Having discussed digital signal processing in fMRI, and having analysed fMRI data in class, students expressed the wish to personally conduct some fMRI assessments to understand the procedure even better. Thanks to the personal engagement of Irene, this soon became possible at the Berlin Center for Advanced Neuroimaging (BCAN) at the Charité (Fig. 3).

Moreover, driven by further suggestions of seminar participants, fMRI scans should elucidate brain activities of digital engineers while processing code. At

**Fig. 2** As a follow-up event of his HPI talk, Chris Chafe offers a hands-on workshop on data sonification in Dec 2019 at the Technical University of Berlin. It is attended by students and staff from the HPI, neurodesign guest lecturers from Humboldt-Universität zu Berlin, and colleagues from the Technical University of Berlin, the University of Art at Berlin as well as the Beuth University of Applied Sciences Berlin. Cross-institutional collaborations gain momentum (photo by Julia von Thienen)

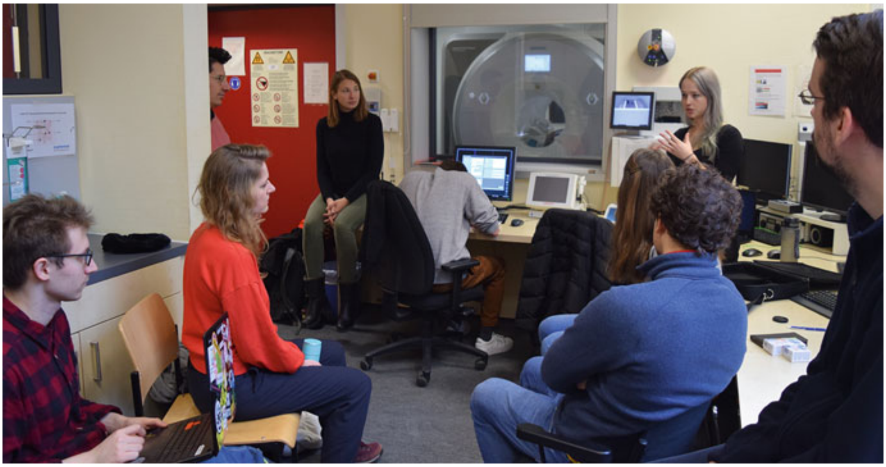

**Fig. 3** Out of interest for the subject, HPI neurodesign course participants come together to conduct fMRI studies in their leisure time. Such assessments are kindly rendered possible by neurodesign lecturer Irene, who organizes and supervises the undertaking. As a study topic, the processing of code is addressed, so that HPI students can also be good fMRI test subjects (photo by Julia von Thienen)

the HPI, already behavioural research had been conducted in the field. Christian Adriano at the chair of Holger Giese had investigated in his PhD research how programmers process and recognize “errors” in source code. At the chair of Robert Hirschfeld, a research group including Patrick Rein, Marcel Täumel and Jens Lincke had studied parallels and differences of people processing natural language vs. code. Christian and Patrick immediately gained interest in brain activities that would occur

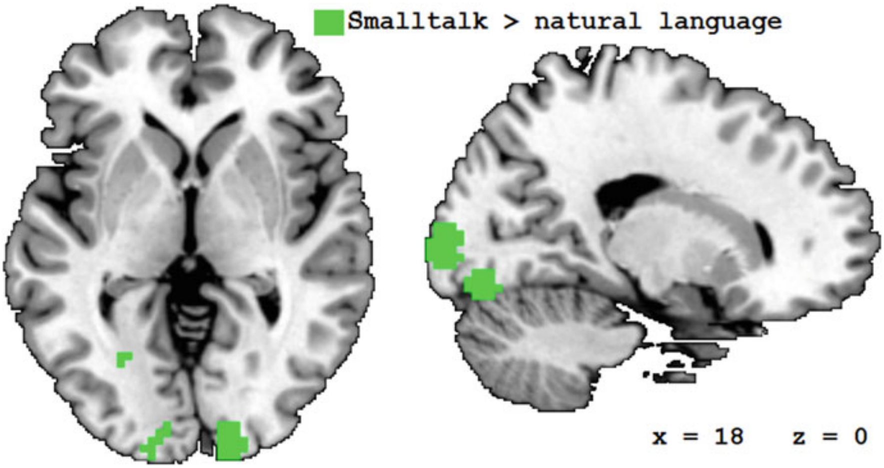


**Fig. 4** Areas activated more strongly during passively reading Smalltalk code compared to a description of the same content in English. The increased activation of visual areas when reading code is probably due to the stimulus material used in this preliminary assessment, where code stimuli tended to be longer and more complex than the content formulated in English

when people tackle their experimental tasks in the fMRI scanner. In rapid work, their available stimulus material was adjusted so as to become more suitable for fMRI scans. Subsequent brief pilot assessments yielded insights for potential follow-up studies.

In one part of the fMRI assessment, natural language was compared to code (Smalltalk) in a passive reading paradigm (Fig. 4). In another part of the study, participants were asked to find errors in Java code (Fig. 5). Both paradigms activated areas associated with visual processing. In upcoming neurodesign courses of the next semester, the topic of designing stimulus material specifically for neuroscientific tests has been included in the curriculum, so that possibly the same research questions can be addressed again in subsequent fMRI or EEG assessments with iterated stimulus material.

As another unexpected development, at the HPI a third class began to work on neurodesign topics. Matthias Bauer and Christoph Meinel jointly offered a web-programming class. Here, students could choose between several projects they wanted to work on over the semester. Julia had submitted one project invitation to this class bearing on the development of an online test platform for creativity tests. This project call complemented several other project invitations, amongst which the students could choose. Serendipitously for us, all students ended up voting in favour of the neurodesign project, so that the whole class came to pioneer web-programming of a neurodesign online test platform. Matthias and Julia were very impressed by the large-scale and impactful results the students engendered, working to a large extent self-organized on this project (cf. Sect. 2).

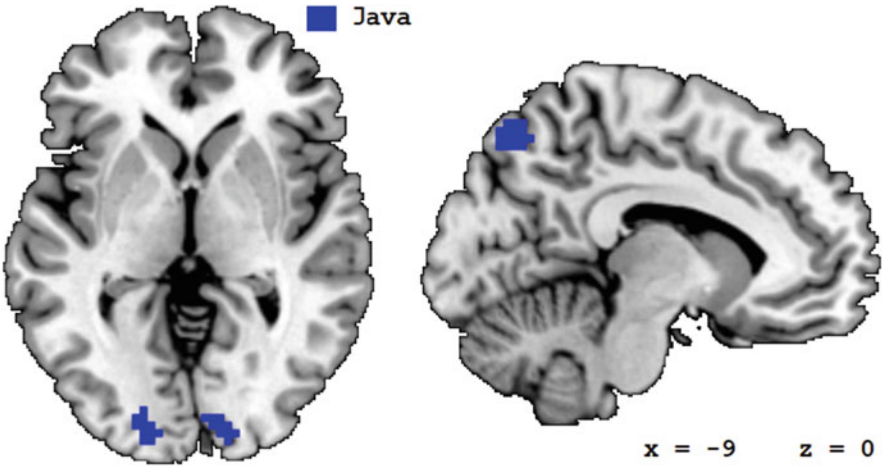


**Fig. 5** Areas activated in the first 10 s of attempting to detect errors in complex Java code. The activation of visual areas is probably due to the complex visual nature of the code, which spanned several lines

Beyond student projects, also the core academic research and teaching team evolved quickly in the course of just one semester.

First of all, Theresa Weinstein discovered neurodesign as a promising area of in-depth work, where she could bring together her formerly separate fields of study. She had completed the basic and advanced track at the D-School and had worked as a design thinking coach; thus she knew design thinking very well from practical perspectives. She had also worked as a student assistant in design thinking research with Martin Schwemmle for more than two years, reflecting her interest in academic studies on creativity, collaboration and innovation. Beyond that, she had studied social and cognitive neuroscience at the Berlin School of Mind and Brain, Humboldt-Universität zu Berlin. Theresa became the first PhD candidate in neurodesign at the HPI.

Babajide Owoyele, educated as an engineer at the Technical University of Berlin, who is a PhD candidate in design thinking research with Jonathan Edelman, also found neurodesign a fruitful area of work, for which he has unique visions. In particular, Babajide gives thought to the uniqueness of the (digital) engineering environment where neurodesign evolves. He notes how creativity and collaboration tests are often designed to be relatively domain-general, whereas ideally we should develop domain-specific assessments as well, especially for the context of digital engineering. As an analysis approach that invokes an embodied cognition perspective, he pioneers gesture studies in creative engineering teams, exploring the use of contemporary technology such as the Microsoft Kinect to capture and understand anonymized posture and gesture-speech data. This is a line of research that certainly can gain further impetus as neurodesign develops towards radically making gesture and speech research accessible to creativity and design research communities.

Shama Rahman, too, gained great interest when she learned about neurodesign, as she was invited to contribute a guest expert talk in the lecture and seminar series. Shama had lived in London for two decades, where she had pursued a variety of passions in seemingly disparate domains. She had studied molecular biology and later obtained a PhD in complex systems mathematics and physics by studying neuro-psycho-physiological processes of artists in a creative "Flow" mental state using EEG. Further interests in making positive impacts in peoples' everyday lives yielded entrepreneurial initiatives. Here, her passion for digital engineering obtained a key role as well. In particular, Shama is CEO of NeuroCreate, a start-up that invokes Artificial Intelligence to facilitate human creativity. NeuroCreate coined the term of 'Augmented Intelligence,' referring to symbiotic designs where AI and humans interact in ways that are well-informed by the underlying neuroscience of creativity. In terms of topics, this engagement brings together works in the fields of deep learning, sensor technology, software development, user experience, creative and collaborative productivity, mental health and wellbeing studies as well as economical concerns. Beyond this already wide spectrum of activities, Shama also pursues artistic passions, such as playing and composing music, acting, staging storytelling and other forms of immersive experiences, theatre, games, installations and salons. Shama immediately noted that all her seemingly so variegated activities fell into the fields (i)–(ii)–(iii) of neurodesign. Shama recognized: She was a neurodesigner, and she had been a neurodesigner for decades.

In the course of the semester, Shama came not only for a single lecture, but she came for a whole week. Her work topics were so interesting to the HPI audience, that even two student teams, not only one, came to work with her intensely in the course of semester projects (Fig. 6). Everyone involved worked so thoroughly, with a time investment much beyond what is common in classes, that both student projects came to be presented at an international creativity conference (McKee et al. 2020a; Adnan et al. 2020). Seeing this large potential of neurodesign to bring about highly novel and worthwhile solutions in the areas (i)–(ii)–(iii) of neurodesign, Shama is now ready to move from London to Potsdam/Berlin to deepen her engagement at the HPI.

In what follows, we will briefly summarise some content of neurodesign education, presented by various lecturers in the last semester. Thus, we want to help readers gain an impression of topics that were discussed intensely over the past months. They contribute to a core evolving knowledge base of neurodesign (Sect. 1). We will then review neurodesign projects that have been conducted so far (Sect. 2). Most of them were based at the HPI. Yet some others already emerged at different institutions in the wider area of Berlin-Potsdam, reflecting a great collaborative spirit in this geographical region at the time. Indeed, the multiple universities concentrated in this area, next to pulsating artistic developments, seem to provide a rich and fertile ground for neurodesign. Section 3 reviews strategic missions we

**Fig. 6** In a D-Flect talk at the HPI, Shama discusses the potential of Artificial Intelligence to facilitate human creativity and collaboration (photo by Stefanie Schwerdtfeger). Together with Felix Grzelka and Holly McKee (both HPI), she invites the audience to take part in a study where this can be probed. Participants will conduct AI-assisted brainstorming sessions while their EEG is recorded with consumer-grade technology, as with a wearable EEG-sensing headband Shama is wearing in the image

pursue in further developments of the field at the HPI. They also inform our outlook on upcoming developments (Sect. 4).

## 1 Neurodesign Education

Here, we provide a brief review of content and insights contributed by neurodesign lecturers in the course of the last semester. The overview begins with talks in the neurodesign lecture and then turns to teaching content of the seminar. Beyond the brief review shared in this chapter, all lecture talks are available in full length online at www.tele-task.de as part of the series "Neurodesign Lecture—Physiological Perspectives on Engineering Design, Creativity, Collaboration and Innovation (WT 2019/20)." There interested readers can find further details including literature references.

### 1.1 Introduction to Neurodesign

In the beginning lecture, Julia von Thienen (HPI) emphasises the importance of boldness and creativity in the exploration of new knowledge domains. To discover possibly fruitful connections across diverse and formerly separated fields of work, it is often important to hypothesize and dream up wildly novel contributions in the beginning. This initial activity can feel like following hunches and speculating wildly. Such bold explorations are, however, an important aspect of discovering and enculturating new work domains. More rigorous tests and criticism become important later in the process, when the objective is to see which connections are robust, and which work avenues seem most worthwhile. Together with the audience, Julia probes some potential points of convergence between the works of several neurodesign guest lecturers who come to present later in the semester. Altogether, her talk explores potential connections between six different topics in design thinking creativity research. These topics can also be looked at as "fragments" or "puzzle pieces." One goal of neurodesign is to *understand innovation beyond fragmentation* (cf. neurodesign missions). This means to probe for connections and a bigger picture across multiple study topics in creativity and innovation research.

Julia begins with questions to the audience as to how children versus adults differ in their creative activities. She shares observations about children at a kindergarten age who spend many hours per day on creative pursuits: They indulge in imaginative play, make spontaneous creations in large numbers, curiously explore novel subjects and learn on the fly. At the same time, as creativity expert Giovanni Corazza from the University of Bologna notes, it seems that in the history of science and technology all the major steps taken by humanity were made by adults. How can these observations about children versus adults excelling in creativity be reconciled? Julia emphasises that clarifications are specifically important for design thinking, because this approach to innovation intentionally fosters and combines both, childlike as well as typical adult approaches, in creative projects. She also refers to an upcoming talk of Julia Rodríguez Buritica, where the audience will be able to learn more about information processing in children versus adults.

As topic (II), Julia reviews design thinking theory, which has evolved over multiple decades. Coherently, design thinking pioneers have described "two roads to creation," one approach predictive of creative leaps, the other predictive of less novel, but highly sophisticated, polished and perfected outcomes. Descriptions of both approaches are condensed in the *Sense Focus Model of Creative Mastery.* When working in a sense-mode, people explore new ways of seeing, hearing, feeling and experiencing. They let loose, do what feels right, act spontaneously, humorously and playfully. They use unstructured approaches, follow their intuitions, impulses and curiosities. This approach is said to facilitate heightened creativity, including creative leaps. By contrast, in a focus-mode people engage in rational planning; based on domain-specific knowledge and skills they reflect, analyse and synthesize. They exert meta-cognitive control and meta-rationality; they follow structured approaches. Activity in a focus-mode is said to engender technically refined, sophisticated solutions. Julia highlights how work in a sense mode often occurs at low levels of cognitive control, whereas work in a focus mode typically invokes high levels of cognitive control. Thus, an upcoming talk of Mathias Benedek on the role of cognitive control in creative pursuits will be pertinent for a better understanding of contributions that can be expected from sense- versus focus-mode activity in creative pursuits. Julia also highlights how children often engage with the world in a sense mode, whereas adults more typically invoke a focus-mode.

As topic (III) Julia discusses a creative process model set forth by Tim Brennan. She highlights how this model can be seen as an overlay of two motion patterns, one being a straight path from A to B, the other being a yarn-ball motion path of walking around in an exploratory or search mode (Fig. 7). She continues by discussing differences in prototypical motion paths of children versus adults. Adults who want to go from A to B typically pre-plan the path and opt for the shortest distance, which is energy efficient. Reliably, adults reach the destination B. By tendency,

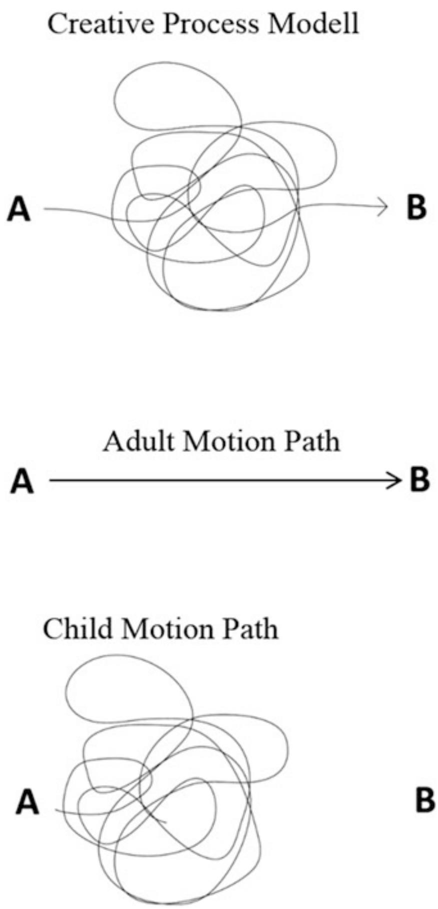


**Fig. 7** Metaphorically, the creative process can be understood as combining two prototypical motion paths: the goal directed shortest distance path often taken by adults, and an exploratory path often taken by children

children at a kindergarten age choose their walking paths more spontaneously. They engage in joyful explorations and make frequent “detours.” If left to themselves, young children may forget about the initial goal of reaching point B and thus never get there. Tentative patterns emerge—as hunches: Children, child-like approaches in creative pursuits, activity in a “sense mode” and free walking of a yarn-ball type appear to predict heightened creativity. By contrast, adults, typical grownup approaches in creative pursuits, activities in a “focus mode” and walking paths of straight rigid lines could be predictive of reliable goal attainment and less radically novel, but more sophisticated solutions. In terms of empirical studies, Julia reviews experiments indicating that free walking of a yarn-ball type does indeed engender heightened creativity, compared to walking along rigid lines. She also invites the audience to listen closely when Caroline Szymanski talks about interbrain synchrony during collaboration, as links between motion and collaboration will be discussed in her talk.

As topic (IV) Julia invokes the headline of “orientation.” She emphasizes that people need an initial cognitive map—a mental representation of an area—in order to pre-plan the shortest path from A to B, at least when B cannot be seen immediately. Such a cognitive map can also help to re-plan the path in case of obstacles, e.g. when a road is closed. Moreover, the cognitive map allows people to recognize what stimuli lie “off-track” and can therefore be ignored as irrelevant. By contrast, free walking of a yarn-ball type does not require an initial cognitive map regarding the terrain. People can approach anything that elicits interest and can try things out. Yet, people will build up a cognitive map gradually based on personal experiences in the field. In creativity theory, a concept akin to cognitive maps is prominently discussed, namely “conceptual spaces.” They are not maps of real geographical areas, but abstract maps of “work areas,” including “steps one can take” in the field. A hallmark of radical innovation is that it does not only add elements in established conceptual spaces, but rather entails a complete restructuring of earlier conceptual spaces. Julia hypothesizes that conceptual spaces might be encoded as cognitive maps in the brain, likely in the hippocampal formation and related regions. She moves on to review the role of emotions in the orientation process. Here, she highlights differences between pre-planned A-to-B paths compared to free walking. In a group of people, all individuals might have different emotions; still they are likely to select the very same A-to-B path based on a common cognitive map and efficiency optimization. By contrast, in the case of free walking, emotions likely play a key guiding role. Based on individual interests, people choose unique paths in the open terrain. In terms of upcoming lecture talks, Julia highlights that Laura Kaltwasser and Sergio Agnoli will also discuss the role of emotions in human behaviour.

Fragment (V) is headlined “attention.” Julia points out that motion paths straight from A to B can easily be carried out with a narrow breadth of attention and the focus rigidly attuned towards goal B. Other information can often be discarded as irrelevant (e.g., what plants there are in a park at the side). By contrast, free walking of a yarn-ball type likely thrives upon a wide breadth of attention, leaky filters, or altogether more flexible and varying attention: Anything in the environment can capture the person's interest. Yet, from the perspective of goal-attainment (reaching B), the person may seem all too easily distracted as she attends to this and that without necessarily moving closer to B. Julia then reviews empirical research results. People with a wide breadth of attention and leaky filters show increased creative performance. In addition, attention is more selective in adults than in children. In further detail Julia also overviews research conducted by Axel Menning and colleagues at the HPI as well as Sergio Agnoli and colleagues at the University of Bologna. While methodologically very different, both lines of research suggest the importance of attending to seemingly irrelevant information in creative pursuits. All in all, a narrow and rigid focus of attention seems to hamper creativity. Such a rigid attentional focus is found in adults more commonly than in children, not least because a narrow and long-enduring focus of attention is enabled by cognitive control systems in the frontal lobe, which are not yet biologically matured in children.

As topic (VI), Julia reviews environments for creative work. She emphasizes that design thinking spaces are designed to facilitate free motion during work hours. An experiment on the impact of places has found that the design thinking environment including free-walking opportunities boosts creative performance compared to traditional seminar rooms.

## *1.2 Social Neuroscience and Teamwork*

Caroline Szymanski (Max Planck Institute for Human Development & HPI D-School) introduces the topic of social neuroscience and discusses its relevance for neurodesign. In particular, social neuroscience examines how the brain mediates social processes and behaviour. As a discipline, social neuroscience dates back to the "Social Neuroscience Bulletin," which was published quarterly between 1988 and 1994; it is thus a relatively novel field in itself. Social neuroscience research covers topics of cognitive science, neuroscience, psychology, cognitive neuroscience, behavioural neuroscience, affective neuroscience, behavioural genetics, psychophysics, philosophy, artificial intelligence, computational neuroscience and more. The main neuroscientific methodologies used are EEG and fMRI. Especially interesting for neurodesign is the social brain hypothesis, set forth by Dunbar and reformulated by Tomasello.

> Human beings are able to pool their cognitive resources in ways that other species are not [...] made possible by a single very special form of social cognition, namely, the ability of individual organisms to understand conspecifics as beings like themselves who have intentional and mental lives like their own. (Tomasello 1999, p. 5)

From this understanding, Tomasello developed the concept of 'shared intentionality,' which denotes the unique human ability of doing something together for the sake of doing it together. Shared intentionality occurs when several individuals attend to the same thing, and understand the situation on a meta-level. Shared intentionality therefore goes beyond joint attention in the important aspect that all individuals (know they) share the same intention. From a developmental perspective, this is the basis of people feeling as a "group member" and developing a "team-feeling." Four- to nine-year olds already understand the concept of team membership as based on shared intentions, in contrast to "arbitrary" non-intention-based group membership, such as persons being grouped together based on gender.

Social neuroscience can help elucidate the physiological underpinnings of design thinking (i.e. collaborative creativity and innovation) by clarifying the neural basis of concepts such as team membership and collaboration. In terms of research outcomes, major 'social brain networks' discovered so far are associated with the frontal cortex. They include in particular: (A) the reward & motivation network, primarily located in prefrontal brain regions, namely the orbitofrontal cortex, (B) the cognitive control network, mainly located in dorsolateral prefrontal cortex and (C) the social perception & attribution network, predominantly located in medial prefrontal cortex and parietal cortex.

In her lecture on social neuroscience, Caroline offers a variety of examples how literature concerning social-brain networks can help elucidate and facilitate design thinking teamwork. (A) The reward and motivation networks are especially important for collaborative creativity, insofar as social reward is a main causal factor that drives people's engagement in collaboration. At the neural level, social reward has been shown to be at least as effective as monetary rewards. By contrast, social exclusion has been demonstrated to be processed by the brain like physical pain. Thus, the awe of social exclusion can even be countered with painkillers developed to antagonize physical pain, such as ibuprofen. (B) Cognitive control research also has specific implications for collaborative creativity. E.g., impulsive people tend to act less socially appropriate, but they are more creative when not restricted in their impulsivity. (C) The neural networks processing social perception information known so far can be mainly classified into empathy and theory of mind networks. They are all part of the so-called Default Mode Network (DMN), which is said to be concerned with feelings regarding oneself together with others and thinking about others. From a design thinking perspective, it is important to realize that understanding others' intentions allows humans to (co)-experience how others feel, i.e. to empathically understand what it is like to walk in someone else's shoes. Moreover, for collaborative teamwork it is helpful to realize that our brains can usually only do one thing at a time (i) focus on empathy and social cues (default mode network), versus (ii) focus on a specific task (task-positive network). Most commonly, only one of these two neural networks can be activated at any given moment. That is clearly an important insight with methodological implications for design thinking, which pursues major aims of empathic understanding.

All in all, social neuroscience and neurodesign are relevant to each other in two major ways: First, social neuroscience provides research insights on collaborative creativity that facilitate mindful design thinking/creative engineering practices. Second, knowledge concerning the biological basis of social interactions hinges on our technical capabilities of tracking relevant phenomena, and digital engineers can make important contributions in this domain.

### 1.3 Interbrain-Synchrony During Collaboration

In a second lecture, Caroline Szymanski reviews the subject of interbrain-synchrony during collaboration, which was her dedicated PhD research topic some years ago. There is converging evidence from numerous research studies that social interaction is characterized by synchronized brain activities amongst those persons who interact. This so-called "interbrain synchronization" has been found to be modulated by social context: Interbrain synchrony is more pronounced during cooperation than during competition. It is stronger in mother-child interaction compared to child-stranger interaction. Similarly, interbrain synchronization is stronger among lovers than between friends; least synchrony is found among strangers. Furthermore, interbrain synchronization has been reported to vary as a function of social dynamics: Lead-follow behaviour is markedly associated with differences in interbrain synchronization. A "natural leader" has the ability to take on other people's perspectives, which is then reflected in increased interbrain synchronization during their interaction, which highlights a possible role for interbrain synchronization as a neural mechanism underlying team formation. In detail, Caroline talks about studies that find team performance to be associated with changes in interbrain synchronization. There is evidence that teams who "synchronize their brains more" also perform better as a team. Caroline closes by suggesting how inter-brain synchrony mediates between bodily synchronization and cognitive synchronization, and how this 'triplet' (body/brain/cognition synchronization) can be used to facilitate teamwork. For instance, joint motion helps brains synchronize, which in turn facilitates joint task attention. This, in turn, can improve team performance. Making explicit use of such mechanisms—(a) bodily synchronization to drive neural synchronization, to foster cognitive team convergence vs. (b) bodily desynchronization to reduce neural synchronization, to foster cognitive divergence—can well be used to facilitate design thinking or other forms of creative collaboration, by means of dedicated coaching interventions.

### 1.4 Sonification of Brain Data for Seizure Detection

Chris Chafe (Director of the Center for Computer Research in Music and Acoustics at Stanford University) speaks about the sonification of brain data. In digital engineering, often information is represented visually, e.g. with texts, graphs or other images. However, information can also be represented in other formats, such as acoustically. As Chris shows with a number of examples, the approach of data sonification is auspicious for different reasons. First, it creates a novel way for people to experience data. For instance, listeners can gain further insight into dynamics of climate change as driven by CO2 levels in the atmosphere. Here, much like background music in films, acoustically represented data has a unique potential to resonate with listeners on emotional levels, beyond cognitive understandings of relevant patterns. Second, body data sonification can be pursued for diagnostic ends. One example is the sonification of EEG data, which allows medical novices to detect silent seizures in patients with a high degree of accuracy. Third, there can also be an artistic use of data sonification, as exemplified by art installations based on brain data. All these examples are described in further detail below, as they have stimulated a multiplicity of neurodesign project work (Sect. 2).

### *1.5 Shared Responsibility in Collective Decisions*

The talk of Marwa El Zein (Institute of Cognitive Neuroscience, University College London) explores the topic of collective work and in particular collective decision-making as opposed to single-person work and single-person decisions. This topic is highly relevant for design thinking, where leading experts often emphasise advantages of teamwork over single-person pursuits. Marwa's review explores an even bigger picture, beyond individuals versus teams. Her perspective covers individuals, teams and also crowds of people so large that individuals do not even know each other. A key question is whether decisions and work results are better when people work individually versus collectively. It turns out: Who performs best—individuals or collectives—is highly context-dependant. This observation is already reflected in seemingly contradictory sayings, such as "two heads are better than one" (collectives get better results) versus "too many cooks spoil the broth" (individuals get better results). Thus, it is important to better understand the parameters when collectives outperform individuals. Marwa introduces the *Wisdom of the Crowd Theory* and the *Jury Theorem*, which already spell out several important conditions for groups to outperform individuals: Decisions to be taken are categorical and they have an objectively correct answer; all answers are formulated independently; moreover individuals opting for a decision ("voters") must perform better than at chance level. Marwa moves on to discuss the importance of "competence similarity," a factor that has been repeatedly found to determine if teams perform better or worse than individuals. Individuals with similar competence levels perform better when teaming up. However, teams where members possess different competence levels perform strikingly worse compared to their best team member alone. Marwa points out that this phenomenon is often interrelated with yet another factor: "confidence." Teams almost universally weigh an opinion stronger when it is communicated by a team member who expresses a high degree of confidence in his stance, compared to an opinion communicated in an unconfident tone. Thus, methodologically, it seems key for teamwork that each individual is aware of his or her competence level, and communicates confidence accordingly.

Marwa further discusses different available methods for determining group decisions based on individual votes, and how these methods do not seem equally suited for delivering best overall outcomes. In the studies she discusses, best outcomes to problems with objectively correct answers are achieved when individuals (experts) are pooled into small independent groups; each small group gives their consensus decision and the average of these consensus decisions is taken as a final answer. This method of "small group voting" outperforms methods of individual voting and voting in a large crowd. It can be seen as particularly encouraging evidence for the "coopetition" approach often taken in Design Thinking, where several teams get to work in parallel on the same challenge.

Another key topic Marwa explores is the motivation of individuals to work in teams. While most research literature focuses on performance benefits of teams, Marwa explores in her research another beneficial side of teamwork, independent of performance, to which she refers as "shared responsibility." She discusses in detail some of her studies, showing that individuals also join teams to share and thus minimize regret and disappointment in the case choices have negative consequences. Moreover, when working in teams, people become less influenced by anticipated regret and disappointment. This is another finding that can be highly relevant for teams working on innovation challenges. After all, throwbacks and resistance are common phenomena in innovation endeavours, and teams seem naturally more resilient to them then individuals.

## *1.6 Psychology of Design: Evolution of the Intersection of Two Inseparable Fields*

Jan Auernhammer (Executive Director of the Leifer Neurodesign Research Program at Stanford University) explores the role and meaning of "neurodesign" at Stanford University. Stanford's Design Group (formally known as the Design Division), including the Center for Design Research founded by Larry Leifer in 1984, has had a strong legacy in developing and researching design practices around the globe. Jan reviews the history of design thinking at Stanford, beginning with seminal works of John E. Arnold, Robert H. McKim and James Adams in the late 1950s and early 1960s. There have been strong lines of continuity at Stanford's Design Group ever since. The Design Division and the Joint Product Design Program started by Arnold and McKim continuously explored synergies at the intersection of art, engineering, psychology, and business management. In terms of psychology, there has been an enduring concern for "human needs" and "human values." Moreover, dedicated research has investigated creative abilities of people, and practices of engineering design teams over decades. As Jan points out, such interests in human needs, creative abilities and thinking in design have advanced content provided by psychologists like Joy Paul Guilford (a psychometrician), Abraham Maslow and Carl Rogers (both representatives of humanistic psychology). In these fields, nowadays, methods of neuroscience have the potential to add important understandings of details. In this sense, activities at Stanford Design have always focused on the intersection of thinking (psychology) and design (practice). Notably, John Arnold was a psychologist and an engineer. He brought psychological insights to design practice. Larry Leifer (head of the Design Thinking Research Program at Stanford) was one of his successors at the department. In his PhD, submitted in 1969, Larry worked on a topic at the intersection of Neurology (under supervisor Leon Cohen), Electric Engineering (with supervisor James Bliss) and Biological Science (with supervisor Donald Wilson). Thus, Larry is one of the very first "Neuro-Designers." Based on this long tradition of work at the intersection of thinking and design, the *Leifer Neurodesign Research Program* aims to bring together Engineering Design, Neuroscience, Psychology, Cognitive Science, and other fields to advance human practices and abilities in design, as well as artificial intelligence through design. Jan emphasizes how collaborations with neuroscientists like Manish Saggar (Brain Dynamics Lab), Allan Reiss (Center for Interdisciplinary Brain Sciences Research) as well as other cognitive scientists and psychologists are important to research, in particular to advance an ever better understanding of thinking in design. Research needs to cover more than predefined cognitive tasks. It needs to elucidate open tasks of real-world complexity in design. It also needs to apply appropriate neurocognitive research techniques in real-world settings. For this endeavour of neurodesign research, funding, sponsors, and active partners will be key.

In this volume, Jan—together with his Stanford colleagues Neeraj Sonalkar and Manish Saggar—also explores the topic "NeuroDesign: From Neuroscience Research to Design Thinking Practice." Here, they explore several gaps between the disciplines of Neuroscience and Design (Thinking). They also suggest a research agenda to bridge the gaps.

## 1.7 Attentional Mechanisms in the Creative Thinking Process: Insights from Psychophysiology

Sergio Agnoli (Marconi Institute for Creativity, University of Bologna) introduces the audience to basics of creativity research. How is creativity defined? What dimensions are important in the measurement of creative performance? Which factors are known to impact the dynamics of creative projects by facilitating or hindering creative performance? His further talk is guided by an "energy metaphor" in the study of human creativity. First of all, he discusses the architecture of the human brain, which yields a computing capacity around 38 petaflops (a quadrillion of floating point operations per second). By comparison, present-day supercomputers such as the Marconi Supercomputer (MS) have a processing capacity of ca. 20 petaflops. Remarkably, the human brain has an average energy consumption of merely 15 W per day, whereas the MS requires 3000 W per day. Thus, the human brain is an incredibly energy-efficient structure. One energy-saving strategy hardwired in the human brain is to develop "heuristics" for the interpretation of reality. Sergio shows a number of examples where study participants fail to notice odd events in the environment, because people only perceive what they expect based on prior knowledge. Overall, when people get trained on a task, the energy needed by the brain decreases rapidly, while the person's task performance increases as rapidly. Sergio discusses a number of mechanisms how the brain achieves this kind of energy-efficiency and performance-curve. He explains how current research at the Marconi Institute is directed towards elucidating the energy expenditure of the brain in the creative process. For instance, in an EEG study participants were asked to generate alternative uses for everyday objects. Analysing time dynamics, the authors find initial answers of participants to be mere recalls from memory of already existing object usages; this is associated with low levels of energy expenditure. Afterwards, as participants think up more novel uses, the brain's energy expenditure is increased; physiologically, synchronization in the EEG alpha frequency band is observed across brain areas. The causal impact of neural synchronization (in the alpha and beta frequency band) on creative performance is then established in a neurofeedback paradigm. Moreover, there is an "energy saving strategy" people can use by paying attention to a single element only, while disregarding surroundings. In another experiment, the authors presented everyday objects on a computer screen: one in the middle and many other objects ordered in a circle around it. Participants were asked to think up uncommon uses for the object in the middle. By means of eye tracking, the authors observed whether participants indeed only attended to the object in the middle or also screened objects around. Those participants showed increased creative performance who dedicated attention not only to the stimulus in the middle, but the surroundings as well. To complement these insights concerning "mechanisms" of creative thinking, Sergio discusses the role of peoples' personality traits, motivations and emotions in channelling energy expenditure.

As part of his talk, Sergio introduces the Marconi Institute for Creativity, which indeed resembles the Hasso Plattner Institute and the Digital Engineering Faculty at Potsdam University in several notable regards. First, the Marconi Institute was co-founded by the University of Bologna and a non-for profit organisation, namely the Guglielmo Marconi Foundation. Similarly, the Digital Engineering Faculty was co-founded by the University of Potsdam and the HPI, which in turn is financed by the non-for-profit Hasso Plattner Foundation. Both Guglielmo Marconi and Hasso Plattner are successful, creative engineers whose non-for-profit foundations have a strong concern for the topic of innovation. Academically, the Marconi Institute for Creativity (MIC) resides also within a laboratory (the MIC Lab) in the Department of Electrical, Electronic and Information Engineering at the University of Bologna—thus at an engineering institute akin to the HPI at Potsdam or Stanford Engineering with its design thinking activities. The Marconi Institute pursues scientific research on the mechanisms underlying creativity. Similarly, at Potsdam and Stanford the Hasso Plattner Design Thinking Research Program sets out to investigate why and how design thinking · creativity · innovation works. The Marconi Institute offers creativity education at the university, and sometimes at schools, to multidisciplinary audiences. Similarly, the HPI and Stanford Engineering offer design thinking education at the university, and sometimes at schools, to multidisciplinary audiences. Finally, the Marconi Institute offers consulting services for companies in the field of innovation, like the HPI Academy at Potsdam. This multiplicity of activities is advanced by institute directors whose personal engagements radiate in numerous academic disciplines beyond single university faculties: Giovanni E. Corazza at the Marconi Institute (who holds a chair on Telecommunications at the University of Bologna), Christoph Meinel at the HPI (holding the chair of Internet Technologies and Systems), Uli Weinberg (professor at the HPI School of Design Thinking), Larry Leifer, Bernie Roth and David Kelley at Stanford (all three of them professors in Mechanical Engineering). As a minor difference in foci of work, the Marconi Institute is a bit more concerned with creative thinking processes of individuals, whereas the HPI and Stanford tend to emphasise and explore collaborative creativity.

### *1.8 We Feel Therefore We Are? About Emotions and Cooperation*

Laura Kaltwasser (Berlin School of Mind and Brain, Humboldt-Universität zu Berlin) combines her talk with an on-site experiment. At the beginning of her lecture, volunteers put on Empatica E4 wristbands, to capture skin conductance and heart-rate measures over time. Laura announces that "something will be happening in class." She will give a signal to the audience, then volunteers shall press a button on the wristband and later the physiological data will be analysed live in class.

Laura's talk focuses on the role of emotion in social decision-making. The subtitle of her talk is "We feel therefore we are," as an iteration of Descartes' famous statement "I think therefore I am." Laura says she is convinced that emotions play a fundamental role in our self-conception and also in actions we take. To convey the tight interrelation of both topics—emotions and social decision-making—she refers to a phenomenon called "negative reciprocity." Here, people punish unfair behaviours of others at the risk of high personal cost. This typically occurs based on strong emotions. An example is the behaviour of soccer player Zinedine Zidane in 2006 during the world cup final. A player from the opposite team had insulted Zidane's mother. Zidane punished this unfair behaviour by bumping his head against the other player's chest. This was obviously an action at the risk of high personal cost. Zidane was shown a "red card." His team, having one player less, lost the championship. It was the last official match Zidane ever played. The tendency of people to engage in such negative reciprocity has been found to vary strongly across cultures; it has been found least expressed in South America and more expressed in Eastern cultures, where it is often called 'a culture of honour.' A complementary concept used in research is "positive reciprocity," which addresses altruism and pro-social behaviour. Again, studies find strong cultural variations as to how much people are inclined to show positive reciprocity. Thus, such patterns of social interaction seem to be strongly impacted by social norms, which differ from culture to culture. At the same time, patterns of interaction are clearly also depending on biological factors. Emotions, for instance, impact social behaviours and they do have marked biological foundations. For instance, people who are blind and people with average eye-sight show similar facial expressions in the case of joy, across all age groups. Thus, the bodily expression of joy seems to have strong biological, culture-independent components. Overall, emotions with their strong biological manifestations seem to play an important role in social decision-making. Laura refers to Antonio Damasio and his "somatic marker hypothesis," according to which the whole body helps us take decisions. Subsequently, Laura discusses how emotion-related parameters are often assessed in research, based on pictures of faces depicting different emotions. She shows some examples. One slide depicts—in a large format—a fearful face. In parallel, a loud screaming sound shatters the lecture hall. Laura gives a signal and volunteers in the audience wearing an Empatica E4 wristband press the button, so that this moment can later be identified in the data analysis. Laura moves on to discuss brain processes that typically obtain when people see stimuli such as fearful faces. Having discussed the measurement of emotion-related parameters in research, she moves on to review measurement approaches for the study of social decision-making, as conducted by means of socio-economic games. To introduce her own research in the field, she reviews earlier studies. Empathy is often measured in terms of people's accuracy in detecting other people's emotions based on their facial expressions. Moreover, research has found that people who show more facial expressions themselves, especially more positive emotions, are also more cooperative. Thus, expressiveness in facial gestures has been discussed as a social signal to indicate cooperativeness. In detail, Laura reviews two of her own studies. She finds that people who show more pro-social behaviour in socio-economic games are specifically better at recognizing fearful faces of others. They also tend to express more emotions by means of facial gestures during social interactions, compared to less cooperative persons. Design thinkers can note how it may be important for teamwork to recognize emotions not just as something that concerns the individual team member and how they feel about something, but as crucial social signals that should not be missed, if the cooperative work is to be successful and effective. In another study, Laura and her colleagues find that pro-sociality and assertiveness are predictors of people engaging in negative reciprocity. This hints at different motives people can have for punishing unfair behaviour at the risk of personal cost. It can be an altruistic undertaking (society should not be unfair, I need to help establish fairness even if this has negative consequences for me). Negative reciprocity can also have more "egoistic" motives related to assertiveness. In her summary, Laura reviews several ways in which studies of emotion and social-decision-making could be improved. She invites audience members to think how respective parameters might be interesting to include even in Digital Engineering master theses. She also shows openly accessible databases, where videos and sounds labelled with regard to emotions can be found, so that they are available as stimulus materials for further studies.

After Laura's talk, Joaquin Santuber shows samples of the data captured with Empatica wristbands during the session. The data of one volunteer is looked at more closely. This person showed a strong increase in electrodermal activity (a stress indicator) in response to the fearful face and scream presented in class. It takes several minutes before the value of electrodermal activity after the scream resumes the low level it had before the scream.

## *1.9 Creativity and Cognitive Control*

In his talk, Mathias Benedek (Karl-Franzens-Universität Graz) addresses the subject of cognitive control in creativity. This is a subject of high relevance for design thinking, as design thinking theory has covered the subject intensely since the 1950s. Based on marked theoretical assumptions, design thinking has been developed as a practice where both processes with high levels and low levels of cognitive control are invoked, sometimes one after the other, but always in close interconnection. Examples of phases with high levels of cognitive control include the synthesis phase in creative processes, where structured methods such as analyses in $2 \times 2$ matrices are invoked. Examples of phases with low levels of cognitive control include experiential approaches, where design thinkers seek immersive experiences in a field to court spontaneous and intuitive insights. Design thinking theory concerning cognitive control is also discussed in greater depth in the chapter "Theoretical Foundations of Design Thinking, Part III: Robert H. McKim's Visual Thinking Theories" in this volume.

Mathias begins his discussion of the subject with a review of the lives and works of famous creators. These provide evidence indicating that both—low levels and high levels of cognitive control—can be important for creative breakthroughs. For instance, the chemist August Kekulé developed an insight regarding the chemical structure of the benzene molecule in a dreamlike state, i.e. in a moment of low cognitive control. At the same time, analyses of the daily schedules of famous creators reveal that many of them followed rigorous agendas, with relatively fixed time windows of intentional and concentrated work: examples of creative activity with high levels of cognitive control. In order to clarify the concept of cognitive control, Mathias refers to the works of Daniel Kahneman and distinguishes between two kinds of cognitive processes. *System 1* processes are automatic, unconscious, fast, undemanding, associative, undirected and spontaneous; they occur at low levels of cognitive control. By contrast, *system 2* processes instantiate high levels of cognitive control; they are deliberate, conscious, slow, effortful, analytical, goal-directed and—obviously—controlled.

Mathias discusses how cognitive processes including creative thinking can be reconstructed in terms of (a) attention processes, (b) memory processes and (c) cognitive control processes. Regarding (a) attention, one major question has been whether it is more favourable to have attention constantly "on task," or whether phases of devoting attention away from the task might also be favourable, e.g. to court incubation (the development of insights by means of non-conscious processing). Research indicates that short tasks are better solved with attention "on task;" here mind wandering does not seem to be helpful. Yet, more complicated problems can benefit from attention "off task," i.e. from break times where the brain can continue to process the problem in non-conscious ways. From methodological perspectives, it seems important to engage in undemanding tasks during breaks, as these appear to impact chances of solving the problem in most beneficial ways. Another key distinction concerns "internally" versus "externally" directed attention.

Studies suggest that internally directed intention facilitates mental simulation, such as imaginations, which are crucial for high levels of creative performance. In the EEG, this internally directed attention is indicated by increased alpha activity. Regarding (b) memory, Mathias discusses how semantic network analyses can be used to elucidate commonalities or differences between the memory structures of highly creative versus less creative individuals. Generally, when seeking novel ideas, people seem to begin with common ideas in the field and gradually come to think about more remote associations; highly creative individuals do this more quickly than less creative individuals. In addition, neuroscientific research suggests that recalling past events, imagining future events and creatively imagining novel events recruit relatively similar brain areas, underpinning the importance of memory for imagining novel solutions. Regarding (c) cognitive control, studies regularly find that high levels of intelligence including executive functioning (which allow people to act at high levels of cognitive control) predict people's creative abilities and also their creative achievements. This argues in favour of cognitive control abilities being beneficial for creative performance. On the other hand, there is a lot of anecdotal evidence of people producing highly creative works in circumstances of reduced cognitive control, e.g. intoxicated with alcohol. Around 70% of the American Nobel Prize winners of the early last century had documented alcohol problems. This suggests a correlation, which does not yet answer questions of causality. Since then, empirical research has sought to clarify effects of alcohol on creative performance. Study findings have been variegated so far. Consistently, higher levels of alcohol intoxication cause reduced levels of cognitive control, especially in terms of reduced working memory functioning. Creative abilities do not seem to be affected consistently; methodologically careful double-blind studies suggest neither an increase nor a notable decrease of creative abilities under an intoxication of ca. 0.6 per mill. However, studies suggest that people find their own outcomes more creative when they believe to be intoxicated, regardless of whether people actually did receive an alcoholic or a non-alcoholic drink in the study. Another important line of research investigates contributions of two cognitive networks during problem solving. The Default Mode Network (DMN) conveys spontaneous, self-generated thoughts, such as mind wandering or episodic remembering (often occurring at low levels of cognitive control). The Executive Control Network (ECN) conveys goal-directed thought, including working memory functions and task-switching. Typically, these two networks show strongly anti-correlated patterns: When activity in one network increases, activity in the other network decreases. However, during many creative tasks the two networks show increased coupling. This may reflect a fruitful interplay of generative and evaluative cognitive processes, as required for effective creative work.

All in all, both information processing at high levels and low levels of cognitive control can facilitate creative breakthroughs. System 2 processes (of high cognitive control) help creators stay focused on a task; they allow people to overcome "dominant" ideas, which are merely uncreative recalls of already known solutions. System 2 processes also allow people to implement effective, goal-directed problem solving strategies. Thus, system 2 is highly relevant for active creative thinking. By contrast, spontaneous thoughts produced by system 1 (at low levels of cognitive control) allow people to process personally meaningful problems even when attention is off-task. In that case, automatic processing continues in non-conscious ways. Moreover, the working memory capacity of system 2 is highly limited; the sheer information processing capacity of system 1 is huge. Finally, goal-directed thoughts produced by system 2 can run into fixation. System 1 acts largely undirected, in an associative manner, and can produce highly surprising "out of the box" solutions: creative leaps.

### *1.10 Normative Aspects in Creativity, Collaboration and Culture Development*

In her lecture on the role of norms in the context of creativity, Julia von Thienen begins with a remark concerning the overall topic selection in class. All talks in the first neurodesign lecture series discuss creativity and collaboration based on research with humans. This makes sense, in so far as there is a central concern for design thinking in class, which is a human practice. At the same time, creativity and collaboration can also be observed in other species. Often it helps to study a full range of phenomena including extreme cases to gain a better overview and understanding of peculiarities. In design thinking, the "power of ten" method asks for a consideration of phenomena at varying degrees of magnitude. This is also the approach Julia takes in the lecture as she explores creative capacities from miniature creative performances to most celebrated achievements, in a cross-species comparison. Fruit flies, for instance, do not react in deterministic ways to stimuli such as light. Most commonly they fly towards it, but in some instances they fly away—a diverging behaviour. This can be considered a miniature creative capacity: the ability to diverge. It is a biological capacity of the individual. Then, on the level of groups or populations, the phenomenon of "culture development" can be observed. Here, individuals need the capacity to build on creative ideas of others. For instance, songbirds learn melodies from neighbouring birds and even teach these to offspring. From a human perspective, however, culture development per se is not yet the greatest creative achievement. There needs to be a trajectory in culture development towards ever better, ever more sophisticated solutions. In the literature, this is called "cumulative culture" or a "ratchet effect." Julia distinguishes three ways in which ratcheting can occur. First, there can be an increasing differentiation of solutions in a domain. For instance, in the prehistory of humanity, in the domain of stone tools, an increasingly differentiated palette of solutions was developed, from tools for hunting and eating to equipment including needles and figurines. Second, the sheer number of solutions in a domain can increase. According to research, this often happens at an exponential growth rate in human culture. E.g., from 1200 to 1900 in many different disciplines—such as philosophy, geology, medicine etc.—the number of publications increased exponentially. Third, solutions can show an increasing performance on a dimension of interest. An example is the top speed achieved with automobiles, which increased markedly from the late 1800s to the present day. Ratcheting yields most celebrated creative achievements in human culture, such as “science as a whole.” Notably, even the brightest human cannot invent science as a whole alone, in a single lifetime. For instance, Einstein is praised for outstanding creative achievements in science. Yet, he did not start from scratch. Rather, he built substantially on inventions made by others. Einstein used, but did not invent, numbers—and generally symbols—, mathematics, writing and books. He also thrived upon general supplies he did not invent himself, such as cooked food, medicine, furniture, pen and paper etc. Creative humans develop solutions that are far more sophisticated than what they could possibly invent all by themselves. Marked creative achievements emerge on a cultural level when creative solutions of previous generations and contemporaries become interconnected in a smart, productive way. Cross-species comparisons indicate that humans excel at the development of cumulative culture. This leads to key questions: In terms of biology and culture organization, what enables a smart interconnection of creative activities, even across countless generations, so as to yield cumulative culture and ratcheting? How can we model (reconstruct and predict) phenomena of culture ratcheting? Julia highlights how the answer may begin with the standard definition of creativity: A creative achievement obtains when a solution is produced that is novel and effective. Julia draws attention to the effectiveness dimension. She says that norm systems specify effectiveness criteria. For instance, in the realm of art people long invoked the norm system that paintings must depict scenes in detailed and naturalistic ways in order to be effective (“good”). Painters practiced and experimented in order to get better and better at these ends. When early modernists entered the stage, they changed the norm system. They rejected the effectiveness standards of detailed and naturalistic depictions. Instead, they introduced novel criteria: Paintings should depict scenes abstractly, based on simple shapes and patterns. Now a novel direction was provided in which artists could practice their skills, and could be creative, in order to produce ever more effective (“good”) paintings. As in this example, Julia says, it is possible to model cases of incremental versus radical innovation based on norm systems. She shows further sample reconstructions from the fields of automobile design, physics, sports, psychology, philosophy, mathematics and music. In all reconstructions, radical innovation builds on changes in the norm system. Julia lays out that in each work domain a paradigm is defined by effectiveness standards that originators follow in their creative pursuits. Effectiveness standards specify tasks: What to do, and how to do it. Changing effectiveness standards changes the paradigm: new rules, new game. In-paradigm-creativity means to advance creative (novel and effective) solutions based on established effectiveness standards. This approach engenders cumulative growth and progress in a field, i.e. incremental innovation. Out-of-paradigm-creativity means to advance (i) new effectiveness standards and (ii) creative solutions based on the new standards. This approach yields radically new solutions, i.e. radical innovation. While design thinkers typically celebrate radical innovation, Julia also cautions the audience. Paradigms are creativity engines. They drive cumulative culture growth and ratcheting. If radical innovation, i.e. paradigm shifts occurred too often, no paradigm would ever become sophisticated. Thus, for the development of culture at large it is important that forces of innovation favouring radical change and forces of innovation resistance that protect existing paradigms balance each other. In the final part of her talk, Julia looks at the biological basis that may allow humans to engage in creativity, coordinated over countless generations by means of cultural paradigms. What biological endowment allows humans to build up, protect and change norm systems, thus enabling cumulative culture and ratcheting next to the invention of novel paradigms? Julia reviews studies into the evolution of human creative capacities. These suggest characteristically human forms of creative performance were rendered possible by the development of theory of mind, sophisticated language and the use of material culture, a.k.a. the increased production of artefacts. In addition, Julia says, people's abilities of adhering to norm systems, and the ability to change rules, are essential. In terms of neuropsychological theory, they are addressed as "executive functions." Julia introduces some tests that are used to assess executive functioning. A volunteer tries the Wisconsin Card Sorting task live in class. Beyond that, norm systems can also be ingrained in cognitive maps concerning work domains. In biological terms, these are likely encoded in the hippocampal formation and related regions. Lastly, Julia addresses the challenge that norm systems define social groups. People who adhere to "your norm systems" belong to "your in-group." People who frustrate your normative expectations are "not like you," they are "strangers." E.g., when a person comes and eats an animal that "is not for eating"—this person comes from a different culture, he/she is "not like you." Julia reviews neuroscientific studies showing that our brains process information differently depending on whether a behaviour is shown by an in-group or an out-group member. Consistently, the same behaviour is processed more negatively when shown by an out-group member. Julia warns that radical innovation changes norm systems. Therefore, radical innovators run the risk of being perceived as an out-group member by everyone in society, leading to a biased and more negative assessment of whatever the radical innovator does or suggests. This can be one reason why it is helpful to develop radical innovation in teams. When the objective is to foster radical innovation, ideally decision-takers develop personal bonds to the innovation team, so that emerging proposals of radical change will not get processed as coming from "out-group members."

In a second part of the lecture, Joaquin Santuber (HPI) addresses normativity in the context of collaboration from an experimental point of view. A key question is how normative-social processes, such as collaboration, can be related to neuro-physiological dynamics in the individual. Using systems theory and an embodied-enactive cognition perspective, he elaborates on how the synchrony of physiological signals can be seen as the coupling mechanisms of people engaged in collaboration. To show the merit of this approach, he presents an experiment conducted at the HPI on physiological synchrony between participants performing three tasks. In all cases, participants get to work in pairs of two persons on varying, wooden dinosaur puzzles. In the first task, participants get to work on a dinosaur puzzle without any specific instruction. In the second task, the two participants obtain different instructions. In the third task, both participants obtain the same instruction. After every task, a self-report questionnaire on perceived team cohesion is completed by the participants (Perceived Team Cohesion Questionnaire, PTC). To study changes in the level of interpersonal synchrony across tasks, for each dyad the following data is gathered and analysed: electrodermal activity (skin conductance), heart rate variability, and automated video analyses of facial expressions as well as head pose. Among all data collected, facial expressions provide clearest results and seem best suited to distinguish between the three social conditions. High level of synchrony of positive facial expressions are found during task 1 and 3. By contrast, interpersonal synchrony of negative facial expressions is higher in task 2 than in task 1 and 3. These results are consistent with questionnaire data; perceived team cohesion correlates with synchrony in positive facial expressions ($r = 0.44$). Joaquin also discusses methodological aspects and challenges of data collection and analysis when feasible and accessible methods are used. The study of synchrony between social and physiological dynamics needs to account for emergent properties of collaboration, as well as the self-organizing neuro-physiological dynamics of each participant engaged in skilled action. In this sense, it is important to complement quantitative data of physiological signals with qualitative data regarding the social process.

## *1.11 The Use of Artificial Intelligence to Facilitate Human Creativity: Entrepreneurial and Artistic Approaches*

Shama Rahman (Complexity Group, Institute of Mathematics and Physics, Department of Condensed State Matter, Imperial College London; Centre for Cognition, Computation & Culture, Goldsmiths University of London; Royal College of Music and CEO of NeuroCreate) reviews the field of Artificial Intelligence and creativity. The topic is already widely discussed, most frequently centering on questions as to whether Artificial Intelligence might itself become creative. Shama, however, invokes a different point of view: (how) could Artificial Intelligence help enhance human creativity? She discusses neuroscientific underpinnings of creative performance, such as creative work in a Flow state. In her PhD and subsequently in her startup NeuroCreate, she has been working on the measurement of Flow via EEG. It can now be detected by proprietary deep learning models.

From philosophical and practical perspectives, Shama explores the potential of a complementary symbiosis between Artificial Intelligence (informed by neuroscientific knowledge) and human creators. This neurodesign avenue of work would lead to ‘augmented creative intelligence.’ Shama discusses how we might all benefit from such an approach.

In a live demonstration, Shama introduces the software FlowCreate™ Innovator developed by NeuroCreate. She discusses how the design is informed by theories and research findings concerning creative processes. This includes Shama’s own

PhD work, where she studied creative performances of musicians, recorded along with EEGs of the performing artists.

Together with the audience, Shama uses FlowCreate™ Innovator during a brainstorming task. Participants witness how Artificial Intelligence is invoked to stimulate ideation. The approach allows humans to think about solution directions they would not normally consider, without the tool. Artificial Intelligence also helps humans be more systematic in the exploration of potential solution spaces during brainstorming. This includes a discovery of personal unconscious biases and blind spots: areas one should consider, but they don't come to mind—unless Artificial Intelligence points them out.

Further insights into Shama's works are provided in Sect. 2, in a discussion of two neurodesign projects conducted under Shama's supervision.

## *1.12 Examining Social Influences on Brain and Behaviour Across Development*

In her talk, Julia Rodríguez Buritica (Biological Psychology & Cognitive Neuroscience, Free University of Berlin) examines social influences on brain and behaviour across development. A key question in this research domain is how individuals make choices. This can be choices of consumers to buy or not buy a software package, choices of digital engineers to use this or that programming language, choices of students in class where they need to select an answer in a multiple choice test, or choices of any one of us in everyday life. Julia discusses the important factor of social influences for human decisions. The paradigm in which she investigates the phenomenon is called "reinforcement learning." Here, each choice alternative has a specific outcome, which is good or bad. The question is how experiences of good vs. bad consequences after deciding on an option impact people's learning, i.e., their future choices. Of course, humans learn from their own experiences. When a choice has negative consequences, the person is less likely to decide on this option again. E.g., when a selected answer in a multiple choice test turns out to be wrong, the student will likely pick a different answer when asked the question anew. Similarly, students learn from the outcomes of others. When a peer selects an answer in class, which is then labelled as incorrect, other students are less likely to opt for that answer henceforth. Notably, humans use roughly the same brain regions when they learn from their own outcomes compared to when they learn from the outcomes of others. Relevant brain regions include the medial prefrontal cortex, which is part of the frontal lobe that matures late in life. It develops until the age of 20 or even beyond. Thus, children vs. adolescents vs. adults differ in how they learn from outcome observations. For children it is specifically difficult to learn from negative consequences. Indeed, this learning involves complex representations in the medial prefrontal cortex, e.g. to inhibit a previously preferred choice option, while the pertinent brain structure is not fully matured in children yet.

As a pedagogical consequence, it has been recommended to use less “red markings of incorrect answers” in primary school; emphasising what the kids did well might be a more effective teaching strategy. All in all, the field of reinforcement learning has developed a high level of sophistication, which allows an accurate modelling of how people learn and decide based on (i) their own experiences, (ii) observations of others and their choice-outcomes, (iii) explicit advice given by others, (iv) the social role of advisors, such as the person being a peer vs. not a peer and (v) inclinations of the individual to explore the field irrespective of social information. Julia highlights the great potential of further collaborations between neuroscientific lab research and practical projects especially in educational contexts. Here, digital engineering solutions could provide a crucial bridge between the fields, and they could advance innovative solutions. Apps could easily track choices made by individual students, could model the influence of others and provide age- or otherwise adaptive learning feedback, e.g., to account for the difficulty that children have in learning from negative outcomes.

## *1.13 Seminar Topics*

In the neurodesign seminar, Joaquin Santuber discusses three specific ***opportunities for neurodesign***: (i) feasibility (off-the-shelf technology), (ii) accessibility (open-source and open-science initiatives) and (iii) HPI expertise (using Digital Engineering knowledge for creative purposes). Thanks to advances in hardware technology, computer vision and data processing, new digitally-enabled methods are available to a broader group of researchers and practitioners. Thus, working with physiological data is not a reserve of experts who harness high-end devices in research labs any more. Nowadays, widely available tools can be combined with open-source and open-access data processing libraries. Data analysis becomes more widely accessible both to researchers and practitioners in a resource-effective manner. For instance, the coding of facial expressions used to be a labour-intensive task that required special training and expertise. By now, automated approaches for the coding of facial expressions are freely available. At the same time, the outstanding expertise of the HPI in Digital Engineering renders this place a fertile environment for explorations into the full potential of such digitally-enabled feasible and accessible methods. Since many of those methods are explained in more detail later in this chapter (Neurodesign Projects), here some brief examples shall suffice. During the seminar, participants come to try out automated analyses of gestures and body postures using computer vision. This method can provide a rich account of non-verbal communication and embodied aspects of creativity (OpenPose). Related insights can be gained by the study of facial expressions and head pose using automated video analyses (OpenFace). Such approaches help shed light on the affective and emotional states of users. Eye-gaze analysis (eye tracking) facilitates studies on attention and patterns of visual perception. Data on heart rate variability and electrodermal activity can be gathered with off-the-shelf technology like smartwatches and fitness trackers. It can augment studies regarding topics such as cognitive load, stress and exertion.

Joaquin's discussion of three specific opportunities for neurodesign at the beginning of the semester—feasibility, accessibility and digital engineering expertise—turns out to be an accurate preface for subsequent works. Almost all neurodesign projects that emerge in the course of the semester tap the full spectrum of these opportunities. Projects typically harness consumer-grade products (instead of cost-intensive neuro-medical lab equipment). Many of the projects yield open-source publications, software and hardware. All projects build on digital engineering expertise to deliver novel and effective solutions. At the same time, the specific area of work differs from one neurodesign project to the other; contributions are developed for the fields of neuroscience, design thinking research and/or creative engineering.

Julia von Thienen discusses ***bodily perspectives on creativity and collaboration***. These have played a key role in design thinking theory and practice for decades. Julia elaborates on the importance of morphology for creative behaviour options. She refers to cartoons such as "Maya the bee," where bugs necessarily are depicted with a changed, more human morphology. Otherwise, stories could not be told about the protagonists encountering problems and finding creative solutions together. Julia invites the audience to reflect on morphological differences between the cartoon characters and real insects, such as bees and dung beetles. E.g., the cartoon characters have hands to handle artefacts. They communicate emotions and intentions by means of facial expressions and body postures. They have frontally positioned eyes with round pupils, allowing them to focus attention, and to focus attention jointly. Overall, Julia emphasises, creativity is a full-body phenomenon; it is not only about "the brain." Another key topic is the well-researched impact of posture and motion on creative and collaborative achievements. Across multiple studies, fluid, bilateral and relaxed (non-strenuous) motion has been found to facilitate creativity. Here, experimental findings regarding the impact of motion are consistent with biographical research, in which people report on the situational circumstances when they found creative breakthrough insights. While it has long been noted how creative insights regularly emerge in situations where people have their attention "off-task," e.g., they take a break, and how relaxation (non-strenuous activities) seems to be important, it increasingly becomes clear that highly conductive situations for creative insights also often involve motion. Typical examples are people going for a walk or taking a shower. These observations are congruent with neuroscientific findings, which suggest an involvement of the cerebellum in high levels of creative performance. The cerebellum is traditionally known for facilitating fluid motion bilaterally. Julia also discusses the role of the environment in stimulating or inhibiting favourable postures and motions, such as the impact of different table or chair arrangements. Notably, design thinking environments designed to facilitate creativity and collaboration encourage motion during work hours.

In other sessions, Julia provides ***introductions to the basics of measurement theory and study design***. She reviews different scale levels of data (nominal, ordinal, interval and rational), quality criteria for measurements (objectivity, reliability and validity) and different ways to assess them, such as re-test versus parallel-test reliability. Another methodological topic is study design, where Julia discusses different theories of causation (Aristotelian, Regularity, Nomological, Probabilistic, Transference, Counterfactual and Interventionist), with the Interventionist Theory of causation being most frequently used as a basis for social science study design. Different sampling methods are discussed, such as convenience, stratified versus cluster sampling approaches. In class, based on study design templates, participants learn to plan, conduct, analyse, criticize and improve randomized experiments.

In terms of work ***presentations***, course participants of both the seminar and the lecture learn to follow common scientific formats when presenting their own work in talks and on scientific posters (introduction—aim—theoretical background—pertinent literature; methods; results; conclusion—discussion—limitations; references; acknowledgements). In the introductory part of project presentations, course participants also learn to invoke the design thinking approach of pointing towards important, unmet needs, which shall be addressed by means of novel (neurodesign) solutions. Again in line with design thinking approaches, course participants learn to develop convincing, captivating visions of where their projects can and should be leading.

Irene Sophia Plank (Berlin School of Mind and Brain, Humboldt-Universität zu Berlin) teaches ***research methodology for neuroscience*** in several sessions. Her lectures cover null hypothesis significance testing, including p-value calculation and interpretation, sampling distributions, common misconceptions about p-values, type-1 and type-2 errors in null hypothesis testing, deficiencies of null hypothesis testing (such as widespread p-hacking by means of multiple tests) and parameter estimations. Irene further covers several statistical tests and their prerequisites, such as t-tests, ANOVAS, linear models and linear mixed-effect models. In class, tests are calculated in R. In homework submissions, student teams can choose between R and Python. In further sessions, Irene covers topics of digital signal processing in electroencephalography (EEG) and magnetic resonance imaging (MRI). She discusses the spatial and temporal resolution of both methods and the neural origins of signals on macroscopic, mesoscopic and microscopic levels. Regarding EEG assessments, Irene discusses resting membrane potentials, action potentials, synapse activities, extracellular field potentials, event-related potentials, visually evoked potentials, mismatch negativity, P300, language-related ERPs, the readiness potential, EEG frequency analysis by means of Fourier analysis, time-frequency analysis and the reconstruction of EEG signal sources in the case of few or many dipoles. Regarding MRI assessments, Irene covers physical and biological foundations of the approach, signal generation, the magnetisation of spin systems, excitations via radiofrequency pulses, the relaxation of the MR signal, T1, T2 and $T2^*$ contrasts, neuronal energy consumption, the cerebral vascular system, haemodynamic responses and the haemodynamic response function, neuronal correlates of the BOLD signal, spatial scales and spatial resolution, the partial volume effect, the temporal resolution based on sampling rates and biological factors, the linear transform model, scaling and superposition, as well as studies indicating shortcomings of present-day fMRI methods. In terms of practical data analysis, regarding the EEG Irene teaches how to conduct data preprocessing, how to calculate event-related potentials and cluster-based permutation analysis. Regarding the fMRI, she teaches data preprocessing, how to conduct a 1st level analysis on single subjects, and how to calculate a 2nd level analysis that integrates data of multiple subjects. Calculations are conducted in class with Matlab, SPM and Fieldtrip.

This rather comprehensive input of Irene on behalf of neuroscientific data processing is also reflected in a relatively large number of neurodesign projects that are specifically concerned with neuroscientific data (pre-)processing.

## 2 Neurodesign Projects

In this section, we review a selection of neurodesign projects that have emerged in the last semester. Most of them will be continued in follow-up projects in the next semester. The abstracts are intended to provide rather self-standing introductions to projects, so that readers can also read selectively about endeavours of particular interest.

### *2.1 Neurodesign Tests*

This project is specifically concerned with the measurement of creativity and collaboration. Up to today, creativity assessments are often conducted with tests in a pen-and-paper format. This approach has a number of severe limitations. First, test-taking with analogue test material is tedious for researchers. Test responses of participants need to be manually re-cast into a digital format to allow for statistical processing; this procedure is time-consuming and error-prone. Second, the analogue test approach is barely scalable; only a limited number of participants can be included in studies with pen-and-paper tests. Third, the rating of standard test responses often requires subjective assessments of "expert raters." Here, the analysis of test responses is resource-intensive and the reliability of test results is not ideal.

On the internet, a few creativity test compilations and platforms are already available. They are typically hosted by engaged creativity scholars who provide a web-service as a "pet project" alongside demanding regular jobs in fields such as psychology and/or neuroscience; the design of internet services is not their primary field of expertise.

In a one-semester project, Nina Ihde, Jannis Rosenbaum, Martin Michaelis, Katharina Blaß, Florian Papsdorf, Philip Weidenfeller, Arne Zerndt, Ahmad AlAbbud and Florian Fregien (2020) have developed a web-based platform for researchers to share and access standardised creativity tests (Fig. 8). The platform is designed to offer state of the art usability experiences. Tests can easily be created, used for study purposes and can be shared with colleagues. The web-platform


**Fig. 8** The platform "Neurodesign Tests" was developed by Nina Ihde, Ahmad AlAbbud, Florian Papsdorf, Jannis Rosenbaum, Philip Weidenfeller, Arne Zerndt, Katharina Blaß, Martin Michaelis and Florian Fregien. It renders standardized creativity and collaboration tests accessible for researchers around the globe for digitally-facilitated testing (photo by Kay Herschelmann)

also offers an immediate connection to Amazon Mechanical Turk (MTurk), so that researchers can administer their tests to huge numbers of study participants. All test results are straightforwardly available in a digital format. Since data is stored safely on HPI servers, confidentiality of research data can be ensured for scholars who use the service.

This project was supervised by Matthias Bauer and Julia von Thienen at the HPI. It benefitted from major input by Mathias Benedek (Universität Graz) and Laura Kaltwasser (Humboldt-Universität zu Berlin). The project team is also grateful to Adam Royalty and Grace Hawthorne (both Stanford University) for sharing and discussing pertinent test material.

The platform Neurodesign Tests is accessible at https://hpi.de/neurodesign/tests.

## 2.2 *Measuring Creativity with an Online Game*

Up to the present day, creativity tests are often administered in pen and paper versions—an approach that induces severe limitations. Most notably, only relatively few study participants can be tested, as the processing of handwritten data is labour-intensive. Furthermore, a number of standard creativity tests involve self-reports,


**Fig. 9** Eva Krebs and Corinna Jaschek develop a web-based computer game for creativity assessments (photo by Kay Herschelmann)

which are not necessarily reliable indicators of either creative potential or actual creative behaviour. Other standard creativity tasks ask participants to engage in rather "unnatural" behaviours, such as naming uncommon uses for everyday objects.

As an alternative to more traditional creativity tests, Corinna Jaschek and Eva Krebs explore opportunities for creativity-measurements via a web-based computer game (Fig. 9). In the game, participants get to work on the goal of protecting a living organism against various attackers. This can be achieved in the game by placing and upgrading objects on the game grid. The approach is realized as a tower defence game, a common subgenre of strategy video games. It is implemented via the open-source game engine Godot.

All game interactions taken by the user—such as placing objects, upgrading objects or halting enemies—are automatically tracked and stored. These events can then be analysed automatically, without the need for a human expert who manually judges the creativity of the player's action. All test results are immediately available in a digital format. Conclusions can be drawn regarding a single participant, but also across all players. For instance, how novel/original is an action taken in the game by a single player, in light of all actions that have ever been taken by players of the online game? Moreover, the effectiveness of actions taken in the game can be assessed objectively, as effective actions stop attackers and help the organism at stake maintain a good health status.

Due to the web-based application, the testing routine can achieve a high level of standardisation in studies across the globe. Moreover, studies can be hosted via

Amazon Mechanical Turk (MTurk) or similar platforms, so that it becomes feasible to work with huge numbers of study participants.

People's complex gaming behaviours permit the calculation of an array of measures, which can serve as indicators of different facets of the creativity construct. Which of the available game-measures best serve to assess the participant's "fluency," "originality," "flexibility," "problem-sensitivity" etc. is currently elucidated in validation studies, which combine the game approach with standard creativity tests on behalf of various creativity facets.

The game is developed based on a design idea by Corinna Jaschek, Tom Beckmann, Kim Borchart and Christian Flach. The project is supervised by Julia von Thienen at the HPI and Oren Kolodny at the Hebrew University of Jerusalem.

## *2.3 Neurodesign Cards*

Why, how and when does design thinking work or fail? Many aspects of design thinking can be understood in depth based on a thorough understanding of the human body: how humans become creative and collaborative—or fail to do so. The field of neurodesign brings together expert knowledge from different strands of methodologically rigorous empirical research. This knowledge is gathered, for instance, in neurodesign lectures at the HPI, with contributions from leading experts of internationally recognized labs and research centres.

In the form of a simple to use card set, Julia von Thienen, Caroline Szymanski and Theresa Weinstein make key research insights available to design thinking practitioners. The cards overview design-thinking-relevant empirical research findings and discuss implications for practice. Thus, design thinking coaches and teams can learn to deploy interventions even more mindfully and purposefully.

In this project, the card set editors develop the overall framework and contribute a basic stock of cards. In addition, further cards can be authored by interested neurodesign experts who review the implications of their own research findings for design thinking · creativity · collaboration practice.

The card set is tested and iterated in collaboration with Annie Kerguenne and Miriam Steckl from the HPI Academy. First prototypes have been discussed and used at the Connect & Do Day organized by the HPI Academy on February 14, 2020.

## *2.4 Sonification of Brain Data*

Brain data is often visualized either through colourful fMRI images or lines of EEG plots. However, much of what goes on in the brain cannot be intuitively understood or analysed by looking at static images only. There is rhythm in the brain. Slow rhythms dominate brain activities when people relax and go to sleep. Creative fluency is also often associated with a rather relaxed rhythm of brain activation. When people concentrate intensely, faster rhythms become prominent. During extreme stress, excessively fast rhythms can take over. There is also the importance of "geography." Does an activation pattern begin in the back of the brain, driven by visual information processing? Or does a burst of activation suddenly emerge in the front of the brain, reflecting conscious control and planning? Is mostly the left hemisphere activated, indicating verbal or symbolic processing? What is going on in the upper-middle zone of the brain, revealing body-related information processing? Such differences of rhythm and directions of activation-spreading could be heard much easier than they can be seen in a picture.

As the pioneering works of neurodesign guest lecturer Chris Chafe show, the sonification of brain data is feasible nowadays and it renders possible very intuitive analyses of what happens in the brain. With 3d sonification models for headphones or even multiple speakers prepared in a room, brain data can be rendered meaningful for listeners.

Based on novel sonification algorithms, questions such as the following can be addressed:

- How does the brain activity of highly creative persons sound, compared to the activity of less creative persons who work on the same task?
- How does the rhythm of brain activity change when people experience creative flow, frustration, high-vs.-low levels of attentiveness etc.?
- Is it possible to discern differences between patient groups and healthy participants acoustically, by means of listening to peoples' brain activities?
- (How) can brain data sonification aid education? E.g., does it help students understand brain functioning when they can walk through a huge 3d brain, where different kinds of brain activity are represented acoustically and analysed together with the lecturer?
- (How) can we help creators better regulate their own work processes by providing acoustic feedback on their own brain activity?
- (How) can we generate captivating art experiences by means of sonified brain data?

Several neurodesign projects explore opportunities in the field of brain data sonification for diagnostic, applied and artistic ends. Currently, they concentrate on the sonification of EEG data (the area where Chris Chafe has already pioneered solutions). In the future, extensions towards fMRI data, or also towards a sonification of full-body-data, are likely next steps.

## 2.5 *Brainwave Sonification Toolbox*

One major challenge for brain data sonification emerges right after the phase of data collection. Raw EEG data is full of artifacts and noise, such as muscle movements and eye blinks that induce strong signals in the recordings. If the measured EEG curve was represented acoustically straightaway, the rhythm of eye blinks would dominate the sound, making it hard to discern dynamics in brain activity proper. Moreover, EEG raw data often comes with technological artifacts, such as "electrode drifts" where the measured voltage of an electrode steadily increases or decreases over time. In a labour-intensive work phase of data preprocessing, neuroscientists remove artifacts from their data sets before analysing and creating EEG plots. Similarly, sonification algorithms can provide best and clearest acoustic representations of brain activity when they are applied to datasets of brain activity that contain as few artifacts as possible.

Another challenge of applying sonification algorithms to EEG data emerges from the multiplicity of recording formats and software packages that prevail in research. Sonification algorithms could be used routinely if written for a standard data format used across labs. However, a variety of different file formats are used in research. Moreover, many EEG data files can only be opened with lab software that is not freely available.

In this project, Leon Papke, Carla Terboven, Philipp Trenz and Simon Witzke (2019, 2020a, b) envision EEG preprocessing for sonification purposes as a (free-of-charge) service. Users can upload EEG raw data and receive preprocessing support by a software package designed for good user experiences. With this service, (i) brain data preprocessing can happen rapidly, (ii) neuroscience expert knowledge is not required, (iii) expensive lab software is not required, (iv) EEG raw data can be uploaded in many different file formats and (v) users can obtain download files in different data formats; the .csv format is suggested as a standard for sonification algorithms.

A first prototype of the Brainwave Sonification Toolbox is available for testing and initial usage. It is realized as a Docker container. Thus, the application can run locally on a computer, but it can also be offered as an intra-net or cloud service. In terms of architecture, the frontend of the service is realized via Angular and the backend via Django. Currently, brain data can be uploaded in the following formats: European Data Format (EDF), BioSemi (BDF) and the file format of BrainVision (.eeg). Users can then define the desired preprocessing pipeline. Common preprocessing steps are represented visually as drag-and-drop boxes with simple explanations. For instance, users can apply high-pass, low-pass or band-pass filters with self-selected values. The application of filters on EEG data is realized internally via MNE (Gramfort et al. 2013a, b), which is an open-source python-based platform for the preprocessing of brain data. Its relevance for professional neuroscientific practice is already reflected by a large number of academic citations. In contrast to the Brainwave Sonification Toolbox, MNE is designed to be operated by neuroscience expert users who are ready to dedicate time and effort to data preprocessing.

This sonification project supports open science initiatives. The code of the Brainwave Sonification Toolbox is published on https://github.com/1p4pk/brainwave-sonfication-toolbox. It is available for free and can easily be extended.

### 2.6 Real-Time EEG Sonification with the BITalino Platform

In the area of EEG sonification, a number of pioneering works have been conducted in recent decades (Väljamäe et al. 2013). Often, projects reside somewhere in between science, engineering and art, where authors vary in the purpose they emphasise most.

An example of a project where primarily artistic aims are pursued is the Gnosisong brain installation by Chris Chafe and Greg Niemeyer at the Centro de Cultura Digital in Mexico City from August 28 to September 24 in 2015 (Berkley Center for New Media 2020; Gnosisong 2020). Here, visitors experience an abstract three-dimensional depiction of a brain, where medical-quality EEG data is conveyed by means of sounds and visuals. Thus, viewers shall be stimulated to experience and reflect on the "mystery of thought." They witness rhythmic patterns emerge or dissolve, the speed of signals increases or slows down, different nodes of the installation (i.e. EEG channels) begin to signal in synchrony and then acquire individual dynamics again.

An example of a project with marked artistic aspirations next to very practical use cases is that of Miranda (2006). He presents a brain-computer interface system that allows users to compose and perform music on a mechanical acoustic piano regulated by their brain activity. Technically, the system tracks activity in different EEG frequency bands of the user, which in turn activates generative rules for the production of original music pieces. While in this project music is understood as an artistic expression of the player, the practical use case Miranda has in mind is a therapeutic treatment for persons with physical disabilities, who cannot play instruments in more traditional terms.

In yet other cases, purposes predominantly reside in the area of (applied) science. Again, a project by neurodesign guest expert Chris Chafe provides a good example. In collaboration with Josef Parvizi and colleagues (Parvizi et al. 2018), a sonification tool was developed to facilitate the diagnosis of "silent seizures." Here, patients enter medical conditions without easy-to-observe bodily convulsions. In a test study, the authors find that untrained personnel using the sonification tool can diagnose silent seizures even more reliably than trained personnel, who reviews the same EEG data by means of visually inspecting EEG graphs. While this project is primarily directed towards goals of applied science, artistic concerns also play a role. In order to create interpretable sounds that highlight brain dynamics of interest, Chris "composed" an acoustic signal in the range of a male voice. Seizure patterns in the EEG data are sonified by means of a screaming or moaning sound that humans can easily produce, imitate and "understand."

In his sonification project, Noel Danz (2019, 2020) brings together elements of previous sonification work from artistic and applied-scientific contexts. He explores opportunities in the area of three-dimensional EEG data sonification—akin to the Gnosisong brain installation—, but pursued for applied rather than artistic ends. In addition, Noel seeks to advance an "ultra-feasible" neurodesign method: (i) EEG data sonification shall be possible in real time. (ii) The method shall be feasible for many persons, due to low budget solutions across the whole production chain, from EEG data acquisition, over sonification software, up to three-dimensional sound experiences. (iii) The sonification algorithms shall help elucidate EEG data of any kind—beyond specific, predefined diagnostic ends.

Earlier works in this direction had been conducted by Baier et al. (2007), who provide a model for real-time three-dimensional EEG data sonification in the service of diagnostic goals. They develop a multivariate event-based sonification approach, which displays salient rhythms, modulates pitch and provides spatial information. The test case of the authors—akin to Parvizi et al. (2018)—is the diagnosis of seizures. In contrast to the project of Noel, the work by Baier et al. (2007) is not necessarily directed towards creating an ultra-feasible method. The EEG data they sonify was acquired in professional medical labs. Thus, the question of how each and every interested user might obtain EEG data for sonification trials is not of concern in their project. Moreover, Baier et al. invoke one very specific test case, i.e. seizure detection. The great bandwidth of questions that might be addressed by means of 3D brain data sonification—including topics of potentially unique brain dynamics in highly creative and/or collaborative persons—are at most a brief side-topic in their discussion. Finally, there are various technical differences between the solution of Baier et al. (2007) versus that of Noel. Most notably, Baier et al. communicate information about the physical location of an EEG signal by means of different pitch levels in the sound. Noel develops a solution where listeners can hear the location of a sound, i.e. people can hear where the EEG signal comes from.

To allow for ultra-feasible EEG data acquisition, Noel opts for the BITalino platform. The BITalino is a low cost, open source, single-board computer. It is designed for purposes of education, prototype development and biomedical research—a solution that won the European Commission Innovation Radar Prize 2017 in the category "Industrial & Enabling Tech." It has a well-document API and offers bindings for many programming environments. In his project, Noel works with the BITalino Plugged Dual kit with additional EEG sensors, yielding overall costs of ca. 300 €. This is cheaper in orders of magnitude compared to regular EEG equipment used in medical or scientific labs. Moreover, compared to other consumer-grade EEG solutions like the Muse 2, which records with a fixed number of four EEG channels in the front of the head, the BITalino platform is more flexible and allows users to self-select locations on the skull where brain activities shall be captured.

As a technical approach to 3D brain data sonification, Noel chooses the paradigm of binaural sound localisation. This approach builds on the human ability to localise sounds in space based on how sound signals reach the ears (Stern et al. 2006). E.g., a sound signal that comes from our left side reaches the left ear first; the sound signal also has a slightly higher decibel-level when reaching the left ear compared to the right.

In terms of design, Noel creates a spatial representation of the brain (Fig. 10). Users can upload EEG data or make their own recordings with the BITalino platform. To explore EEG data acoustically, the user can position a microphone by means of drag-and-drop actions somewhere on the brain map. Now the microphone

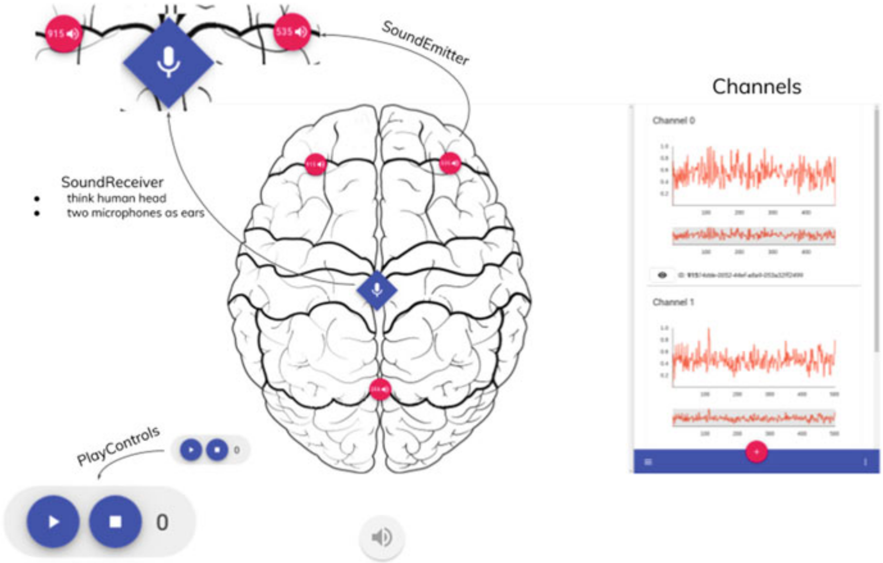


**Fig. 10** Based on binaural sound localisation, listeners can hear EEG data captured at different positions of the skull [image reprinted with permission from Danz (2020)]

indicates the position of the listener in the brain. In a next step, the user can select one or more EEG channels for sonification. If a selected EEG channel resides on the left side of the microphone, the sound is emulated, so that the listener experiences it as coming from the left direction. EEG channels being closer versus more distant from the microphone also get represented in different ways. Again, the sound is emulated, so that listeners experience the sound as coming from more distant versus closer sources. Technically, this is realised by means of an open source WebAudioApi "Panner3D," which emulates the ways in which sounds reach human ears based on the position of the audio source in relation to the listener. Presently, the sonification algorithm is implemented to signal acoustically relevant changes in the EEG plot.

Noel's sonification solution is available here: https://hv10.github.io/neurodesign_sonification.

## 2.7 *From EEG Data to 3D Sound Spatialization*

The aim of a project by Lukas Hartmann, Tim Strauch, Philipp Steigerwald and Luca Hilbrich (from the Technical University of Berlin) is to use EEG data to create a 3D sound installation, which renders distinct rhythms and topographies of brain activity in such a way that it can be easily interpreted, even without extensive prior training in neuroscience.

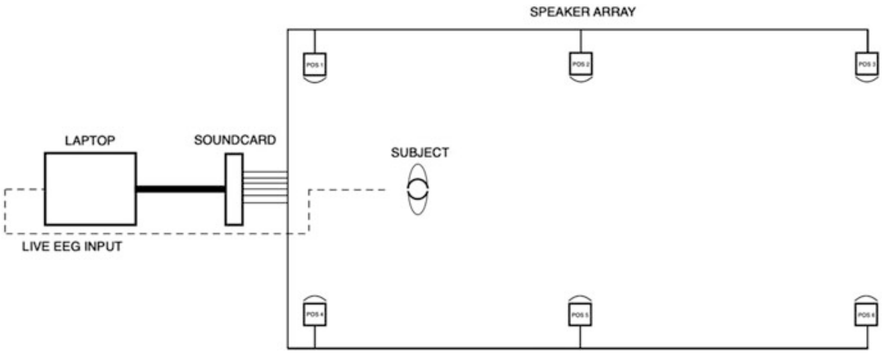


**Fig. 11** A multichannel sonification array set-up is planned for brain data sonification

After preliminary testing with PyLive and Ableton as well as SuperCollider, the team is currently developing a spatialization system that enables users to distribute audio live, across a speaker array (Fig. 11) using EEG data as a control input. A first realization of the system is planned in lecture hall 3 at the HPI, and/or in the Design Thinking Research Lab of the HPI main building on the 3rd floor.

To control audio parameters, the team tracks energy in different EEG frequency bands over time (alpha, low beta, high beta etc.). The distribution of audio channels mirrors EEG channel locations on the skull: EEG activity captured at frontal positions triggers speakers in the front of the room, while, EEG activity from medial positions on the skull is represented by speakers in the middle of the room and EEG signals at occipital positions (the back of the head) by speakers in the back of the room.

This platform is intended to host a multitude of projects in the field of brain data sonification. With the audio input left open-ended, a wide variety of purposes can be addressed.

Notably, sounds need to be designed mindfully for each purpose. Simple and concise sounds are likely to be most serviceable for diagnostic and educational applications. Ideally, even untrained persons can discern constituent frequencies and their relative ‘geography’ in sonified EEG signals. Listeners shall obtain an easy and effective way to interpret brain activities with just a little help of experts, who provide short introductions to the meaning of sounds that can be heard from different locations of the room. In other applications, it may be desirable to use more complex inputs. For instance, based on real-time measurements of EEG activity, live audio—such as instruments—could be used and distributed by the platform to stage live performances.

Ultimately, the project aim is to engage listeners with brain data, to help audiences understand brain dynamics, and to foster critical design thinking around the human brain.

### *2.8 Brainwave Sonic Instrument for Sound, Multi-channel Sound Installation and Live Performance*

Nico Daleman (from the University of Arts at Berlin) explores solutions for brainwave sonication in the form of an open source virtual instrument compatible with sound installations and multichannel systems. Here, the aim is to create immersive sonic experiences and musical performances. In a current solution co-developed with colleagues from the Technical University of Berlin, six speakers are distributed in an architectural space. They convey brain activities captured at frontal, medial and occipital regions of the brain (cf. project described above, Fig. 11).

For his project, Nico decided to work with .csv files that are processed through the open source software Supercollider. Naturally, multichannel EEG measurements—with data recorded from various locations on the skull—translate to a multichannel audio environment and multitrack audio recordings. Indeed, neuroscientific brain measurements by EEG or fMRI include crucial information about spatial locations. For the interpretation of signals it is key to know where each signal was measured, e.g. in the front or the back of the brain. Thus, recorded brain data could not be adequately sonified with traditional stereo sound solutions, where listeners could only distinguish signals coming from the left versus the right side of the brain. Surround sound is needed to convey precisely whether brain activity signals originate more from frontal or occipital regions, from the left or the right hemisphere. In this endeavour, multichannel audio spatialization techniques, particularly Object-based audio (Tsingos 2018) and Binaural rendering (Roginska 2018) can be very serviceable to create a unique sonic experience of the recorded brain data.

Unlike Chris Chafe's seizure-detection project, which aims for an overall sonic rendering of EEG data (but more in line with his composition Gnosisong), Nico's approach is designed to deliver a novel sonic immersive experience, in which the complexity of brainwaves can be perceived spatially. A first prototype (based on Bovermann et al. 2011) has been set up for eight different EEG channels, but could be expanded to 16 or more channels, depending on the input data provided. Technically, the channels figure as "objects" in the framework of Object based audio techniques, using the Ambisonic Toolkit (Anderson and Parmenter 2012). Based on energy in the different EEG frequency bands over time (alpha, low beta, high beta and theta), different audio frequencies are generated. Due to the low frequency characteristics of the original signals, these are also used as Low Frequency Oscillators (LFOs) to modulate between audio output frequencies, and to control or modify different parameters of the piece, including filter cut off frequencies, spatial position and amplitude. These parameters can be controlled in a live musical performance via a MIDI controller such as the Novation Launch Control XL, which allows the performer to improvise and react in real-time to the outcome of pre-recorded brain data. Using LFOs to modulate audio outputs also allows further experiments outside the digital domain. Alternatively, EEG signals captured with devices such as the 16-channel-EEG cap OpenBCI can be used in real-time to regulate, for instance, CV controlled devices such as modular synthesizers. This opens up new collaborative frontiers between neurodesign, sonification practices, electronic musicians and sound artists. Thanks to the flexibility of Object based audio techniques, the original eight-channel solution can also be experienced in a six-channel speaker setup, or alternatively as a binaural rendering. A first prototype of the instrument and the sound results can be found at https://github.com/nicodaleman/brainwave-sonic-instrument.

### *2.9 Measuring Creative Flow in Real-Time Using Consumer-Grade EEG and a Neural Network*

When an individual works in a mental state of creative Flow, she feels fully immersed in her activity. She is highly concentrated, works productively, enjoys the activity and experiences self-fulfilment. The concept of Flow was introduced by Csíkszentmihályi (1975, 1990). According to his model, individuals experience Flow when they find their work task challenging in a positive sense, and when they have the necessary skills to tackle the objective well.

Flow states are desired for several reasons: They are prized for yielding best work outcomes. Subjectively they feel joyous and individuals experience a sense of fulfilment. 'Innovation-training' in particular, which naturally enables more creative Flow states, has even been found to increase brain health (Chapman et al. 2017).

With her start-up NeuroCreate, Shama Rahman wants to bring research findings to the world of everyday applications. The company's platform FlowCreate™ Innovator uses Artificial Intelligence to facilitate human brainstorming processes. Presently, biofeedback regarding Flow states is being added to the system. NeuroCreate's proprietary deep learning model applied to EEG datasets has been used to identify the physiological signature of high versus low levels of Flow, such that real-time classification is possible. Respective data had been gathered with state-of-the-art EEG lab equipment (64 active electrodes in the 10–20 Biosemi configuration), by Shama in the course of her PhD research. Now for the public to enjoy biofeedback regarding Flow levels, data from consumer-grade wearables or other sensors will have to suffice as information input.

An experiment by Holly McKee, Felix Grzelka, Laurenz Seidel and Pawel Glöckner (2019, 2020b, c) explores physiological signatures of Flow states during brainstorming, identifiable with consumer-grade wearables and webcam recordings. According to Csíkszentmihályi (1990), Flow states will only be achieved regarding brainstorming when people have high skill levels in brainstorming and experience the given brainstorming tasks as challenging. Thus, in terms of sampling methodology, only persons experienced in brainstorming should participate in the study. A talk at the HPI D-school with an audience of design thinkers was used to acquire test participants; only volunteers with at least half a year of design thinking experiences were included in the study. Data collection was supposed to occur in subsequent weeks at the HPI, but got delayed due to the COVID crisis.

The study is designed as an experiment with repeated measures. Participants get to work on brainstorming tasks in two-person-teams. Each team conducts two brainstorming rounds, on different but structurally similar brainstorming tasks A and B. As an experimental manipulation, work on one of the tasks gets disturbed, e.g. by "technical difficulties" that constantly disrupt brainstorming activities, so that study participants cannot achieve a Flow state. There are four different study conditions, to which pairs of participants are randomly assigned. (1) Participants work on task A first, then on task B; activities in task A get disturbed. (2) Participants work on task A first, then on task B; activities in task B get disturbed. (3) Participants work on task B first, then on task A; activities in task A get disturbed. (4) Participants work on task B first, then on task A; activities in task B get disturbed.

In this experiment, physiological data is acquired with the consumer-grade 4 channel EEG headband Muse 2 (which captures EEG, heart rate and motion), the wristband Empatica E4 (which captures electrodermal activity, heart rate and motion) as well as webcams to record faces (later analysed in terms of facial action units determined by the software OpenFace).

For each pair of participants, the study begins with equipment being put on. Then, baseline measures are obtained: 1 min with open eyes, 1 min with closed eyes (to elucidate eye-related artifacts in the EEG signal); followed by 5 min of talking on 'mundane' un-creative non-task related topics. Participants then obtain an introduction to the platform FlowCreate™ Innovator, where they will jointly conduct brainstorming. This screen-based brainstorming routine serves to reduce motion artifacts in the data, compared to standard design thinking brainstorming routines where people move around quite a bit; at present motion tends to induce high levels of artifacts especially in EEG recordings. The chosen brainstorming scenario with FlowCreate also resembles intended later use cases for biofeedback as envisioned by the project partner, e.g. as amendments to existing NeuroCreate platform software. In terms of experimental procedure, participants work in teams of two on brainstorming tasks according to one of the study conditions (1)–(4). They also fill out questionnaires that capture demographic data, subjective reports of Flow states in the course of the study and subjective reports of how challenged people felt by tasks A and B.

The data is analysed to identify patterns indicative of high vs. low Flow states in people. Research questions include: Can we identify a "physiological fingerprint" of Flow using consumer wearable technologies? Can NeuroCreate's deep learning model, which has resulted from an analysis of sophisticated EEG lab data, also predict Flow states based on data acquired with consumer-grade hardware? Considering multivariate data from different sensors, such as EEG, motion, heart rate, EDA and webcam recordings of faces: which data and means of data analysis provide most reliable and valid indicators of Flow states, or would this rather be a combination of all?

A subsequent study by Samik Real and Sami Adnan (2020) compares the performance of three different deep learning approaches in determining Flow states based on EEG data. Two different datasets serve as input material. First, the team can work with a proprietary dataset of NeuroCreate, where 64-channel-EEG-recordings have been conducted while professional musicians improvised pieces of music. Later, expert judges reviewed audio of the musical performances and rated whether or not musicians were in Flow over time, alongside self-assessments of the participants themselves. This dataset showed consistent EEG patterns related to expert-judged classifications, and thus provides a very well-labelled dataset for training deep learning models. Secondly, data from the study of Holly McKee, Felix Grzelka, Laurenz Seidel and Pawel Glöckner can be analysed, where EEG data should be captured during brainstorming with the Muse 2 as a consumer-grade sensor technology. Here, the data is labelled once in terms of study conditions (Flow, uninterrupted work versus no-Flow, interrupted work) and also by means of self-reported Flow experiences of participants captured via questionnaires. All these EEG recordings deliver time-series data of voltage fluctuations measured on the skull, at the position of respective electrodes. An EEG power spectrogram can also be computed.

In this project, three different deep learning approaches are implemented and compared, to see which performs best in classifying Flow states. The first is a Recurrent Neural Network. This approach is currently state-of-the-art in assessing time-series data and/or language, or in the analysis of other datasets where judgements depend on "time of occurrence" and "sequence." Models work with a memory of previous calculations in order to analyse subsequent inputs. However, a lot of computational power is needed to parallelize different analysis chains, because previous calculation results must be stored for subsequent analyses in each case. The second model to try is a Convolutional Neural Network (CNN). It uses images (such as power spectrograms or topographical images) as input. Filters are used to extract features/patterns automatically. This approach is currently state-of-the-art in the field of computer vision. To render the approach applicable in the realm of EEG assessments, it can be applied to EEG spectrograms. The third model to be tried is a Temporal Convolutionary Network (TCN). This approach is similar to CNN, but it works with one-dimensional data (like EEG raw 'wave-form' data of voltage changes), not with two-dimensional data (such as power spectrograms or topographical images). Thus, in contrast to the former CNN model, with TCN no initial data-conversion is needed. Moreover, in contrast to RNN, calculations can easily be parallelized.

Regarding the technical realization, Pandas, NumPy and ScikitLearn are used for the preprocessing of data. Models are created with TensorFlow in the backend and Keras in the frontend.

Major goals of the project are (i) to classify Flow states based on power spectra or wavelength patterns, (ii) to compare the performance of different deep learning models and (iii) to deploy models for real-time classification.

Since this project processes EEG data recorded by the end of the winter semester, it will be continued and finalized in the summer semester.

Ultimately, the vision of both projects is to help people achieve peak performance Flow mental states by providing real-time biofeedback on low versus high levels of Flow. This can improve people's self-regulation and can also help people take informed decisions (e.g., when best to take a break from work). Artificial

Intelligence could also make suggestions to users, or could automatically make adaptations in the environment (e.g., on the screen), that allow people to achieve Flow states more regularly. This would have direct implications for future 'gamified' designs of the FlowCreate™ Innovator.

### *2.10 Deep Learning on EEG Data of Team Collaboration*

Electroencephalography (EEG) is one of the most common methods to record brain activity. It plays an important role in neuroscientific studies of brain functioning. It is also a central diagnostic tool in medical assessments regarding brain activity or brain-mediated functions, such as sleep.

The processing of EEG data is currently a time-intensive task handled by human experts. EEG data is noisy in several respects, and even in carefully conducted EEG lab assessments the data is full of artifacts. The mere act of eye-blinking in subjects induces strong artifact-signals in the recordings. Body motion and sweating in subjects also disturbs the signal. Moreover, there are so-called "electrode-drifts," where the measured voltage of an electrode constantly increases or decreases over time. In addition, EEG recordings vary from one person to another; individual differences need to be accounted for in the data analysis. All in all, the preprocessing and analysis of EEG data is currently a resource intensive undertaking that can only be conducted by topic experts.

Deep learning is an approach of machine learning that invokes artificial neural networks. Pre-defined deep learning models are supplied with data, so that they can "learn." Deep learning approaches may be very fruitful to facilitate the preprocessing and also the analysis of EEG data. One major advantage of deep learning is that it can be applied to EEG raw data—no prior filtering is needed. Indeed, the model itself can learn to recognise artifacts, and remove them if desired. Moreover, models can learn to detect any feature of interest (such as indicators of sleep disorders or EEG-patterns indicative of good creative performance), while at the same time learning to disregard uninformative artifacts. Results of deep learning models might even be better than outcomes of human assessors, because the machine can detect relevant patterns in the data that humans may be unaware of.

Tobias Bredow and Emanuel Metzenthin (2019, 2020) explore the potential of deep learning in one sample domain of EEG research that is specifically relevant to design thinking. Here the question is whether or not members of a team collaborate well together. Indicators of good vs. bad team collaboration shall be found in people's EEG recordings.

In order for deep learning models to identify suitable indicators of team performance, well-labelled EEG data is needed. It must be clear what EEG data stems from well-collaborating teams and which data stems from not-well collaborating groups.

The data for this deep learning project is provided by Caroline Szymanski. The original neuroscientific study is discussed by Szymanski et al. (2017). In the experiment, 42 participants perform a visual search task first alone and then in teams of two. The EEG is recorded with 64 electrodes per person, each sampled at a rate of 5000 Hz, later reduced to 1000 Hz by a bandpass filter. Teams are classified as collaborating well together when they perform better together than any individual team member performed alone. The difference between individual performance versus team performance also provides a metric of how good the team works together. Each search round endures for an average of 7 s. In the original neuroscientific study, it is possible to determine good versus bad team collaboration by analysing the first 1.5 s of EEG recordings from each search round. In the analysis, brainwave-synchronization across team members is identified as a predictor of good team collaboration. By using statistical regression models that include brainwave-synchrony and other parameters, Szymanski et al. can explain 74% of the variance in team collaboration scores. (If regression models explained 100% of team collaboration scores, parameters in the regression model would suffice to determine exactly how well teammates work together in each search round.)

To train their deep learning model, Emanuel Metzenthin and Tobias Bredow first dichotomise team collaboration scores, so that each EEG recording is labelled as either indicating good or bad teamwork. Available EEG recordings up to 10 s in each search round are included in the study. Then, ten samples out of each 1 s (altogether 1000 data points per search task) are extracted for the training of deep learning models.

This project compares the performance of four different deep learning approaches: (1) A Convolutional Neural Net (CNN) applied to EEG raw data, (2) A Convolutional Neural Net (CNN) applied to pre-processed EEG data, (3) a Long-Short-Term-Memory model (LSTM) applied to EEG raw data and (4) a Long-Short-Term-Memory model (LSTM) applied to pre-processed EEG data. In cases (1) and (2), the CCN is realized with four convolutional max-pooling layers. It includes batch normalization. There is one dense layer with 100 neurons; the output layer has one neuron. In cases (3) and (4), the LSTM is a single unit long; it has one dense layer and one output layer.

The EEG recordings available to this project include raw data only. To obtain data for trials (2) and (4), the authors apply a high-pass filter at 0.5 Hz. This is a common EEG preprocessing step, though it has also been critically reviewed as impoverishing data quality (Tanner et al. 2015).

All deep learning models are validated on a set of 961 data samples not used for training before. This validation sample includes roughly equal amounts of “good team collaboration” (54% of the cases) versus “bad team collaboration” (46% of the cases). Results are reported in Fig. 12.

The CNN applied to EEG raw data performs best. It achieves an accuracy of 99%. This indicates a strong increase in prediction accuracy by means of deep learning compared to the best performing regression model reported in the original neuroscientific study.

Notably, applying deep learning on preprocessed data reduces the model performance in this test. The prediction accuracy drops from 99 to 92% with CNN

| Model / Dataset | Accuracy | Precision | Recall |
|---|---|---|---|
| CNN / Raw | 99% | 0: 1.0; 1: 0.97 | 0: 0.97; 1: 1.0 |
| CNN / HP filtered | 92% | 0: 0.86; 1: 0.98 | 0: 0.98; 1: 0.87 |
| LSTM / Raw | 54% | 0: 0.0; 1: 0.54 | 0: 0.0; 1:1.0 |
| LSTM / HP filtered | 54% | 0: 0.0; 1: 0.54 | 0: 0.0; 1: 1.0 |

**Fig. 12** The performance of four different deep learning models to predict good (1) versus bad (0) team collaboration based on EEG-recordings of team members [image reprinted with permission from Bredow and Metzenthin (2020)]

models. While this result may be due to a non-ideal preprocessing of EEG data in this study, or to a CNN design that is not ideally suited for this kind of data, the neuroscientific community is also well advised to pay close attention to the finding. One century ago, breakthroughs were achieved in the field of statistics when Ronald A. Fisher (1925) began to analyse data that had previously firmed under the label of "measurement errors" and was thus disregarded. A quick recollection: While in statistical analyses, initially only the arithmetic mean compared across study conditions was considered informative, and deviations from the mean were disregarded as "errors," Fisher pioneered thinking about these presumed errors. Might valuable information be extracted from them? This line of thinking led Fisher to invent the concept of data "variance" and statistical approaches to analyse it. Such procedures nowadays underlie most statistical computations. Similarly, neuroscientists may be encouraged to think about valuable information that might potentially be extracted from data that is regularly removed in the phase of data preprocessing. Even if humans do not presently know what to make of the information that is readily removed, deep learning models can potentially benefit from it already today.

The project by Emanuel Metzenthin and Tobias Bredow also has a practical "product" outcome. The authors have packaged a solution, so that interested neuroscientists can easily try out CNN or LSTM machine learning approaches on their own neuroscientific datasets. The package is available for free at https://pypi.org/project/deepeeg/0.1/. It supports (i) the training of models with chosen data, (ii) the application of high-pass, low-pass or bandpass-filters on EEG data and (iii) outcome reports to evaluate model performance. This package can be used by neuroscientists who have basic Python skills, but have no deep learning experiences and thus could not set up CNN or LSTM models themselves. By trying out the models on datasets, neuroscientists can explore whether such deep learning approaches may provide fruitful solutions in a work area of interest.

### 2.11 The Impact of Remote vs. Face-to-Face Collaboration on Team Performance

In the industry, remote collaboration becomes ever more popular (Bitkom 2020). Increasingly often, companies provide opportunities for employees to work in "home office" or at other self-selected locations. This has not only become an option for employees who work on rather self-contained tasks, but just as much for employees who are supposed to collaborate with colleagues.

In a noteworthy contrast to industry trends, research on team performance suggests that collaboration tends to be more effective in teams that work face-to-face as opposed to teams that collaborate remotely (Fletcher and Major 2006; Szymanski 2019). Yet, research in this field has only just begun. Fletcher and Major analyse self-report data. How about measures of behavioural performance or physiological assessments? Szymanski draws attention to tendencies in an array of neuroscientific studies that seem to imply disadvantages of remote collaboration; however, the studies themselves have not been specifically designed to elucidate the contrast of face-to-face versus remote teamwork.

This situation provides the background of a study by Justus Hildebrand, Kim Borchart and Hendrik Rätz (2019, 2020a, b), which pursues two ends. First, a dedicated experiment shall be conducted where face-to-face versus remote team collaboration is compared directly. It shall yield quantitative measures regarding behaviour and physiology. Second, the study seeks to draw attention to different contexts, which can impact dynamics of remote collaboration. In some contexts, remote collaboration may be very difficult, whereas in other contexts it might work well. This study explores a context where remote collaboration is likely to be rather successful—and thus might also provide a model for successful remote collaboration elsewhere. In particular, in this study (i) team members share a clear and emotionally engaging vision: They do not get to work on arbitrary, tedious work objectives, but instead play a captivating online game that they want to win together. Furthermore, (ii) team members know each other personally very well before engaging in remote collaboration. Factors (i) and (ii) have been discussed by Szymanski (2019) as likely means to facilitate remote teamwork. In addition, (iii) there is an engaging online game environment where collaborators meet each other digitally, which could provide a substitute for the experience of face-to-face interactions in the real world.

In this pilot study, a pair of participants (friends) get to play the game Counter Strike in wing-man mode. They play 20 rounds altogether. First, participants play 10 rounds in a remote-collaboration scenario where verbal communication occurs via voice chat through Discord. Then, on another day, 10 rounds are played with participants co-located in the same room, allowing for face-to-face communication. All games are played on the same map ("Inferno") and participants use the same hardware in both settings. During all games, participant faces are filmed with mobile phones positioned at a fixed location in front of each player. Video data is later analysed via the software OpenFace, which extracts "action units" related to different parts of the face, such as eyebrows or corners of the mouth. Thus, facial gestures indicative of emotions can be analysed automatically. In addition, objective game data is captured, such as round length, matches won versus matches lost etc. All in all, this study covers ca. 230 min of gameplay. It yields about 500 min of video material (47 GB), and 208 MB of OpenFace data.

In the data analysis, team synchrony is used as an indicator of successful team-building and good team performance (cf. Szymanski 2019). The study specifically considers emotional synchrony. For each peak of one player on an analysed emotional dimension, such as happiness, the time frame of 1 second is screened in the other player, to assess whether this person also produces an emotional peak on that emotional dimension. Thus, dichotomous results are obtained: Regarding each emotional peak of one player, emotional synchrony is either attributed or not to the other player, depending on whether or not this person produces a corresponding emotional peak in the 1-second-frame of analysis. Overall, the assessment covers emotional dimensions labelled as "happiness" (OpenFace action units 6 + 12), "sadness" (action units 1 + 4 + 15) and "anger" (action units 4 + 5 + 7 + 23).

In terms of findings, it is first of all noteworthy that significantly more emotions get expressed in the face-to-face situation ($p = 0.006$), as Hildebrand et al. (2020c) report. However, more emotional synchrony is found in the remote-collaboration condition ($p = 0.023$), as depicted in Fig. 13.

As an interpretation, emotional expressiveness might generally be greater in face-to-face interactions, allowing for multi-facetted communication. In remote collaboration, people might only express emotions when the subjective sentiment was strong; thus, in well-collaborating teams a lot of synchrony could likely be

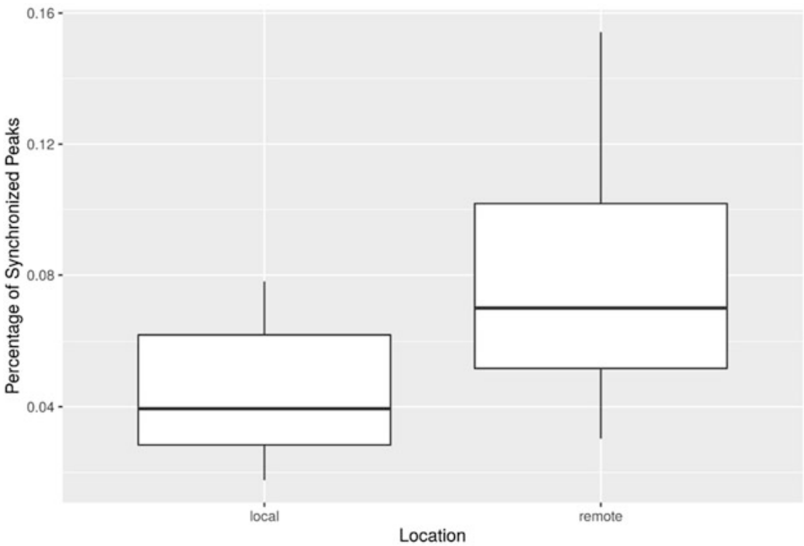


**Fig. 13** More emotional synchrony is found in the remote compared to the co-located setting [image reprinted with permission from Hildebrand et al. (2020c)]

found. This may hold even more when team members pursue a joint goal and react to the same events in their digital environment. Thus, team synchrony in such remote scenarios could be due more to joint immersive experiences and joint goals than reactions to each other.

Overall this study finds quantitative indicators of collaboration working fairly well in remote teams, i.e., teams producing rather high levels of emotional synchrony. This positive finding could be rendered possible in this particular study by context parameters such as (i) team members knowing each other very well prior to remote collaboration, (ii) a captivating joint goal of winning a game together and (iii) an engaging virtual environment where teammates collaborate, substituting for face-to-face meetings in the real world. On the other hand, emotional expressiveness was found to be much reduced in the remote collaboration condition. That means teammates only obtain impoverished information from each other. Possibly information transfer can be optimised for good team performance regarding clearly defined goals. Yet, in many work contexts the rich information content of numerous, emotionally expressive facial gestures might provide benefits that need to be elucidated in further studies.

## 2.12 Healthcare as a Domain of Neurodesign

Neurodesign has been introduced at the HPI as a field at the intersection of (i) neuroscience, (ii) engineering and (iii) design thinking · creativity · collaboration · innovation. In their project, Manisha Manaswini and Maroua Filali rethink what neurodesign can be and what it can do. They emphasise how the field of healthcare has a lot of overlap with neurodesign objectives, even though descriptions of neurodesign have not yet mentioned the keyword "healthcare" explicitly so far.

Why and how is healthcare relevant to neurodesign?

First, neurodesign is concerned with the physiological underpinnings of creativity and collaboration. The dimension of health-to-illness is relevant to people's inclinations and abilities of being creative or collaborative. For instance, neuroscientific research has found that physiological damages at certain brain regions impact people's creativity (Mayseless et al. 2014) and collaboration (Flanagan et al. 1995). Moreover, linkages between mental health and creativity (Maslow 1962; Kaufman 2014) or linkages between mental health and people's ability to engage with others constructively (Widiger 2012; Livesley and Larstone 2018) are long-studied topics.

Second, "neuroscience" must be understood in a broad sense in the realm of neurodesign. It is not only about the brain, it is about the whole body. Many "neurodesign assessments" that have been endeavoured in recent neurodesign projects track body motion, heart rate, facial gestures, electrodermal activity etc. (cf. neurodesign missions and other neurodesign projects). Thus, under the headline of "neuroscience" the community is interested in all body-related data. Information on health versus illness is body-related data, and therefore relevant to include in neurodesign studies.

Third, some novel healthcare solutions are examples of innovative engineering. Ideally, they also have a design thinking focus on human needs, i.e., they are well-designed to deliver exactly what the users need.

Fourth, there can be a fruitful interplay between healthcare solutions and solutions for the analysis and facilitation of creativity or collaboration. This is what the project of Manisha Manaswini and Maroua Filali (2020) sets out to elaborate, based on suggestions for a technology transfer from known healthcare applications to possibly fruitful, novel applications in neuro-design-thinking contexts.

One example is the capturing of sound-levels via microphones that has already been pioneered in health studies (e.g., Goelzer et al. 2001). Design thinking, or creative collaboration more generally, typically involve varying sound levels as well. Microphones can be used to extract only loudness information in a room. Thus, no personal information regarding conversation content or speakers is captured and the data is strictly anonymous. Such loudness information cannot only be used to study impact on health, but also to elucidate the impact on creative or collaborative performance. Research shows that high sound levels in the environment tend to impair concentration and communication, though dynamics seem to be complex (Dalton and Behm 2007; Keller et al. 2017). In design thinking, music is often used to guide the mood of creative teams. Sometimes, music is played rather loudly to prevent discussions—conversations get difficult when the sound level in the room is high—, to encourage instead the use of hands and a bias to action during prototyping. Also apart from music, the open environment of design thinking spaces filled with many actively working teams tend to create high levels of background noise. This is often perceived by design thinking participants as "activating." However, there are also anecdotal reports of people feeling exhausted after "noisy" design thinking days (Meinel et al. 2017). Thus, a better understanding of the role of sound levels on creative performance and recreation needs after active design thinking would seem highly desirable. The same holds for investigations into the impact of different sound-types (e.g., conversations vs. music) on design thinking performance in varying process phases.

In healthcare, motion has been tracked with devices such as the Microsoft Kinect, for purposes such as monitoring the risk of falling in elderly people (Parajuli et al. 2012) or to track respiration (Ernst and Saß 2015). Creativity research indicates a causal impact of posture and body motion on creative performance (Leung et al. 2012; Slepian and Ambady 2012; Oppezzo and Schwartz 2014; Andolfi et al. 2017). Again, a re-use of sensor technology that has been successfully deployed in health studies, now for neuro-design-thinking research purposes, seems highly promising. In addition, communication and collaboration are clearly impacted by the way in which people move, e.g. the gestures they make. Thus, sensor technology to track motion—especially when there is also a potential of recognising gestures—would seem highly serviceable for design thinking creativity and collaboration research: It allows more systematic analyses of how motion relates to creative and collaborative performance. Once clear patterns have been established, feedback could be given to individuals or teams based on motion assessments.

Another area where neurodesign can benefit from technology already deployed in health studies concerns recreation. Sleep is a relevant subject for design thinking research. The role of sleep, relaxation and dreaming for creative performance has long been emphasized in the community (McKim 1972). Experimental evidence underpins the belief that sleep is indeed important for people to perform well on creative tasks (Wimmer et al. 1992; Marguilho et al. 2015). To allow for a contact-less and therefore convenient ways of sleep-tracking, the tool Sleepiz can be suggested. It allows everyone to spend nights without the disturbance of wearables, and yet ample data is generated that permits a grand scale analysis of how sleep and creative performance interrelate. With a clearer understanding of this relationship, advice could also be given adaptively to design thinkers, as to when some rest would likely increase people's prospects of finding good, creative solutions.

These are just some examples of how sensors that have been successfully deployed in healthcare contexts could be re-used to facilitate design thinking—creativity—collaboration research. Readers are invited to think up further, possibly fruitful areas of application. All in all, the field of healthcare has many resources to offer that can be highly pertinent for the emerging field of neurodesign.

### *2.13 Neurogaze: Exploring the Potential of Eye Tracking in Digital Engineering*

The standard way to interact with computers—by mouse clicks—was invented more than half a century ago. This traditional solution is currently being reconsidered. Might there be other or additional ways to interact with computers that would seem highly fruitful? Computers or other digital solutions might react to human emotions. What if people could direct computers with the power of thought, i.e., by means of recorded brain activities? Moreover, heart rate data or other physiological parameters could provide relevant input for digital applications. The present study by Philipp Bode and Christian Warmuth (2020) explores yet another sensor-based approach for novel solutions in human-computer-interaction: eye tracking.

The human eyes have long been considered a "window into the mind." Both historically and recently, interest in the eye and gaze tracking is great, so that sophisticated theoretical understandings have already been achieved in this field (Radach et al. 2003). Eye tracking has been discovered as a field of great potential—but also as a field of some technical challenges—by scholars of human-computer interaction and usability studies (Jacob and Karn 2003; Poole and Ball 2006; Majaranta and Bulling 2014; Zhang et al. 2017).

In their project, Philipp Bode and Christian Warmuth (2020) take a close look at this promising field of research and make three major contributions. (1) They have developed the tool "Neurogaze," which supports the assessment and interpretation of eye tracking data. (2) They have conducted pilot studies on the use of eye tracking in varying application contexts. (3) They sketch out a research agenda regarding the use of eye tracking to determine the "cognitive load" in a user, so as to facilitate the design of adaptive systems.

In their project, Christian and Philipp work with the Tobii Pro Nano Hardware Package. This technical equipment supports eye tracking in one person at a stationary position; it is designed to record eye activities of a user who looks at a computer screen. The sampling rate of this device is 60 Hz, thus it yields 60 data points per second. As a professional eye tracking device, it produces highly reliable and valid eye tracking raw data.

To complement the sensor hardware, Christian and Philipp have programmed a python-based tool, *Neurogaze,* that supports the gathering and interpretation of eye tracking raw data. The tool has two major parts.

First, there is the *Application Tracker*. It documents over time which application is open (e.g., Firefox), which Tab is open (e.g., Google search), click-events in each window, how windows are positioned on the screen etc. Thus, eye tracking data can later be used to indicate where a person was looking at a certain time, e.g. on a particular website. Since eye tracking hardware delivers many data points per second, large amounts of data accumulate quickly. Thus, in the software design care has been taken to enable efficient data storage, by using binary representations to reduce storage overhead.

Second, the *Gaze Tracker* stores information provided by the eye tracking device. It collects 3-dimensional information of how the eyes are positioned in front of the sensor bar. Thus, one can tell, for instance, how far a person sits away from the screen and how she moves over time. In addition, the Gaze Tracker collects information about pupil diameters and about x-y coordinates of gaze on the screen (i.e. where the person is looking from moment to moment). Moreover, the Gaze Tracker supports an accumulated display of gaze points for a chosen time frame. Thus, when the user looks at a horizontal chat-input-bar for one minute and rarely looks elsewhere, the display of accumulated gaze points in the one-minute-timeframe shows large numbers of data points forming a horizontal "bar" exactly at the position where the chat input occurs on the screen.

Neurogaze is available at: https://github.com/christianwarmuth/neurogaze.

In pilot studies, Christian and Philipp recorded their own eye activities in front of their computers over a couple of days, using the Tobii Pro Nano and Neurogaze. With this pilot data, several interesting applications can be pursued. First, by accumulating gaze point data over longer times, "activity profiles" can be displayed regarding applications of interest. Thus, it can become obvious how a user is strongly focused on a "message input bar" in a program, how the person occasionally reads messages from others that appear at a certain location on the screen, and otherwise disregards large portions of the window (Fig. 14).

A second interesting analysis is to consider gaze motion across the x-y coordinates on the screen separately. For instance, it can be tracked how gaze moves between left versus right on the screen, by analysing gaze data on x-coordinates only. Plotting this data yields a characteristic graph, e.g., when the person is reading. During that activity, her gaze moves regularly between left versus right (Fig. 15). By analysing derivations of this curve, velocity and acceleration data can be obtained.

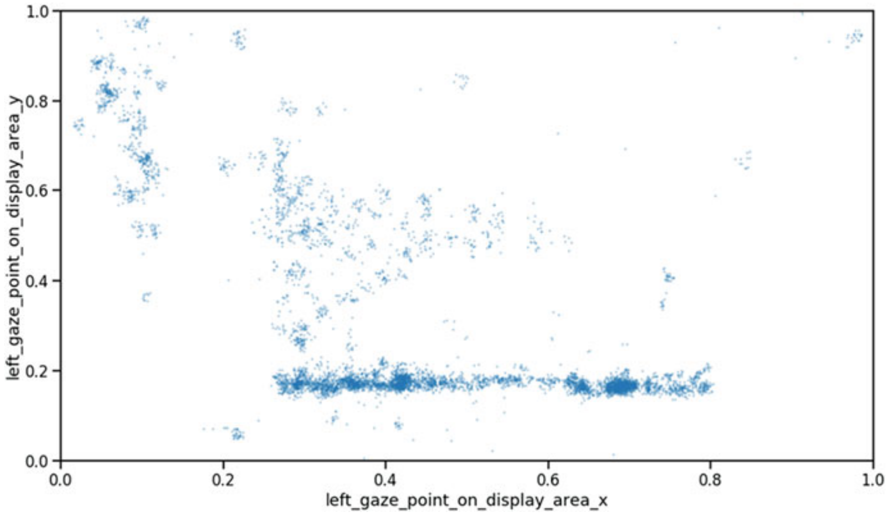


**Fig. 14** Accumulated gaze points on the x-y coordinates of the screen indicate that the person has mostly looked at the message input bar in the application of interest [image reprinted with permission from Bode and Warmuth (2020)]

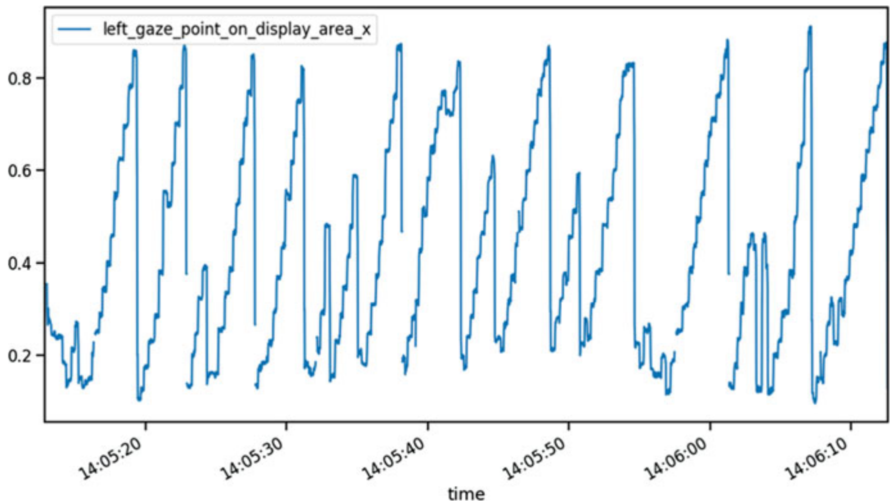


**Fig. 15** Eye motion during reading: Plotting gaze-motion on the x-dimension of the screen yields a characteristic pattern in the case of reading [image reprinted with permission from Bode and Warmuth (2020)]

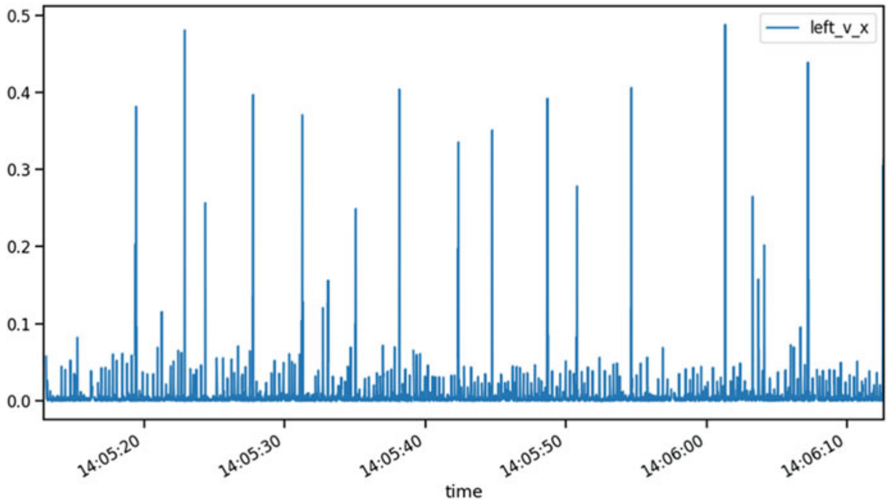


**Fig. 16** Eye motion during reading: Derivations of the graph in Fig. 15 yield a graph depicting gaze motion velocity that can be used for activity classification [image reprinted with permission from Bode and Warmuth (2020)]

These provide a good basis for activity classification. For instance, in reading there is usually a relatively low level of gaze motion velocity as it takes people time to read bit by bit until the end of a line. Yet, at regularly occurring intervals, gaze motion speeds up drastically as the gaze shifts rapidly towards the beginning of a new line (Fig. 16). This pattern is significantly different from eye-motion during other activities, such as programming or drawing.

Another interesting application is to look at moments in time where the eye tracking sensor does not record data. Losses of signal for a duration of roughly 100–400 ms most likely indicate eye blinks of the user. Analysing their own data, the authors find a clear pattern in their eye activities, with thus determined eye-blinks: Over the course of a workday the number of eye blinks increases significantly. This may reflect increasing tiredness of the eyes, increasing tiredness of the person, or both.

Based on adaptive threshold values (Dar et al. 2020), Christian and Philipp also classify eye activities. They distinguish between fixation (steady gaze on a point), pursuit (such as following a moving object or reading a line) and saccades (the rapid change of gaze points).

Third, Christian and Philipp envision a research agenda for the use of eye tracking to determine cognitive load and thus support the development of adaptive systems. “Cognitive load” is a concept known to the public especially in the variant of “cognitive overload,” meaning a situation where the awake person cannot process novel information productively any more. In science, Cognitive Load Theory

(Sweller 2011) explores phenomena regarding human processing abilities based on characteristics of the human biological information processing "architecture."

Cognitive load is a relevant topic for system design. Ideally, systems deliver information to the user in such a way that he or she can easily process the content. If for instance a car driver is experiencing cognitive overload, this situation can pose serious risks for the safety of the driver and others. A well-designed adaptive system might help to reduce the driver's cognitive load by down-regulating information complexity; moreover, safety-relevant information may have to be emphasized for the driver.

As Christian and Philipp submit, eye tracking could potentially provide reliable and valid indicators of cognitive load. One possible indicator they suggest for further study is the rate of eye blinks. In their pilot studies, they had found increased rates of eye blinking in the afternoons compared to morning hours; this might correlate to people approaching levels of cognitive overload in the afternoon while people enjoy fully available processing capacities in morning hours (after recreative sleep). A second eye tracking parameter that could indicate cognitive load might be microsaccades, as already suggested by Krejtz et al. (2018).

To elucidate the psychometric properties of eye blink rates and microsaccades as measures of cognitive load, Christian and Philipp suggest a repeated-measures-study according to the "n-back" paradigm (described and applied in Bedford et al. 2009). Here, participants are presented with digits one after another and need to recall elements that came earlier. For instance, participants can be presented—one after the other—the following digits: P, X, T, S, with "S" being the most recent stimulus. Asked about previous digits, it is relatively easy for participants to move one step backward and report on the stimulus right before the present one (T). Cognitive load increases as participants are asked to move further steps backward, e.g. to report on the digit that came three steps before the present stimulus (P). In the data analysis, both the reliability and validity of eye blink rates and microsaccades as indicators of cognitive load ("numbers of steps backward") can be explored.

## 3 Neurodesign Missions

As a third resource, we share missions and aims that have guided the development of neurodesign at the HPI in the first implementation phase. As results have been found fruitful, these goals will continue to inform developments of the curriculum and related research programmes.

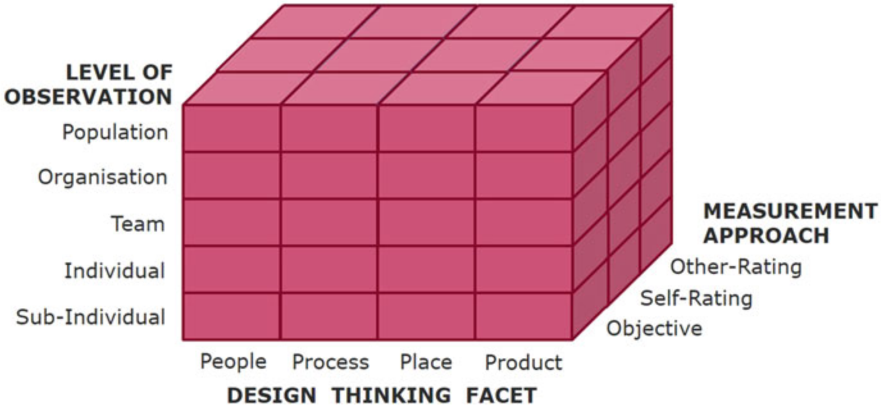


**Fig. 17** Design thinking—creativity—innovation research explores multiple facets in a complex realm of phenomena. Research tends to focus on fragments and puzzle pieces. For an understanding of creativity and innovation at large, knowledge sharing and holistic views are important as well [graphic inspired by Batey (2012)]

## 3.1 Understanding Innovation Beyond Fragmentation

Innovation is a basic phenomenon of culture development—in humans and potentially also in other species. Studies into this ubiquitous phenomenon necessarily take place on multiple levels of observation, from macro- to micro-levels (Fig. 17).

In design thinking innovation research, different facets of the phenomenon have been elucidated in detail. Studies have addressed characteristics of creative people, creative processes, the impact of places, creative products, and other topics.

Obviously, innovation studies also benefit from a great variety of research methodologies. These methods include objective assessments (such as performance metrics in the assessment of products, or EEG-recordings in human research), self-ratings (e.g., people finding their own work outcome more versus less creative) and other-ratings (for instance, experts judging the originality of participants' test responses).

Innovation researchers develop deep expertise by concentrating on some pieces of the overall puzzle. This fragmentation is a helpful and maybe necessary manoeuvre to advance sophistication in specific directions. Yet, to understand innovation as a whole, it is important to move beyond fragmentation.

## 3.2 Professional Bridges Between Theory and Practice

Much research on the biological basis of creativity and collaboration is conducted in neuroscientific labs, far away from the studios where creativity, collaboration

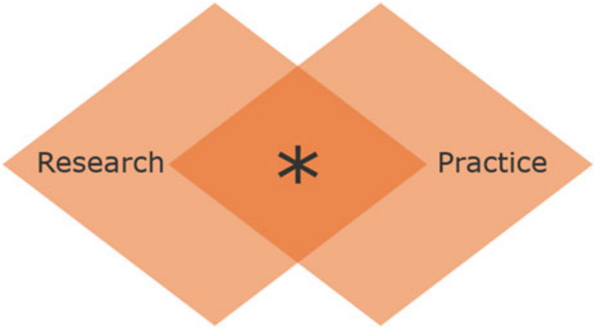


**Fig. 18** Neurodesign seeks to bring research and practice closer to one another, by facilitating personal exchange among experts of both, and by facilitating joint projects

and innovation are taught and realized on a daily basis. The gap between research and practice is often so severe that only popular-writing authors with limited pre-experiences in at least one of the domains endeavour publications that span both fields. We believe that regular exchange between research and practice is important for the prosperity of both. Ideally, this exchange is a priority shared by leading experts from both sides and is promoted at high levels of professionalism. We believe this exchange between research and practice can happen best in teams or larger groups, where members of varying backgrounds make joint experiences and collaborate (Fig. 18).

### 3.3 Inspiration from Nature for Digital Engineering

Gaps between the analogue versus the digital—or the natural versus the artificial—are often large. For instance, living creatures including humans naturally spend their days moving about, engaged in manifold physical activities. By contrast, today for many persons around the globe digitally organised work enforces relatively static body positions over multiple hours per day, such as sitting in front of a computer with limited motion opportunities. *How might digital engineering solutions of the future facilitate natural human behaviours rather than imposing non-natural behaviours onto people?*

Humans naturally possess many senses and use them to navigate the world, such as the senses of vision, hearing, smell, touch, taste, of body position, temperature and so forth. Present-day digital solutions commonly address very few of the human senses. Information is usually provided visually on a computer screen, commands are typically entered through the banal motion act of pressing buttons.

In our digital age, many people need "mindfulness trainings" where they learn by means of time-intensive training how to better attend to the full set of human senses, including smell, touch, body position etc., in order to achieve psychological wellbeing. By contrast, in many hours of human-to-computer or human-to-screen interaction per day, humans learn the opposite: how to disregard and not use these senses. Indeed, senses of smell, body position etc. would ground people in the here-and-now of their physical environment—often a context that is very different from things going on at a screen (where people indulge in work objectives, game or film scenarios). Digital solutions that lead people to unlearn the natural use of their full set of senses are unhealthy; they call for a re-design.

*How might digital engineering solutions of the future help people use and enjoy all of their senses?*

Human-to-human communication is highly multifaceted and takes place on many levels. There is exchange by means of language and tone. Much information is conveyed visually and sometimes audibly by means of gestures, postures and motion. People touch each other. There is also the huge domain of communicating by action: doing something that conveys intentionality—revealing what the person is trying to do; making physical arrangements in space, such as creating physical prototypes; doing something meaningful, or doing something unintentionally that still conveys important information about the acting person. Given this richness in human-to-human communication, it is surprising how limited communication channels are in human-to-machine interactions. For instance, the programming of a digital engineering solution is usually language based, and barely any representation system other than language can be used. *How might the programming of machines take place in different representation systems, beyond language? How might the greatest possible variety of representation systems be used in human-to-machine interactions?*

Also, human-to-human interactions are characterised by role-flexibility. Even a simple conversation often means to have changing leads and initiatives in a single minute, such as person A making a contribution and then person B making another independent, sensible contribution. When humans program digital engineering solutions, the roles of a human versus the machine tend to be static. *How might we enable humans and machines to flexibly adapt their roles during interactions?*

In general, living organisms are an effervescent source of inspiration for artificial designs. Nature has created solutions that are fascinating and highly effective in many different regards. *In which ways do we want artificial solutions to become better? What examples from nature could inspire novel and more effective technical solutions?*

### *3.4 More Digital Engineering in Neuroscience*

We want to leverage more digital engineering expertise in the field of neuroscience. This aim is based on observations about traditional career paths in neuroscience. Many neuroscientists are originally trained in fields such as psychology, medicine or biology, some also in physics. Yet, the day-to-day tasks of neuroscientists are to a large extent digital engineering tasks, such as data processing, data modelling or data visualisation. Furthermore, new research designs that take neuroscientific experiments outside of the lab to study human behaviour in a "natural" environment are often requested. However, these settings typically require different and new technological solutions and analysis procedures, compared to traditional lab-based approaches. Therefore, we believe that the creativity and expertise of digital engineers is very fruitful when brought to play in the field of neuroscience on a much larger scale.

### 3.5 An "Embodied Cognition Perspective"

Design thinking has a long tradition of attending the whole body, both in research and practice, to promote good design and radical innovation. The approach builds on concepts such as visual thinking, which elucidates the role of the senses in creative design, and ambidextrous thinking, which emphasizes the importance of bilateral body engagement for creativity and innovation. In more recent terminology, neurodesign invokes an "embodied cognition" perspective on creativity and collaboration. With this outlook, it helps to underpin design thinking in two major respects. First, neurodesign embeds prevailing design thinking interventions like bodystorming in theoretical frameworks. Thus, it enables innovation practitioners to make use of such techniques in more goal-directed, efficient ways. Secondly, neurodesign guides the development of novel interventions based on concepts of embodied cognition. Altogether, we encourage physiological research beyond the brain. Also in creative design practice, we track and facilitate full-body engagement.

### 3.6 Novel Career Models for Neuroscientists

We want to create novel job opportunities for neuroscientists and support a greater variety of life models in the field. This concern is based on observations about career choices that many well-trained neuroscientists need to make during or after their PhD. To progress on the academic career path, neuroscientists are often expected to be equally active in fields such as study planning, data acquisition, data processing etc., leading to a weekly workload considerably beyond 40 h with little flexibility to adapt life models on demand. Also, work beyond academic research—even when concerned with the same phenomenon otherwise studied in the lab—is rarely appreciated; it rather tends to impact people's career prospects negatively. While for example in clinical neuroscience the exchange between lab research (e.g., on depression) and application (e.g., clinical depression treatment) is lively and well-integrated into many research programs, this is rarely the case in social neuroscience. Here, neuroscientists that research phenomena such as collaboration, creativity or social (team) interaction are expected to dedicate all their time to lab research and their career development is based on scientific publications only. In neurodesign we decidedly promote both: exchange between researchers and practitioners, as well as giving individuals the career option to distribute their time between neuroscientific research and applied work in their domain of expertise.

### *3.7 Merging Science, Engineering, Philosophy and Art*

Ever since its earliest beginnings, design thinking has a strong tradition of merging science, engineering, philosophy and art. This is evident both in terms of collaborations across disciplines and in terms of people's individual biographies. When John E. Arnold lay important groundworks for design thinking at Stanford University, he did so in close collaboration with guest experts who personally came to lecture in the courses; these guest experts had varying academic backgrounds covering science, engineering, philosophy and art. Moreover, in terms of personal biographies, many design thinking protagonists unite two or more disciplines in deep ways. John Arnold was a social scientist and engineer. Buckminster Fuller and Robert H. McKim as two other protagonists who shaped the emerging concept of design thinking in early days both drew from engineering and art alike, with regard to their public works and personal lives. Beyond that, institutional co-operations reflect the bold intention of merging disciplines. Notably, the Joint Program in Design at Stanford University was offered collectively by the Mechanical Engineering Department and the Art Department. Neurodesign continues in this legacy. We wish to include experts from all fields in the neurodesign curriculum, who address creativity, collaboration and innovation from varying academic perspectives. Moreover, we encourage students to work across the borders of traditional disciplines. This can happen either in interdisciplinary teams or also in single-person work. Participants in neurodesign courses are invited to invoke artistic freedom, and to include artistic aspirations, in the creation of innovative engineering solutions for neuroscience and beyond.

## 4 Outlook

Based on stirring experiences in the first semester of neurodesign education at the HPI, it is clear that this area of research, teaching and practice is extraordinarily fruitful and shall be further advanced. The next step is to establish a more comprehensive curriculum at the HPI, which covers neurodesign-relevant topics in an increasingly systematic way.

The format of seminars has been found highly practical to convey relevant methodological knowledge. It also yields sufficient creative freedom for student teams to think up innovative project ideas and iterate towards amazing solutions.

A greater number of different seminars shall be developed in the near future to provide even more in-depth knowledge regarding methodological topics and the devising of scientific publications. Here, the curriculum shall become increasingly well-orchestrated with courses developed by colleagues at the institute. As a notable example, Falk Übernickel (holding the chair of design thinking and innovation research at the HPI) offers courses on social science research methodology and scientific writing skills for PhD students, which can inspire much fruitful exchange.

Another area where further explorations shall be endeavoured concerns ultra-feasibly methods for the assessment of body data. Already in the last semester, the repertoire of tools increased rapidly. At first, parameters such as skin conductance, heart rate and arm motion were measured with Empatica E4 wristbands, automated emotion-analyses were conducted based on webcam-recordings, and the Kinect was used to analyse body-motion. Soon the available equipment came to include four different technical solutions for EEG assessments, eye-tracking technology and various further body sensors. This repertoire shall be further extended and opportunities as well as limitations of such ultra-feasible methods shall be explored in further detail.

In the upcoming teaching term, the seminar Ambidextrous Thinking (2020) at the HPI will provide an opportunity for students to acquire or deepen knowledge in theoretical, methodological and technological neurodesign domains. The course is partially an iteration and partially a continuation of the Neurodesign Seminar (2019/20). In subsequent teaching terms, a larger number of seminars might be offered at the HPI to allow for more in-depth probing regarding specific topics of interest.

One specific area where selective seminars can be expected in the near future concerns data sonification. Marisol Jiménez joins the neurodesign teaching staff at the HPI for upcoming courses. She completed her Doctor of Musical Arts at Stanford University in 2011, where Chris Chafe was one of her teachers. Marisol's works include composing numerous electroacoustic music works, sound and mixed media installations as well as the prototyping of instruments that permit experiments with the tactile process of creating sound—possibly a new field for human-machine interaction. Marisol will co-teach in upcoming HPI courses of the summer semester 2020 and might subsequently offer unique ambidextrous sonification seminars.

Further in-depth courses regarding neuroscientific topics shall be developed. Here, more intense collaborations with the Psychology Department of Potsdam University, specifically the master program "Cognitive Science—Embodied Cognition," can be a fruitful avenue for further advancements of the curriculum.

Beyond the seminar, the format of a lecture series with guest expert talks has been found highly effective to collocate up-to-date knowledge regarding various work domains relevant to neurodesign. In such a lecture series, students hear about specific topics from those experts who have been researching the particular field intensely over many years, so that best-informed overviews are provided and the latest state of knowledge is conveyed.

In the past semester, by means of invited guest experts, great emphasis was placed on the neuroscience of creativity and collaboration in human research. While these topics are certainly central for neurodesign, they are not at all exhaustive. In subsequent years, lecture series might be hosted to advance the neurodesign cross-disciplinary knowledge base in further directions. For instance, there could be a neurodesign lecture series that is more directed towards digital engineering than neuroscience. Another lecture series might be dedicated to comparative creativity and innovation studies across species; possibly, it could also cover “artificial species” such as particular digital engineering systems. Moreover, the expanding HPI advances novel work domains such as Digital Energy, which can also inspire courses. The energy efficiency of the human brain was already discussed in some neurodesign inputs (Agnoli 2019; Plank 2019). It could be an interesting comparative topic for further classes, where topics such as the following might be explored: (i) Roughly, human brains work in a low-energy mode when the person utilizes status quo knowledge. By contrast, learning something new and changing one’s cognitive system as required for radical innovation is energy-intensive. (ii) Political and bureaucratic systems regulate levels of continuity versus change in states partially by regulating energy-demands of different endeavours. Most commonly, states facilitate continuity with the past, while making change difficult: Inhabitants or organizations need to invest much more energy to obtain permissions for endeavouring change than to obtain permissions for leaving things as they are. E.g. inhabitants don’t need to dedicate energy to bureaucratic activities in order to leave their houses as they are; however trying to build a new house can be a very energy-demanding undertaking measured by the bureaucracy people need to manage. (iii) There is a multiplicity of digital engineering solutions designed to be energy-efficient. These can be compared to energy-efficient solutions in the field of biology. Overall, somewhat varying core topics can be addressed in upcoming neurodesign lectures from year to year, where ideally experts from varying backgrounds contribute up-to-date knowledge in each semester.

Beyond such a collocation of expertise from different disciplines and institutions by means of guest expert talks, there is also the objective of systematically amending in-house knowledge concerning the theoretical basis of design thinking. In previous years, empirical studies and theories on why and how design thinking works have been conveyed in the lecture Design Thinking for Digital Engineering. So far, this course was mostly concerned with research findings engendered with social-science methods, such as psychological experiments or survey studies. Clearly, this knowledge stock needs to be amended with insights regarding the physiological basis of design thinking phenomena. This is endeavoured in the upcoming semester in a lecture now called (Neuro-) Design Thinking for Digital Engineering.

Finally, neurodesign thrives as a cross-disciplinary and cross-institutional initiative. It draws its power from mutual curiosity and passionate collaboration. We do our best to facilitate further fruitful developments beyond single locations. Institutions that wish to build up neurodesign themselves are more than welcome to get in touch and we will support initiatives as we can. We also very much appreciate personal exchange, such as persons coming from one institution to spend some time at another. In addition, on the neurodesign homepage we publish project calls, where experts from either domain—(i) neuroscience, (ii) engineering or (iii) design thinking · creativity · collaboration · innovation—can invite projects at the intersection of fields. These can be endeavoured in the form of bachelor, master or PhD projects. Also students with expertise in one or more of the fields are strongly encouraged to unfold their full creativity and explore what they can render possible in the novel realm of neurodesign.

## References


Adnan, H. S., Real, S., & Rahman, S. S. (2020, Sept. 14–16). Measuring creative Flow in real-time with consumer-grade EEG and deep learning networks [symposium session]. 4th MIC Conference. Bologna, Italy.

Agnoli, S. (2019). *Attentional mechanisms in the creative thinking process: Insights from psychophysiology*. Talk in the Neurodesign Lecture: Physiological perspectives on engineering design, creativity, collaboration and innovation. Retrieved from https://www.tele-task.de/lecture/video/7830/

Anderson, J., & Parmenter, J. (2012). *3D sound with the Ambisonic Toolkit*. Presented at the Audio Engineering Society 25th UK Conference, 4th International Symposium on Ambisonics and Spherical Acoustics, York.

Andolfi, V. R., di Nuzzo, C., & Antonietti, A. (2017). Opening the mind through the body: The effects of posture on creative processes. *Thinking Skills and Creativity, 24*, 20–28.

Baier, G., Hermann, T., & Stephani, U. (2007, June 26–29). Multi-channel sonification of human EEG. In *Proceedings of the 13th International Conference on Auditory Display*, Montréal.

Batey, M. (2012). The measurement of creativity: From definitional consensus to the introduction of a new heuristic framework. *Creativity Research Journal, 24*(1), 55–65.

Bedford, A., Cosic, I., & Valladares, L. (2009). Effects of caffeine on cognitive tasks. *Proceedings of the Annual Meeting of the Cognitive Science Society, 31*(31), 1563–1568.

Berkley Center for New Media. (2020). *GNOSISONG: An audiovisual installation by Chris Chafe and Greg Niemeyer*. Retrieved from http://bcnm.berkeley.edu/news-research/1716/gnosisong-an-audiovisual-installation-by-chris-chafe-and-greg-niemeyer

Bitkom. (2020). *Vier von zehn Unternehmen setzen auf Homeoffice*. Retrieved from https://www.bitkom.org/Presse/Presseinformation/Vier-von-zehn-Unternehmen-setzen-auf-Homeoffice

Bode, P., & Warmuth, C. (2020). *Eyetracking research*. Presentation in the neurodesign seminar, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8020/#t=2118

Bovermann, T., Rohrhuber, J., & de Campo, A. (2011). Laboratory methods for experimental sonification. In T. Hermann, A. Hunt, & J. G. Neuhoff (Eds.), *The sonification handbook* (pp. 237–272). Berlin: Logos Publishing House.

Bredow, T., & Metzenthin, E. (2019). *Predicting team performance using Machine Learning on EEG data*. Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7918/#t=1219

Bredow, T., & Metzenthin, E. (2020). *Deep Learning on EEG data*. Final presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8016/#t=2504

Chapman, S. B., Spence, J. S., Aslan, S., & Keebler, M. W. (2017). Enhancing innovation and underlying neural mechanisms via cognitive training in healthy older adults. *Frontiers in Aging Neuroscience, 9*, 314.

Clancey, W. J. (Ed.). (2016). *Creative engineering: Promoting innovation by thinking differently*—by John E. Arnold. Stanford Digital Repository. http://purl.stanford.edu/jb100vs5745

Clancey, W. J. (2019, March 6). *Cognition and design: A developmental perspective*. Talk at the Stanford Neurodesign Symposium, Stanford.

Csikszentmihalyi, M. (1975). *Beyond boredom and anxiety*. San Francisco: Jossey-Bass.

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. New York: Harper & Row.

Dalton, B. H., & Behm, D. G. (2007). Effects of noise and music on human and task performance: A systematic review. *Occupational Ergonomics, 7*(3), 143–152.
Danz, N. (2019). *Realtime EEG sonification with the BITalino platform*. Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7918/#t=1541
Danz, N. (2020). *Realtime EEG sonification with the BITalino platform*. Final presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8016/#t=1837
Dar, A. H., Wagner, A. S., & Hanke, M. (2020). REMoDNaV: Robust eye movement detection for natural viewing. *BioRxiv*, 619254. https://doi.org/10.1101/619254.
Ernst, F., & Saß, P. (2015). Respiratory motion tracking using Microsoft's Kinect v2 camera. *Current Directions in Biomedical Engineering, 1*(1), 192–195.
Fisher, R. A. (1925). *Statistical methods for research workers*. Edinburgh: Oliver & Boyd.
Flanagan, S., McDonald, S., & Togher, L. (1995). Evaluating social skills following traumatic brain injury: The BRISS as a clinical tool. *Brain Injury, 9*(4), 321–338.
Fletcher, T. D., & Major, D. A. (2006). The effects of communication modality on performance and self-ratings of teamwork components. *Journal of Computer-Mediated Communication, 11*(2), 557–576.
Gnosisong Org. (2020). *Gnosisong*. Retrieved from http://www.gnosisong.org/
Goelzer, B., Hansen, C. H., & Sehrndt, G. (2001). *Occupational exposure to noise: Evaluation, prevention and control*. Geneva: World Health Organisation.
Gramfort, A., Luessi, M., Larson, E., Engemann, D., Strohmeier, D., Brodbeck, C., Goj, R., Jas, M., Brooks, T., Parkkonen, L., & Hämäläinen, M. (2013a). MEG and EEG data analysis with MNE-python. *Frontiers in Neuroscience, 7*. https://doi.org/10.3389/fnins.2013.00267.
Gramfort, A., Luessi, M., Larson, E., Engemann, D., Strohmeier, D., Brodbeck, C., Goj, R., Jas, M., Brooks, T., Parkkonen, L., & Hämäläinen, M. (2013b). MNE software for processing MEG and EEG data. *Neuroimage, 86*, 446–460. https://doi.org/10.1016/j.neuroimage.2013.10.027.
Hildebrand, J., Borchart, K., & Rätz, H. (2019). *Influence of mode of communication on collaboration in online video games.* Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7918/#t=2049
Hildebrand, J., Borchart, K., & Rätz, H. (2020a). *Influence of mode of communication on team synchrony in online video games.* Final presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8016/#t=4170
Hildebrand, J., Borchart, K., & Rätz, H. (2020b). *Influence of mode of communication on team synchrony in online video games.* Presentation in the neurodesign seminar, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8020/#t=0
Hildebrand, J., Borchart, K., & Rätz, H. (2020c). *Influence of remote vs. face-to-face communication on team synchrony in online video games*. Project Poster. HPI, Potsdam.
HPI (Organizing Institution). (2017, Sept 15). *Neurobiology and design thinking*. Discussion panel at the d.confestival with Sergio Agnoli, Stefanie Faye Frank, Manish Saggar and Caroline Szymanski, organized and moderated by Julia von Thienen, Potsdam. Recording retrieved from https://www.tele-task.de/lecture/video/6388
HPI (Organizing Institution). (2018, Sept 10). *Neuroscience and physiological perspectives on design thinking and creativity*. Symposium organized by Julia von Thienen, chaired by Allan Reiss, with contributions from Julia von Thienen, Naama Mayseless, Serena Mastria, Caroline Szymanski, Manish Saggar and Stefanie Faye Frank, Potsdam. Recording retrieved from https://www.tele-task.de/series/1219/
Ihde, N., Rosenbaum, J., Michaelis, M., Blaß, K., Papsdorf, F., Weidenfeller, P., Zerndt, A., AlAbbud, A. & Fregien, F. (2020). *Neurodesign Tests*. Final presentation in the class Web Programming and Web Frameworks, HPI, Potsdam. Retrieved from: https://www.tele-task.de/lecture/video/8016/
Jacob, R. J., & Karn, K. S. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. In R. Radach, J. Hyona, & H. Deubel (Eds.),

*The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 573–605). Amsterdam: Elsevier.

Kaufman, J. C. (Ed.). (2014). *Creativity and mental illness*. Cambridge: University Press.

Keller, S., Tschan, F., Semmer, N. K., Candinas, D., & Beldi, G. (2017, June 18–22). Effects of noise on communication and concentration during surgeries: the moderating role of experience and task. In *Conference proceeding of the 12th ICBEN Congress on Noise as a Public Health Problem*, Zürich.

Krejtz, K., Duchowski, A. T., Niedzielska, A., Biele, C., & Krejtz, I. (2018). Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. *PLoS One, 13*(9), e0203629.

Leung, A. K.-Y., Kim, S., Polman, E., Ong, L. S., Qiu, L., Goncalo, J. A., et al. (2012). Embodied metaphors and creative acts. *Psychological Science, 23*, 502–509.

Livesley, W. J., & Larstone, R. (Eds.). (2018). *Handbook of personality disorders: Theory, research, and treatment*. New York: Guilford.

Majaranta, P., & Bulling, A. (2014). Eye tracking and eye-based human–computer interaction. In S. H. Fairclough & K. Gilleade (Eds.), *Advances in physiological computing* (pp. 39–65). London: Springer.

Manaswini, M., & Filali, M. (2020). *Healthcare as a domain of neurodesign.* Project Poster. HPI, Potsdam.

Marguilho, R., Neves de Jesus, S., Viseu, J., Domingues, R. B., Brandolim Becker, N., Dias Matavelli, R., Quevedo, R., & Buela-Casal, G. (2015). Sleep and creativity: A literature review. In M. Milcu, M. Gaspar de Matos, & I. P. Vasilescu (Eds.), *Advanced research in health, education and social sciences: Towards a better practice* (pp. 131–140). Editura Universitară.

Maslow, A. H. (1962). Creativity in self-actualizing people. In A. H. Maslow (Ed.), *Toward a psychology of being* (pp. 127–137). Princeton: Van Nostrand.

Mayseless, N., Aharon-Peretz, J., & Shamay-Tsoory, S. (2014). Unleashing creativity: The role of left temporoparietal regions in evaluating and inhibiting the generation of creative ideas. *Neuropsychologia, 64*, 157–168.

McKee, H., Grzelka, F., & Seidel, L. (2019). *NeuroCreate—Achieving peak performance*. Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7918/#t=0

McKee, H., Grzelka, F., Glöckner, P., Seidel, L., Rahman, S, von Thienen, J., & Meinel, C. (2020a, Sept. 14–16). Measuring creative flow in real-time using consumer-grade EEG coupled with a neural network. Presentation at the 4th MIC Conference. Bologna, Italy.

McKee, H., Grzelka, F., Glöckner, P., & Seidel, L. (2020b). *NeuroCreate—Achieving peak performance*. Final presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7999/#t=1674

McKee, H., Grzelka, F., Glöckner, P., & Seidel, L. (2020c). *NeuroCreate—Achieving peak performance*. Presentation in the neurodesign seminar, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8020/#t=4265

McKim, R. H. (1972). *Experiences in visual thinking*. Belmont, CA: Wadsworth.

Meinel, C., Weinberg, U., & Krohn, T. (Eds.). (2017). *Design thinking live. 30 perspectives on making innovation happen*. Hamburg: Murmann.

Miranda, E. R. (2006). Brain-Computer music interface for composition and performance. *International Journal on Disability and Human Development, 5*(2), 119–126.

Oppezzo, M., & Schwartz, D. L. (2014). Give your ideas some legs: The positive effect of walking on creative thinking. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1142–1152.

Papke, L., Terboven, C., Trenz, P., & Witzke, S. (2019). *Brainwave sonification toolbox*. Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7918/#t=561

Papke, L., Terboven, C., Trenz, P., & Witzke, S. (2020a). *Brainwave sonification toolbox*. Final presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/7999/#t=0

Papke, L., Terboven, C., Trenz, P., & Witzke, S. (2020b). *Brainwave sonification toolbox*. Presentation in the neurodesign seminar, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8020/#t=1211

Parajuli, M., Tran, D., Ma, W., & Sharma, D. (2012). *Senior health monitoring using Kinect*. In 2012 Fourth International Conference on Communications and Electronics (ICCE) (pp. 309–312). IEEE.

Parvizi, J., Gururangan, K., Razavi, B., & Chafe, C. (2018). Detecting silent seizures by their sound. *Epilepsia, 59*, 877–884.

Plank, I. S. (2019). *Analysis of EEG and fMRI with SPM*. Talk in the Neurodesign Seminar: Physiological perspectives on engineering design, creativity, collaboration and innovation.

Poole, A., & Ball, L. J. (2006). Eye tracking in HCI and usability research. In *Encyclopedia of human computer interaction* (pp. 211–219). IGI Global.

Radach, R., Hyona, J., & Deubel, H. (Eds.). (2003). *The mind's eye: Cognitive and applied aspects of eye movement research*. Amsterdam: Elsevier.

Real, S., & Adnan, S. (2020). *Comparing deep learning models for EEG data*. Midterm presentation in the neurodesign lecture, HPI, Potsdam. Retrieved from https://www.tele-task.de/lecture/video/8016/#t=3525

Roginska, A. (2018). Binaural audio through headphones. In A. Roginska & P. Geluso (Eds.), *Immersive sound: The art and science of binaural and multi-channel audio* (pp. 88–123). New York: Routledge.

Saggar, M., Quintin, E.-M., Bott, N. T., Kienitz, E., Chien, Y.-H., Hong, D. W.-C., Liu, N., Royalty, A., Hawthorne, G., & Reiss, A. L. (2016). Changes in brain activation associated with spontaneous improvisation and figural creativity after design-thinking-based training: A longitudinal fMRI study. *Cerebral Cortex, 27*(7), 3542–3552.

Slepian, M. L., & Ambady, N. (2012). Fluid movement and creativity. *Journal of Experimental Psychology: General, 141*, 625–629.

Stern, R. M., Brown, G. J., & Wang, D. (2006). Binaural sound localization. In D. Wang & G. J. Brown (Eds.), *Computational auditory scene analysis: Principles, algorithms and applications* (pp. 147–185). Hoboken: Wiley.

Sweller, J. (Ed.). (2011). *Cognitive load theory*. New York: Springer.

Szymanski, C. (2019). *Neural team dynamics*. Talk in the Neurodesign Lecture: Physiological perspectives on engineering design, creativity, collaboration and innovation. Retrieved from https://www.tele-task.de/lecture/video/7952/

Szymanski, C., Pesquita, A., Brennan, A. A., Perdikis, D., Enns, J. T., Brick, T. R., et al. (2017). Teams on the same wavelength perform better: Inter-brain phase synchronization constitutes a neural substrate for social facilitation. *Neuroimage, 152*, 425–436.

Tanner, D., Morgan-Short, K., & Luck, S. J. (2015). How inappropriate high-pass filters can produce artifactual effects and incorrect conclusions in ERP studies of language and cognition. *Psychophysiology, 52*(8), 997–1009.

Tomasello, M. (1999). *The cultural origins of human cognition*. Cambridge: Harvard University Press.

Tsingos, N. (2018). Object-based. In A. Roginska & P. Geluso (Eds.), *Immersive sound: The art and science of binaural and multi-channel audio* (pp. 244–275). New York: Routledge.

Väljamäe, A., Steffert, T., Holland, S., Marimon, X., Benitez, R., Mealla, S., Oliveira, A., & Jordà, S. (2013, July 6–10). A review of real-time EEG sonification research. *International Conference on Auditory Display*, Łódź.

von Thienen, J. P. A., Clancey, W. J., Corazza, G. E., & Meinel, C. (2017). Theoretical foundations of design thinking. Part I: John E. Arnold's creative thinking theories. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research. Making distinctions: Collaboration versus cooperation* (pp. 13–40). Cham: Springer.

von Thienen, J. P. A., Clancey, W. J., & Meinel, C. (2021). Theoretical foundations of design thinking. Part III: Robert H. McKim's visual thinking theories. In H. Plattner, C. Meinel, & L. Leifer (Eds.), *Design thinking research*. Cham: Springer.

Widiger, T. A. (Ed.). (2012). *The Oxford handbook of personality disorders*. Oxford: University Press.

Wimmer, F., Hoffmann, R. F., Bonato, R. A., & Moffitt, A. R. (1992). The effects of sleep deprivation on divergent thinking and attention processes. *Journal of Sleep Research, 1*(4), 223–230.

Xie, H., Howell, A., Schreier, M. Sheau, K. E., Manchanda, M. K., Ayub, R., Glover, G., Jung, M., Reiss, A. L., & Saggar, M. (2019). Finding the neural correlates of collaboration using a three-person fMRI hyperscanning paradigm. *bioRxiv*. https://doi.org/10.1101/782870.

Zhang, X., Liu, X., Yuan, S.-M., & Lin, S.-F. (2017). *Eye tracking based control system for natural human-computer interaction. Computational intelligence and neuroscience*, *2017*. (p. 9) https://doi.org/10.1155/2017/5739301.