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Exploring the Interplay of Design Expertise, Sketching, and Prototyping

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DOI
10.4233/uuid:f557489f-ff75-4130-959b-39d258691bec

Publication date
2023

Document Version
Final published version

Citation (APA)
Jobst, B. S. (2023). *Learning from Outstanding Designers: Exploring the Interplay of Design Expertise, Sketching, and Prototyping* . [Dissertation (TU Delft), Delft University of Technology].
https://doi.org/10.4233/uuid:f557489f-ff75-4130-959b-39d258691bec

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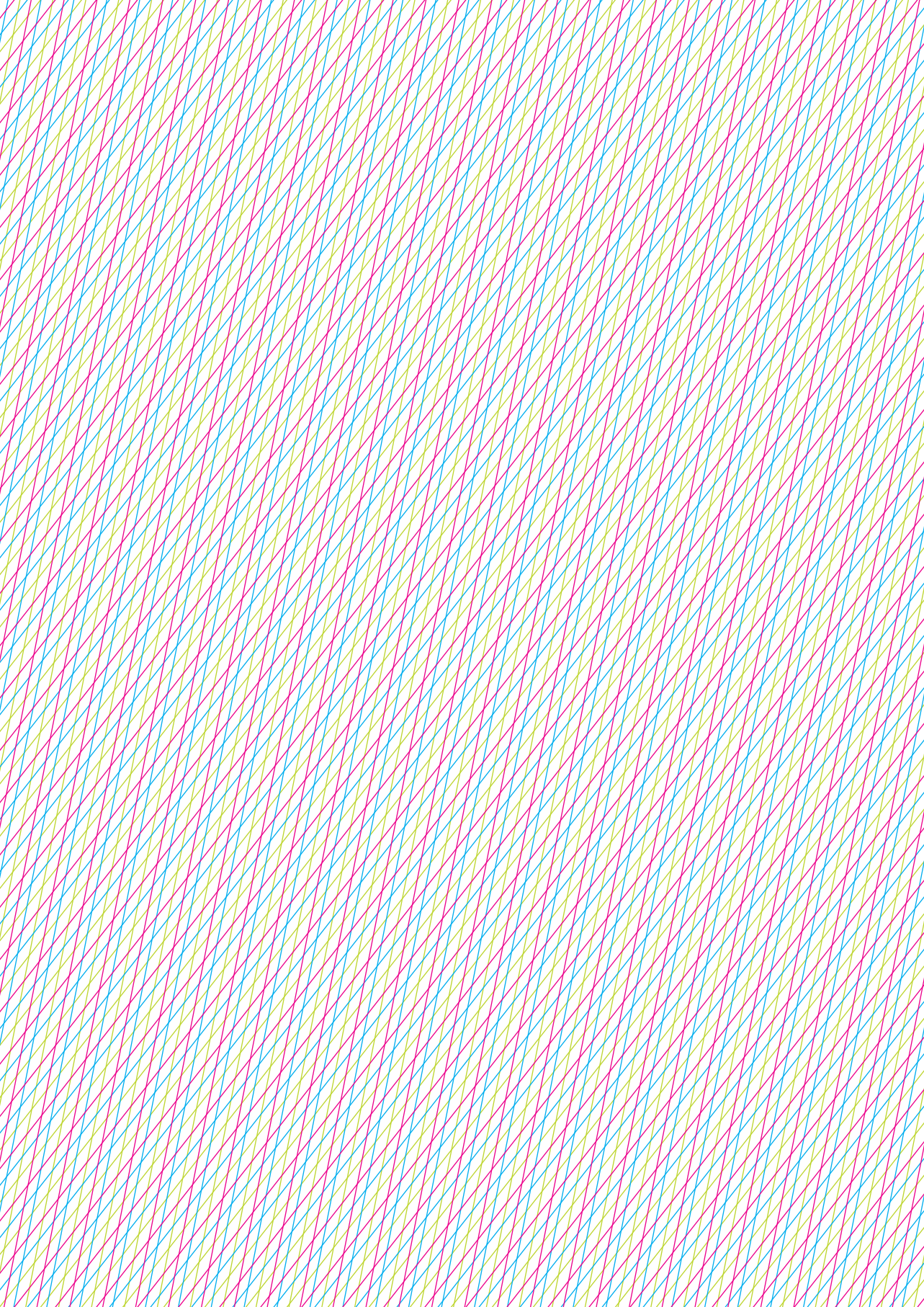

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Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J van der Hagen,
chair of the Board for Doctorates
to be defended publicly on
Monday, September 11, 2023 at 12:30 o'clock

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ISBN 978-94-6419-900-0

Printed by: Gildeprint, The Netherlands

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ENGLISH SUMMARY

As more serious complex problems of our time need to be solved, more people should be empowered to help solve them. Therefore, increasing efforts are made to embed problem-solving strategies not only into schools (OECD, 2022) but also into companies and for non-designers (Brown, 2009).
Sketching and prototyping are activities known to impact the process of complex problem solving. Coherently, a large body of research has been done for contributing to a better understanding of sketching's and prototyping's impact on the process (Bilda et al., 2006; Deininger et al., 2019; Goldschmidt, 2002; Purcell & Gero, 1998; Yang, 2005) and on the designer (Dow et al., 2009, 2011; Gerber, 2009; Gerber & Carroll, 2012). Whereas little research has been done to compare both activities and to explore their interplay (Bao et al., 2018).
Furthermore, little is known about how designers with a high expertise level – the Outstanding Designers (OD) (Cross, 2001, 2003; Cross & Lawson, 2005; Roy, 1993) – are using sketching (Lawson, 1980) and prototyping. This thesis contributes with findings from two studies and a comparison to understand the interplay of design expertise, sketching, and prototyping. The aim is to learn from successful designers and their sketching and prototyping activities.

This PhD thesis is structured into two parts: an explorative part and a design part. In the first part – the explorative part – two studies were conducted exploring how Proficient Designers (PDs) and Outstanding Designers (ODs) use sketching and prototyping in their design process. Therefore, a survey study (Study 1) was conducted with 54 designers, who graduated, and made first professional experience: the Proficient Designers (PD). The survey study provides an ample overview of topics, such as motivation, related to sketching and prototyping. In addition, an interview study (Study 2) was led with seven high performers, the ODs, to explore their use of sketching and prototyping in the design process. Based on the insights from two studies, two status quos –from the ODs and the PDs– were generated. The results of the two studies were compared to identify similarities and differences in order to deduce learning opportunities. In addition, through comparison in chapter 5, we revealed valuable insights regarding the relevance of professional experience and highlight the sketching and prototyping skills necessary to become an Outstanding Designer.

Based on our results, we posit that PDs overly rely on sketching to generate ideas without fully developing these ideas. We refer to this behaviour as the 'Proficient Designers' sketching overflow'. Whereas the ODs' sketching approach is realistic, and goal focused and results in a behavior called 'sketching with purpose'. The answers from the PDs suggest that they avoid the step of manifesting their ideas in tangible prototypes to achieve certainty. We refer to this behaviour as the 'Proficient Designers' prototyping bonding gap' (Jobst, 2020). Compared to the PDs the ODs emphasised prototyping for gaining certainty and cooperating with clients. They expressed a strong attachment regarding prototyping that results in specific routines. We call this behavior the ODs' 'bonding with prototyping'. We attribute the main reasons for these behaviours to the different approaches PDs and ODs have toward reflection based on sketches and prototypes. The findings suggest ODs follow a more structured and reflective approach than PDs, being fully aware of the relevance of their sketching and prototyping activities.

Based on the main findings, we synthesised an explanatory model outlining the interplay of design expertise, sketching, and prototyping. The models illustrate not only the need, but also provide a foundation for the development of tools to support reflection through sketching and prototyping.
The second part – the design part – was used to design tools to transfer research results into education. According to the main results of the first part of the thesis, we identified the different needs of awareness for reflection in the process of sketching and prototyping. Consequently, a tangible toolkit for creating awareness for reflection and for guiding reflection was developed.
The toolkit contains three elements: first, the Awareness Card set to supply best practice examples; second, Breathing Exercises that provide calmness and concentration; and the Reflection Canvas, designed for analysing the situation and possible interventions.
The tools were used to intervene in two design workshops in a design education context. The interaction of the design students with the tools provided insights for the iteration of the toolkit. The toolkit is designed to create awareness of reflection and to guide reflection activities targeting design students in the early stage of their design education to support the development of future designers' abilities.

NEDERLANDS SAMENVATTING

Aangezien er meer ernstige complexe problemen van onze tijd moeten worden opgelost, moeten meer mensen in staat worden gesteld om ze te helpen oplossen. Daarom worden steeds meer inspanningen geleverd om strategieën voor probleemoplossing niet alleen in scholen (OECD, 2022) maar ook in bedrijven en voor niet-ontwerpers in te voeren (Brown, 2009).
Schetsen en prototypen zijn activiteiten waarvan bekend is dat ze het proces van complexe probleemoplossing beïnvloeden. Er is veel onderzoek gedaan naar de impact van schetsen en prototypen op het proces (Bilda et al., 2006; Deininger et al., 2019; Goldschmidt, 2002; Purcell & Gero, 1998; Yang, 2005) en op de ontwerper (Dow et al., 2009, 2011; Gerber, 2009; Gerber & Carroll, 2012), terwijl er weinig onderzoek is gedaan om beide activiteiten te vergelijken en hun onderlinge wisselwerking te verkennen (Bao et al., 2018). Verder is er weinig bekend over hoe ontwerpers met een hoog expertiseniveau - de *Outstanding Designers* (OD) (Cross, 2001, 2003; Cross & Lawson, 2005; Roy, 1993) schetsen (Lawson, 1980) en prototyping gebruiken. Dit proefschrift draagt bij met bevindingen uit drie studies om de wisselwerking tussen ontwerpexpertise, schetsen en prototyping in kaart te brengen. Het doel is te leren van succesvolle ontwerpers en hun schets- en prototypingactiviteiten.

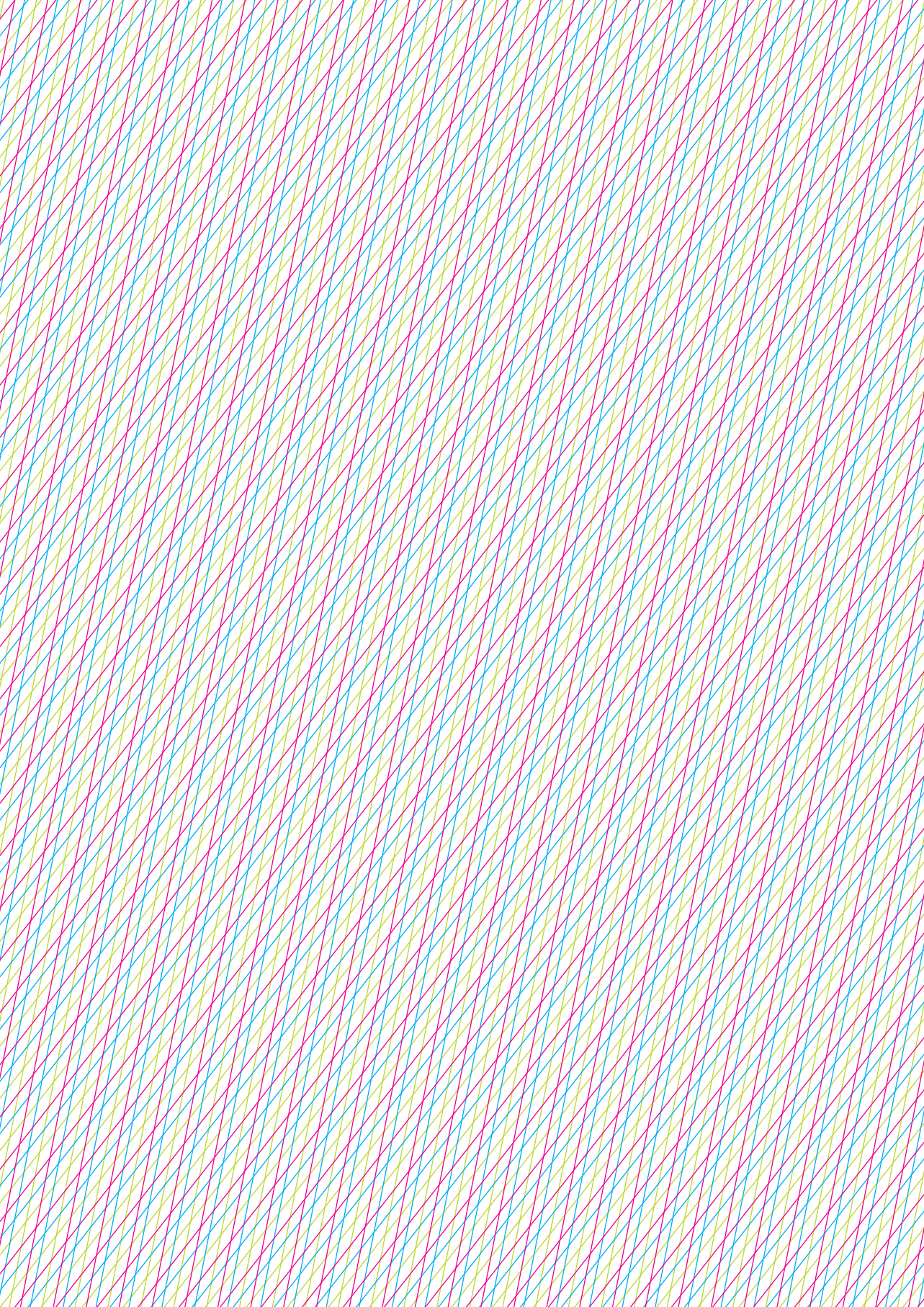
Dit proefschrift bestaat uit twee delen: een exploratief deel en een ontwerpdeel. In het eerste deel - het exploratieve deel - werden drie studies uitgevoerd die onderzochten hoe *Proficient Designers* (PDs) en *Outstanding Designers* sketching en prototyping gebruiken in hun ontwerpproces. Daarom werd een enquête (studie 1) afgenomen bij 54 afgestudeerde ontwerpers die hun eerste professionele ervaring aan het opdoen waren: de Proficient Designers. De survey studie geeft een uitgebreid overzicht van onderwerpen, zoals motivatie, gerelateerd aan schetsen en prototyping. Daarnaast werden interviews (Studie 2) afgenomen bij zeven *high performers*, de OD's, om hun gebruik van schetsen en prototyping in het ontwerpproces te onderzoeken. Op basis van de inzichten uit twee studies werden twee status-quo's -van de OD's en de PD's- gegenereerd. De resultaten van de twee studies werden vergeleken om overeenkomsten en verschillen vast te stellen en daaruit leermogelijkheden af te leiden. Bovendien brachten we door de vergelijking in studie 3 opnieuw waardevolle inzichten aan het licht betreffende de relevantie van beroepservaring waarbij

de nadruk ligt op schets- en prototypevaardigheden die nodig zijn om een uitmuntend ontwerper te worden.
Op basis van onze resultaten stellen wij dat PD's te veel vertrouwen op schetsen om ideeën te genereren zonder deze ideeën volledig uit te werken. Wij noemen dit gedrag de 'sketching overflow van vaardige ontwerpers'. Terwijl de schetsbenadering van de OD's realistisch en doelgericht is en resulteert in een gedrag dat 'doelgericht schetsen' wordt genoemd. De antwoorden van de PD's suggereren dat zij de stap vermijden om hun ideeën te manifesteren in tastbare prototypes om zekerheid te verkrijgen. We noemen dit gedrag de 'Proficient Designers' prototyping bonding gap' (Jobst, 2020). Vergeleken met de PD's benadrukten de OD's prototyping voor het verkrijgen van zekerheid en de samenwerking met opdrachtgevers. Zij uitten een sterke gehechtheid ten aanzien van prototyping die resulteert in specifieke routines. Wij noemen dit gedrag van de OD's 'binding met prototyping'. Wij schrijven de belangrijkste redenen voor dit gedrag toe aan de verschillende benaderingen van PD's en OD's ten aanzien van reflectie op basis van schetsen en prototypen. De bevindingen Suggereren dat OD's een meer gestructureerde en reflectieve aanpak volgen dan PD's en zich volledig bewust zijn van de relevantie van hun schets- en prototyping-activiteiten.

Op basis van de belangrijkste bevindingen hebben we een verklarend model opgesteld dat de wisselwerking tussen ontwerpexpertise, schetsen en prototypen schetst. De modellen illustreren niet alleen de behoefte aan hulpmiddelen ter ondersteuning van reflectie door middel van schetsen en prototyping, maar bieden ook een basis voor de ontwikkeling ervan.

Het tweede deel – het ontwerpgedeelte – werd gebruikt om instrumenten te ontwerpen voor de overdracht van onderzoeksresultaten naar het onderwijs. Op basis van de belangrijkste resultaten van het eerste deel van het proefschrift, identificeerden we de verschillende behoeften aan bewustwording voor reflectie in het proces van schetsen en prototypen. Op basis daarvan werd een tastbare toolkit voor het creëren van bewustzijn voor reflectie en voor het begeleiden van reflectie ontwikkeld. De toolkit bevat drie elementen: ten eerste, de *Awareness Card Set* om beste praktijkvoorbeelden te leveren; ten tweede, ademhalingsoefeningen die zorgen voor kalmte en concentratie; en het *Reflection Canvas*, ontworpen voor het analyseren van de situatie en mogelijke interventies.

De instrumenten werden gebruikt om te interveniëren in twee ontwerpworkshops in een ontwerponderwijscontext. De interactie van de ontwerpstudenten met de tools leverde inzichten op voor de bijstelling van de toolkit. De toolkit is ontworpen om bewustwording van reflectie te creëren en reflectieactiviteiten te begeleiden die gericht zijn op ontwerpstudenten in de vroege fase van hun ontwerpopleiding om de ontwikkeling van hun vaardigheden als toekomstige ontwerpers te ondersteunen.



1 INTRODUCTION

1.1 THE INTERPLAY OF DESIGN EXPERTISE, SKETCHING, AND PROTOTYPING

Coping with complex design problems and the use of supportive activities, such as sketching and prototyping, are becoming much more valued for the 21st century (OECD, 2022). The demand for such know-how and skills exceeds the design discipline. In this way, Tim Brown (2009) claims that change by design through Design Thinking based on expertise and prototyping is most relevant for inspiring innovation in organisations. For this reason, we want to learn from Outstanding Designers about their use of design activities, which have successively been elaborated through many years of engagement 'in dedicated and focused practice' (Ericsson & Williams, 2007, p. 119).

In this research, we focus on the two design activities highlighted for their effect on the design process: sketching and prototyping. Both activities are part of visual language and help cope with complex problems (Dow et al., 2011; Ferguson, 1994; Gerber & Carroll, 2012; Goldschmidt, 1991, 2017; Sachse et al., 2004; Sachse & Hacker, 2012a; Yang, 2005). Furthermore, these activities are also part of cognitive processes, such as thinking, reflecting, and decision-making.

To learn from the expertise of Outstanding Designers (ODs), we compare the use of sketching and prototyping activities of ODs with that of designers who have graduated and are beginning their professional practice, referred to as Proficient Designers (PDs). We consider this comparison relevant for identifying differences between experienced and less-experienced designers and for deriving learning opportunities to bridge the gap between young professionals and ODs.
The ODs can be described as having created many successful designs and for being admired for their work within and outside their peer group (Cross, 2004a). Outstanding designers are not only experienced experts, but also 'stand out' regarding their design outcomes when compared with other designers.

In previous research, expert designers have often been compared with novice designers (Ahmed et al., 2003; Björklund, 2013; Casakin, 2004; Chen & You, 2004). That research has yielded many differences between the two categories. Initially, our research approach may seem part of this well-known research scheme comparing novices and experts. However, we are interested in the special characteristics of PDs and ODs. We chose PDs who have gained their first professional experience and compare them with ODs. Based on our comparison, we reveal valuable insights regarding the relevance of professional experience and highlight the sketching and prototyping skills necessary to become an OD.

1.2 IMPLICATIONS AND RELEVANCE

The contributions of this research aim at informing practice and theory.

1.2.1 PRACTICAL RELEVANCE

The PhD's aim is to learn from the 'best' designers – from outstandingly well-performing designers and their use of sketching and prototyping activities. Sketching and prototyping are known to facilitate the complex problem-solving design process (Goldschmidt, 1992; Römer et al., 2000; Sachse, 1999).

There is evidence that learning from ODs' sketching and prototyping activities offers the possibility for design students to accelerate their development towards higher expertise (levels). We share Cross' perspective postulated in his paper 'The Nature and Nurture of Design Ability' that through a 'better understanding the nature of design ability, design educators may be better able to nurture it' (Cross, 1990, p. 128).
Based on two studies (Study 1 and Study 2) we aim to explore PDs' and ODs' use of sketching and prototyping. The results from both studies will be compared to identify similarities and differences in the use. Based on our research results, we aim to develop explanatory models to visualise the interplay of design expertise, sketching, and prototyping. The models provide actionable advice for the development of means based on insights from ODs' best sketching and prototyping practices and addresses the identified deficits in PDs' sketching and prototyping. The results of this research aim to establish the creation

of supportive sketching and prototyping habits and to nurture these design abilities of design students.

The deduced models will be used for developing means to support design students and design education. The means shall contribute to nurture better-than-average design abilities in design students. Moreover, they can be used as guidelines by teachers and practitioners inside and outside the design context. We argue that the models will contribute to the development of future supplementary means, such as tools, methods, and training.

1.2.2 THEORETICAL RELEVANCE

Although high achievers in design are admired for their outstanding design outcomes, little research has been conducted on this group of designers. Most of this research was done more than 20 years ago (Candy & Edmonds, 1996; Cross, 2001b, 2002a, 2003; Cross & Clayburn Cross, 1996; Lawson, 1994; Roy, 1993). There are many reasons to investigate ODs, being high performers. Nevertheless, researchers focused on drawing comparisons between novices and experts (Ahmed et al., 2003; Björklund, 2013; Casakin, 2004; Chen & You, 2004). In this context, the addressed research topics are among others design tasks, differences in initial mental representations, use of visual analogy as cognitive strategy, and sketching in conceptual design.

Ahmed and colleagues (2003) investigated how six novice and six experienced engineering designers approach design tasks based on an observational study. The novice designers were not observed to question data. *'They tended to consider issues sequentially, and were not observed to differentiate between important and less important issues'* (Ahmed et al., 2003, p. 6). The novice designers were found to be much more likely to treat numerical data, including computer models, as accurate values. The novice designers expressed 'that they were often uncertain about a decision they had made' (Ahmed et al., 2003, p. 6). Ahmed and colleagues (2003) concluded their research with one (of several) finding; that experts 'used particular design strategies' whereas novices are unaware of these design strategies and tend to use trial and error patterns (Ahmed et al., 2003, p. 10).

In their pilot study, Chen and You (2004) compared the sketching of two novice and one expert designers in Conceptual Design and presented four findings.

They found out, that the sketches of expert compared to novice designers show more complexity and have a good balanced transformation activity for concept generation. The concept of fluency – producing a high number of ideas – was defined by Torrance (1969) as one dimension of evaluating creativity. Fluency was used as one variable to compare novice with expert designers' sketching in concept generation. The research from Chen and You (2004) supported the finding, that the more the designer sketch the higher the fluency vice versa (Chen & You, 2004, p. 8). Additionally, they figured out that the experts show a good ability on problem definition and product specification' (Chen & You, 2004, p. 8) whereas the novice designers were not able to configure the ideas clearly during concept generation. The study indicated that expert designers' solution space is obviously bigger than that of the novice designers (Chen & You, 2004, p. 8). The difference in the process of recalling data is attributed to expertise by the researchers. Further study insight is the description of an 'ideal' approach for the concept generation being characterised by the development of concepts based on repeatedly applying a divergent and convergent process. The described finding is similar to models from other researchers (Cross, 1994; Pugh, 1991).

Cross and Clayburn (1998) have investigated exceptional and Outstanding Designers and have commented that, 'many studies of designer behaviour have been based on novices (usually students) or, at best, designers of relatively modest talents' (Cross & Clayburn Cross, 1998, p. 141). Hence, Cross and Clayburn object that investigating only 'modest talents' will limit our view of design expertise. Cross argues that 'studying outstanding or exceptional designers may give us different, and more relevant insights and understanding of design expertise' (Cross, 2004, p. 438).
Furthermore, Cross und Lawson (2005) claimed relevance to study Outstanding Designers to advance research in order to 'not holding back progress in design methodology'. They argue that not investigating exceptional or Outstanding Designers would lead 'to weak or even inappropriate models of design activity' (Cross & Lawson, 2005, p. 283).

To loosen the limitations and sharpen the conditions for data collection to create a better understanding of design expertise at a high level, we focused our investigation on ODs. Based on an interview study with ODs, we examine their expertise and their sketching and prototyping activities. As with the ODs, the

PDs have not been the focus of much research. Nevertheless, the sample of PDs is very interesting for understanding how their design education shaped their sketching and prototyping behaviour.
As reported before, comparisons of novice and expert designers are relatively common in design research. Novices, who are only at the beginning of their design education, rarely have got much experience with prototypes and sketches. In contrast, PDs are likely to be educated (graduate degree from design, art or eingineering school) and trained in sketching and prototyping methods and approaches. In addition, PDs have had their first professional experiences in practice.
In this research the use of prototyping and sketching activities from designers with different levels of expertise are compared. It made sense to conduct our research with PDs instead of novices, as the latter would not provide much data on prototyping and sketching informed by professional practice.

We investigated PDs. A PD is at the stage when a designer, having graduated, starts their professional path. We consider the PDs as being the 'result' of design education (curriculum) rather than a result of their limited professional experience. To understand PDs' expertise better, we employ a survey study (Study 1) to determine the status quo of design expertise and the exercise of sketching and prototyping activities after graduation.

Therefore, we conduct a survey study (Study 1) to determine the status quo of design expertise and the use of sketching and prototyping activities after graduation. This approach helps to understand which topics related to sketching and prototyping should be emphasised in design educational programs in the future.

Regarding theoretical relevance, our research findings offer a better understanding of ODs' and PDs' expertise — a research field that has not gained much attention, yet. Based on the results of two studies, four theoretical models were developed and assembled into one conceptual model outlining the interplay of PDs' and ODs' expertise in sketching and prototyping. The models can be used by other researchers to build on in future research. We provide an additional research facet that contributes to the better understanding ODs' and PDs' expertise in their sketching and prototyping activities and the interplay between these.

1.3 THESIS STRUCTURE, RESEARCH, AND DESIGN QUESTIONS

This PhD thesis contains both a research part and a design part (see Figure 1). In the first part, the theoretical relevance is elaborated, and results from the studies with the PDs (Study 1) and ODs (Study 2) are compared. The results were synthesised into several conceptual, explanatory models. In the second part – the design part – a supportive toolkit is developed and evaluated. The thesis contains seven chapters. The research section begins with an introduction and then lays out the theoretical groundwork before introducing the studies and the data collection (Chapters 1 and 2).

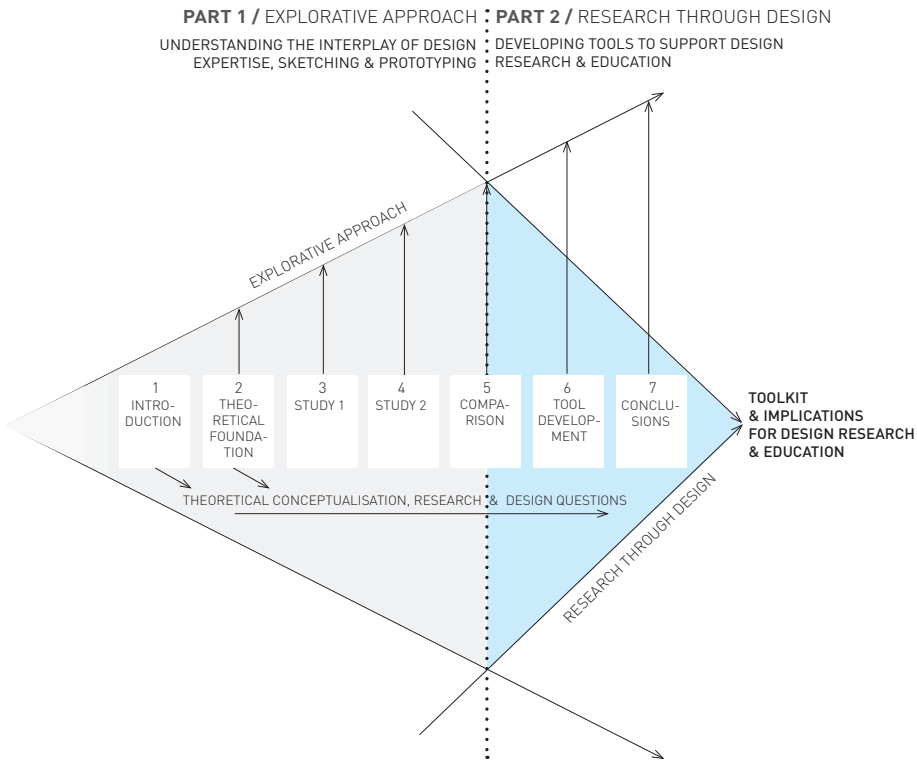


Figure 1. The structure of the thesis.

We conducted two empirical studies to investigate the use of sketching and prototyping by PDs and ODs to answer two research questions (Chapters 3+4).

The results of both studies were compared to identify similarities and differences and to develop several conceptual models representing the interplay of design expertise in sketching and prototyping (Chapter 5). In the design part, based on results from the empirical part and facilitated by the models, we developed a toolkit and evaluated it with design students (Chapter 6). In the seventh chapter, we draw conclusions from our PhD research and provided an overview.

The following subsections introduce the research and design questions guiding this PhD research. This thesis was designed to obtain knowledge regarding design expertise and focus on the sketching and prototyping activities of PDs and ODs. To learn from ODs, we compared the study results of ODs with the results of PDs to identify potential improvements for sketching and prototyping activities. This PhD research is guided by three research questions. Based on the results, we developed a toolkit with two guiding design questions. To gain knowledge of PDs sketching and prototyping use, we developed the first study.

A Survey Study with Proficient Designers (Study 1)

To answer the first research question (RQ1), we conducted a survey study with PDs (Chapter 3).

> *RQ 1: How do Proficient Designers use sketching and prototyping in the design process?*

Using a questionnaire, we asked 54 PDs how they use sketching and prototyping activities in their design process and how they assess the relevance of sketching and prototyping for their work. The PDs' answers to the closed questions were analysed quantitatively (and descriptively). To analyse the answers to open-ended questions, a coding system was developed. To answer the second research question, we conducted a second study.

An Interview Study with Outstanding Designers (Study 2)

The second study's aim is to learn from ODs' use of sketching and prototyping activities (Chapter 4).

> *RQ 2: How do Outstanding Designers use sketching and prototyping in the design process?*

Therefore, the sample of the second study are ODs. To answer the second research question, we interviewed seven ODs. For reasons of comparability, we transferred the questions from the survey to the interview guideline. The ODs' responses were analysed using the same coding system as in the previous study.

Differences in the Use of Sketching and Prototyping Activities by Proficient Designers and Outstanding Designers

In a further step towards answering the third research question, we compared the results of the two studies to identify learning opportunities for design students.

> *RQ 3: What are the similarities and differences regarding the use of sketching and prototyping by Proficient Designers and Outstanding Designers?*

To synthesise our findings and to derive the consequences from the results for supporting education, we created several explanatory models that illustrate the interplay of design expertise, sketching, and prototyping.

Development and Design of a Toolkit

In Chapter 6, a toolkit is developed based on the findings and insights of the two studies. The toolkit consists of three elements: a breathing exercise, a template of a canvas and a card set. This toolkit aims to guide reflection activities based on prototyping and sketching and to support future designers' abilities and expertise. The toolkit was introduced to design students in two workshops, and student interaction with the tools was evaluated in an iterative action research approach. In the first of two steps in the tool development process, we guided the application of reflection activities such as analysing, structuring, and selecting. The first design question is as follows:

> *DQ 1: How can we support design students' reflection activities in the early stages of the design process?*

In addition to the tool for reflection-guiding activities, we propose creating reflection awareness. Hence, the second design question is as follows:

> *DQ 2: How can we create awareness of reflection among design students through appropriate tools during the design process?*

Our toolkit aims to support the development of reflection processes through routine activities targeting designers in the early stage of their design education. Habits must be changed, but it is necessary to allow time to abandon long existing habits and create new habits (Lally et al., 2010). Therefore, the toolkit must be implemented as early as possible in the design education process.
In Chapter 7, we summarise our research results and discuss the conclusions from the research project. We also derive and formulate recommendations for future research. We developed a toolkit for design students to lay the foundation for a reflection use of sketching and prototyping activities. The toolkit is intended to support design students becoming better-than-average designers and to hasten their development towards a higher expertise level.

1.4 RESEARCH APPROACH

This thesis project is divided into two parts, the explorative approach (part 1) and the research though design approach (part 2). The research approach of this PhD thesis is set out in the following.

1.4.1 EXPLORATIVE APPROACH (PART 1)

We began this research with an ample and exploratory approach. Researchers usually use exploratory research when the topic under study is new or when the process of data collection is challenging. In this work, the topic under investigation is new as it involves a sample of PDs and their sketching and prototyping activities. So far, designers at this level of expertise have very rarely been the subject of research. Added to this new topic is the sample of ODs, so the topics explored in this work are at once rare and challenging. Therefore, we chose an explorative research approach because it is 'designed to maximize the discovery of generalizations leading to description and understanding' (2001, p. 3). As part of the exploratory research approach, we started data collection and conducted a survey among PDs (Study 1) and an interview study with ODs (Study 2).
This approach enabled us to understand better the use of sketching and prototyping activities of designers of different expertise levels, and to identify their

strengths and weaknesses. A survey study with open-ended questions was used for collecting data from PDs. Open-ended questions contribute to a better understanding of the topic and reveal implicit reasons and motivation (Ahmed et al., 2003; Cross & Clayburn Cross, 1996, 1996; Deininger et al., 2017). We also used a retrospective approach. This viewpoint builds on methodological approaches from other researchers to collect data using a retrospective approach, meaning to enquire about an activity that took place in the past (Cross, 2001b; Deininger et al., 2017) in the design context. We build on the assumption that the answers of the PDs provide insights regarding frequently performed activities, motivation, and assessed relevance. According to Reason (1990), activities practised frequently are closer to a person's consciousness than activities executed rarely. In general, activities that are more frequently used are more conscious. More conscious activities are mentioned more often than activities that are executed rarely (Reason, 1990). Therefore, our first study offers a better understanding of PDs' use of sketching and prototyping activities.

For the second study we aimed to better understand sketching and prototyping activities of ODs. To gain insights and collect data we decided to use the survey from the first study for reason of comparability also for the ODs. The ODs refused to answer a questionnaire with scales and closed questions. So, we had to change the survey to another method and therefore, conducted interviews. For the interview we used –as in the first study– a retrospective approach and we based the guideline on the same set of questions (congruent to 60%).

Although we decided on two studies – a survey and an interview study – both follow the same basis and key assumptions. We detail the differences later in this subsection and present the main similar lines of the two studies, consisting of the same set of (open-ended) questions following a retrospective approach.

We followed other studies that have conducted fundamental research with outstanding and exceptional designers. Research in design expertise has been contributed to by, among others, Cross. Cross did many interesting studies in design expertise and used among others approaches retrospective interviews. For example, Cross interviewed three ODs and created a 'general model of creative process strategies' (Cross, 2002b, p. 19). This study used a retrospective interview approach to learn about the activities of ODs in the design process. For researching high(est) design expertise, two methods are mainly used: a

(thinking-aloud) protocol study and retrospective interviews as e.g., by Cross (Cross, 1998, 2001, 2002). During protocol studies, the designer is usually exposed to a problem and must generate solutions for it within a limited timeframe. We consider this approach to the early phase as disadvantageous to our research aim of stressing the exploration of sketching and prototyping activities.

There is evidence that ODs take on and work on projects that have a certain complexity and whose processing and realisation can extend over years. The method of working on this type of project made a specific research methodology, such as shadowing or observation, difficult. Therefore, researchers might use think-aloud protocols as a research methodology. In this approach, in most cases, the respondent is given a highly simplified task that he or she works on in a laboratory-like situation for a maximum of several hours.
This type of research enables a focus on the early phase, but this is disadvantageous to our research, which stresses an explorative approach to sketching and prototyping activities that are relevant in all phases, not just the early phases. The use of retrospective interviews is a dominant and often-used approach when addressing higher or highest design expertise levels (designated as outstanding and exceptional, respectively). We used this `best practice´ research approach and interviews as our research method. We share this view with other researchers, and we refer to methodological approaches from other researchers regarding open-ended questions contributing to a better understanding and revealing implicit reasons and motivations (Ahmed et al., 2003; Cross, 2001b; Cross & Clayburn Cross, 1996; Cross & Cross Clayburn, 1998; Deininger et al., 2017). Based on the above arguments, we conceptualised and developed the two studies that are described in more detail in the following subsections.

Survey Study (Study 1)

In Chapter 3, the results from the survey study (Study 1) were presented. The purpose of a questionnaire is collecting 'thoughts and beliefs and opinions etc., about the past, present and the future' (Blessing & Chakrabarti, 2009, p. 271). In the first study, we utilised a questionnaire, which is appropriate when a high number of respondents are involved (Blessing & Chakrabarti, 2009). One advantage of a questionnaire is the comparability of answers. Additionally, we

pursued an explorative approach to gain a better understanding of the use of sketching and prototyping and which aspects were emphasised by the respondents. Therefore, we developed a questionnaire to attain two types of answers and data using open-ended questions and questionnaire items. Open-ended questions are suitable for exploratory research, whereas questionnaires facilitate the comparative analysis of answers (Blessing & Chakrabarti, 2009). Therefore, we developed a questionnaire comprising open-ended and closed question types and scales. The findings from the first study map the status quo of PDs' sketching and prototyping activities. We focused on identified patterns and tendencies in the answers, which led to a restructuring of the questionnaire and adding another set of questions for the second study to focus on the emerged topics and their exploration.

Interview Study (Study 2)

It lies in ODs exceptionalism that there are fewer ODs available. The sample of ODs is smaller than the PDS sample size because their numbers are fewer, and they were less willing to answer a survey. The first two ODs that we met, refused to answer on Likert scales and check boxes, thus the questionnaire was not employed. The ODs seemed to feel uncomfortable in several ways: one was to not be wasting precious time and another expressed a feeling of being treated in a 'standardised' way. In the acquisition phase one OD distrusted and rejected to research; he explicitly mentioned had bad experiences with researchers involved in a project with clients and rejected being interviewed. So, we decided to collect the data only based on the open questions and based on the semi structured guideline and to conduct an interview.

Interestingly Lawson and Dorst (2005) referred to difficulties in engaging ODs as participants for research aims. Thus, 'studying ODs is particularly problematic because of their limited availability as participants' (Cross & Lawson, 2005, p. 284). This might be the reason that most of the studies with ODs are based on interviews 'because that seems to the only way to gain access' to ODs (Cross & Lawson, 2005, p. 284). In addition, to these reasons, the advantage of conduct interviews is to gain more in-depth insights on ODs' exceptionalism through the possibility to ask further and 'deeper' questions when an interesting aspect appears. Hence, interviews 'gives a 'rich picture' rather than formalised data (...) and enables insights to emerge that were not in the researcher's prior assumptions' (Cross & Lawson, 2005, p. 284). Furthermore, for ambiguities that

arose in the surveys, we were able to develop and ask new questions in the interviews.

In Chapter 4, we introduce Study 2. For this study, we decided on an interview approach. The interviews share the same scope as the questionnaires: to elicit answers 'about the past, present and the future' (Blessing & Chakrabarti, 2009, p. 271). An interview is a verbal interaction between two people with a specific purpose in mind. Interviewing is a method for collecting data, and there are two major research tools: structured and unstructured interviews. Interviews can be based on a predetermined list of questions, known as the 'interview schedule' and called 'structured interviews', or without a schedule and called 'unstructured interviews' (Kumar, 2014, p. 145). A structured schedule enables the asking of the same set of questions to ensure the comparability of answers. An unstructured schedule enables the researcher to deepen and expand the answers of the interviewee (Rubin & Rubin, 2005).

We opted for a combination of the presented interview types and selected a semi-structured interview schedule that ensured we asked the same set of questions to all ODs. The advantage of a semi-structured schedule is that there is enough freedom to ask additional questions when, for example, surprising answers are given. With this combined schedule, it is possible to compare answers and to follow a new path that appeared during the interview. Therefore, we developed a semi-structured interview guideline building on the questionnaire from the first study, and thus used around 60% of the same questions.

Comparison and Model Deduction

A coding system was developed to analyse the answers from Studies 1 and 2. The development of the coding system is described in detail in the data analysis sections of each study (in Chapter 3 and 4). To draw comparisons regarding the use of sketching and prototyping activities from PDs and ODs, we analysed the answers from two studies and compared the results regarding similarities and differences. These results aligned with theoretical concepts and were synthesised and deduced into explanatory models.

The abstract models outline the interplay of design expertise, sketching, and prototyping. The models facilitate the deduction of actionable advice and the development of the toolkit.

1.4.2 RESEARCH THROUGH DESIGN (PART 2)

For the development of the toolkit, we referred to a design science approach. Cross (2007) writes in the editorial of 'Forty years of design research' that the foundations for 'a science of design' were established by Simon in his book *The Sciences of the Artificial,* first published in 1969. Design science is, according to Simon (1996), a research method to investigate scientifically a designed artefact, in contrast to investigating the natural: '*The natural sciences are concerned with how things are'* in contrast to design, which *'is concerned with how things ought to be'* (Simon, 1996, p. 114). For the development and design of the tools of the toolkit, we applied a Research-through-Design (RtD) approach. For the evaluation and iteration of the designed toolkit, we used an action research approach. Both approaches are introduced in the following sections.
To develop such an artefact, the design field suggests several –more or less– scientific approaches. For the toolkit development, we chose a 'research through art and design' approach (Frayling, 1993, p. 5). This term was coined by Frayling (1993) in 'Royal College of Art Research Papers' and marks a substantial start within the research in design discussion. In this approach, design is considered relevant for conducting research. In the chapter 'Doing design as a part of doing research', RtD is described as an approach using design activities, such as framing, reframing, conceptual mapping, and prototyping, to generate designerly contributions. This approach assigns design (and prototyping) as central in knowledge generation. Stappers emphasises 'the designing act of creating prototypes is in itself a potential generator of knowledge' (2012, p. 87).

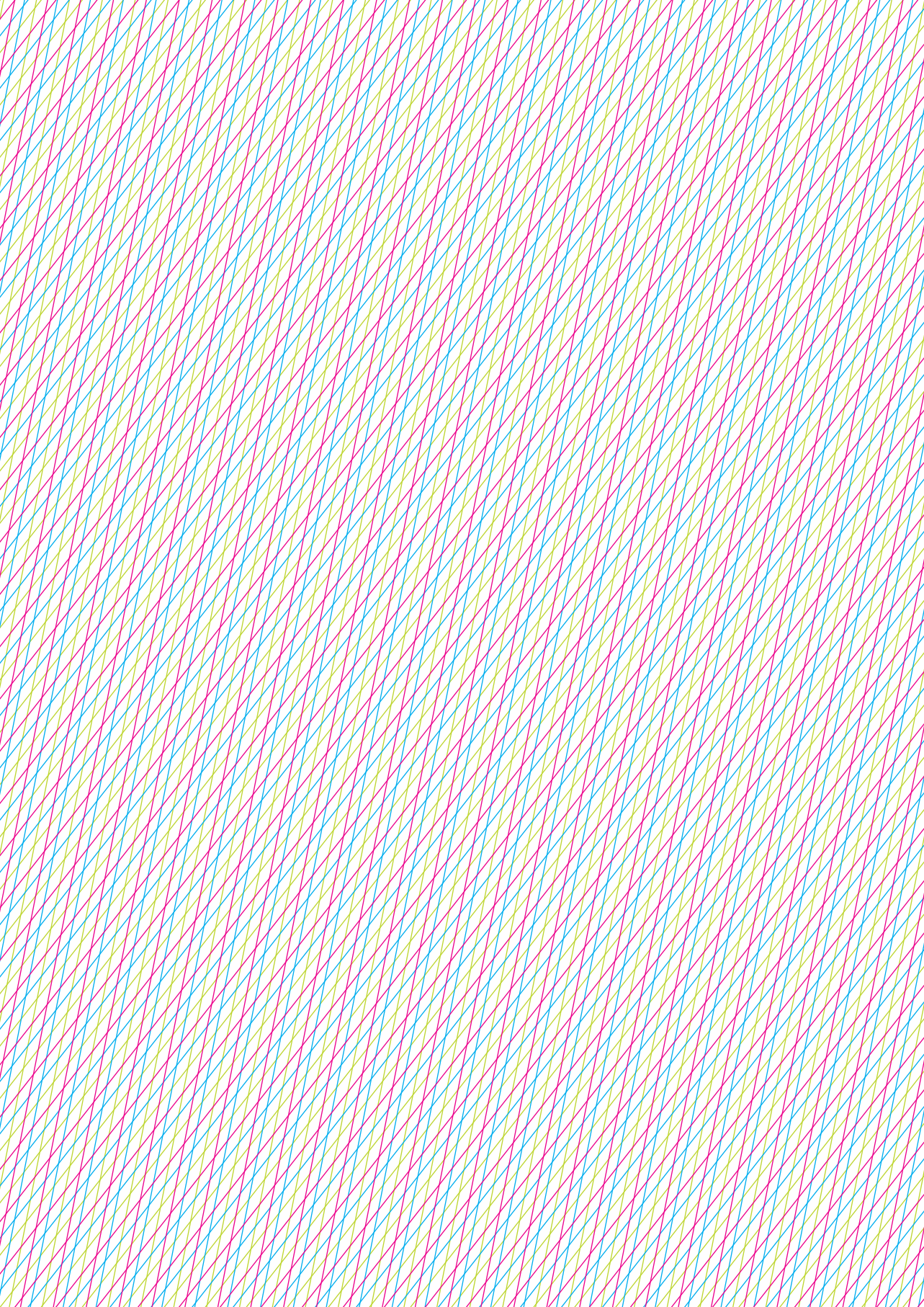
Furthermore, it is important that RtD must be accompanied by fundamental documentation (Agnew, 1993) and the communication of results (Frayling, 1993, p. 5). Although the discussion started in the 1990s, the 'formative stage' of RtD as an explicit theory is still an ongoing process and the same concerns consistent guidelines (Stappers & Giaccardi, 2017, p. 1). Even if there is no consistent theory or guideline to apply the RtD approach, we utilised it because it fits our research aim to develop an artefact (in this case, a toolkit). For the design of the tools of the toolkit, we used an RtD approach, and for the evaluation and iteration of the designed toolkit, we used an action research approach, as mentioned by Frayling (1993).

Action Research

Part of doing scientific research is reflection and evaluation. We opted for an action research approach (Lewin, 1946) to evaluate the toolkit in a design education environment that serves also to inform the later iteration of the tools. Action research has been established as a research philosophy and research method in the social sciences for almost eight decades. Kurt Lewin, the famous Gestalt psychologist, coined the term in his paper 'Action Research and Minority Problems' (Lewin, 1946). In the paper, Lewin describes action research as a transformative change in taking action and doing research at the same time, bound by critical reflection. Action research enables the researcher to intervene in a given situation and then analyse the changes that were influenced because of the intervention. Action research is a method to evaluate design methods and design artefacts in a qualitative manner (Lewin, 1946; Oosthuizen, 2002).

There are several existing guidelines on action research. We followed Kemmis' (2013) four-step action research cycle covering the following activities: plan (Step 1), act (Step 2), observe (Step 3), and reflect (Step 4). We designed a toolkit based on our research findings to generate knowledge via interventions in design workshops. To evaluate the tools of the toolkit, we used them as interventions. The tools were introduced in the design workshops to design students (Steps 1 and 2). The design workshops were not set up as special events but were existing workshop formats. The toolkit was introduced to design students, their interactions were observed (Step 3), and their answers regarding the tools were captured using the questionnaires. Based on the results, the tools were refined and iterated for further evaluation (Step 4). Having introduced the research approaches in this PhD thesis, an overview is provided in the next part of the entire thesis structure, with the guiding research and design questions.

Throughout the thesis, the pronoun 'we' is used. It refers to the author of this PhD thesis and includes both readers and colleagues who assisted in parts of the research. Therefore, 'we' is used synonymously with 'I'.



2 THEORETICAL FOUNDATIONS

In the previous chapter, the thesis' relevance to explore the interplay, of sketching, prototyping, and design expertise for education, practice and research was emphasised. In this chapter, the overarching concepts of the research topic are introduced. The following section prepares the theoretical groundwork for this thesis and gives an overview of the research literature on designers as human being, design expertise, sketching, prototyping, and their interplay.

2.1 CONCEPTS

Research on expertise has involved high-performers' behaviours and learning approaches to understand their strategies to improve performance (Ericsson, 2014; Ericsson & Lehmann, 2003). The successful outcomes of a design process depend on multiple interplaying aspects of designer behaviour. Of the many definitions of behaviour proposed in the literature, we build on Lewin's (1936) behavioural equation. According to Lewin, human behaviour (b) can be explained by the function (f) of the person and his or her environment (Lewin, 1936, p. 12).

$$b = f(person, environment)$$

To understand behaviour, we must specify the two elements of the equation: person and environment. Therefore, we focus on specific variables, such as a designer in the complex design problem environment. In this study, 'person' corresponds to a 'designer'. Designers are individuals and share some underlying human principles, such as cognition and motivation.

For this thesis, we investigated designers with different expertise levels: PDs and ODs. We found evidence that a designer's expertise is reflected in his or her behaviour. Additionally, we specify 'environment' in our research as equivalent to design problems respectively dealing with design problems in a design process. To cope with design problems, a variety of methods and activities can be applied by the designer and are part of his/her behaviour: 'The life of every human being is a never-ending stream of activities (…) This includes not only the many kinds of actions or communications [but also] experience – mental

activity as perceptions, thoughts, feelings and ideas' (Heckhausen & Heckhausen, 2010, p. 2); (translated by the author). We investigated designers' behaviour respectively their design behaviour, which we specify as design activities. We define activities (a) as a function (f) of a task, person, and interaction.

$$a = f(task, person, interaction)$$

Moreover, we focus on two specific design activities: sketching and prototyping. Having introduced and specified the elements of Lewin's equation, we visualised these in Figure 2.

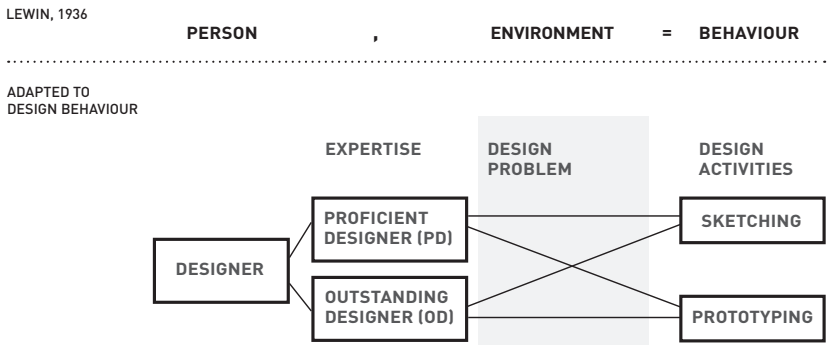


Figure 2. Core concepts for this thesis, building on Lewin (1936).

In this research, we aim to reveal the interplay of design expertise, sketching and prototyping – to inform design education and research.

2.2 DESIGNER

In the centre of our research is the designer, in his/her environment with his or her design behaviour and expertise. The designer is primarily a person. We introduce core concepts relevant to understand the underlying general principles of humans, what generally steers behaviour, design activities, and the concept of design expertise to gain a better understanding of their connectivity.

Human behaviour

Human behaviour is steered by cognition, motivation, and emotion (Heckhausen & Heckhausen, 2010), and are relevant concepts for exploring the interplay of sketching, prototyping, and design expertise. Designers cope with design problems, which we consider as complex problems. Such complex problem-solving challenges the designer on motivational, emotional, and cognitive levels. Cognition is the processing of information (i.e., thinking processes) derived from perceptual processes. Cognitive processes include using knowledge and acquiring and generating new knowledge (Coleman, 2003). The designer, when addressing complex problems, must cope with information that can be contradictory, intransparent, and have different goals (Dörner & Funke, 2017), which can challenge a person's working memory. 'Working memory is critical for making sense of anything that unfolds over time, for that always involves relating what came earlier to what came later.' (Diamond, 2016, p. 12). Working memory is used to store information – that is no longer perceptually present in mind – and to work mentally with this information. (Baddeley & Hitch, 1994; Diamond, 2013; Smith & Jonides, 1999). The working memory is limited, in terms of limited number of information that can be stored in a limited length of time (Bilda & Gero, 2007; Miller, 1956). Therefore, working memory also has been described as a bottleneck of thinking' (Sachse et al., 2014).

The Cognitive Load Theory states that a person's working memory is limited, and moreover that performance and learning are hindered when the total cognitive load associated with a task exceeds the capacity of a person's working memory (Sweller, 1994). Cognitive load refers to the load placed on a person's cognitive system by the performance of a particular problem-solving task (Sweller, 1994; Van Merrienboer & Sweller, 2005). Therefore, the cognitive load of a design task that surpasses a designer's cognitive abilities for an extended period of time can lead to increased stress and burnout (Kahn & Fellows, 2013). Sun and Yao (2012) investigated the relationship between cognitive load and creativity in conceptual design through a pilot study with engineering design students and experienced designers. The results indicate that 'mental effort is more related to novelty and quantity, while experience in design has more effect on variety and quality' (Sun & Yao, 2012, p. 308). Calpin and Menold (2023) investigated the cognitive load on engineering designers (with undergraduate degree) while working on a design task. The results indicate that cognitive load during ideation correlates positively with the uniqueness, usefulness, and

elegance of ideas, depending on the design task. Furthermore, the results suggest that there is a significant difference in cognitive load experienced by the designer during ideation and prototyping (Calpin & Menold, 2023). Nelson and Menold described prototyping as a 'combination of psycho-motor (Krathwohl, 2002; Simpson, 1972) and cognitive skills' (2020, p. 3). To date, little is known about the impact of psycho-motor on cognitive load in design.

One relevant cognitive process that enables people to focus on a specific stimulus or cue in the environment is awareness. A cue is a specific piece of information that can be extracted from the sensory input and can be haptic, audible, or, often, visual. Visual cues are the dominant source of information (Posner et al., 1976). We postulate that, to perceive cues consciously, a certain awareness is needed. Awareness of a situation and the environment involves a certain state of mind (Endsley, 1988). This point is relevant for designers they must be aware for cues which are beneficial hints for e.g., unwanted deviation from expectations.
Perception is the process of experiencing the world through our senses, or, as Graham (1869) phrases it, 'Perception is whatever we perceive or gain a knowledge of. It is an idea of something—something presented to the senses' (Graham, 1869, p. 131). Through the perceptual process, we receive information about our environment. Perception covers the absorption, processing of sensory information, and stimuli (and cues), as well as the response to this information. Based on perceptual processes, we can adapt to the environment and react to it. Perception covers concepts such as pattern recognition, memory strategies, and memories of visual information.

In addition to cognition, also emotion is relevant for behaviour. Emotions are how an individual deals with situations, matters, and people they find personally significant. Emotions influence thought and behaviour through physical and psychological changes (Schacter et al., 2019). For example, our heart beats faster when we face a situation that we interpret as a challenge. A supplementary concept relevant for the behaviour of individuals is motivation.
According to Heckhausen and Heckhausen (2010) motivation relates to the processes involved in selecting and setting goals. If there is no goal-orientated motivation, there is no action. Human action is determined by organised behaviour and experience. Perceptions, thoughts, emotions, skills, and activities are used in a coordinated way to either achieve goals or to withdraw from

unachievable or non-rewarding goals (Heckhausen & Heckhausen, 2010). Actions to achieve goals are driven by motives: 'Motivational processes are aroused by perceived situational cues, and they influence perceptions of the situation in turn' (Heckhausen, 1977, p. 284). These external impulses can be the first step of possible action. Motivation is used to explain purposeful and goal-directed aspects of human behaviour (Wasserman & Wasserman, 2020). One source of motivation is self-efficacy and can be described as the belief in one's own capabilities (Bandura, 1982). Self-efficacy beliefs are based on self-estimation and can be enhanced by four sources: mastery experiences, social persuasion, vicarious experiences, and psychological and physiological states. A high self-efficacy belief influences behaviour and impacts emotion and motivation. This belief also increases the willingness to face a challenge and makes individuals more likely to choose more challenging tasks. To fulfil their task, people with high self-efficacy do everything needed to overcome obstacles. Such people are more resistant to setbacks and try harder to achieve their aim (Bandura, 1982).

Summary

The essential concepts introduced here, are necessary to better understand the interplay of design expertise, sketching, and prototyping, which will be explored in the following sections. Design expertise is part of a designers' behaviour, and is steered by cognition, emotion, and motivation. An example for the interplay is that a piece of information is processed on a cognitive level and influence the designer at an emotional-motivational level (e.g., joy, uncertainty, fear). Similarly, emotions influence perception and cognition, so the same situation can be interpreted and predicted in different ways (e.g., positively, negatively, optimistically).

2.3 EXPERTISE

Expertise relates to a higher level of knowledge or skill in people (Newell & Simon, 1972; Ericsson, 2014). The main aims of expertise research are to investigate why some individuals perform better than others and how performance can be improved.

In the field of problem-solving, the investigations began in chess (De Groot, 1946). Later, in the 1970s, research in expertise started to become a larger field across domains (Dreyfus & Dreyfus, 1980; Ericsson & Smith, 1991; Simon & Chase, 1973). Based on results from researching expertise, we know the concept of expertise is domain specific and must be investigated as such. However, expertise shares similar characteristics across domains. Moreover, we learned about the relevant characteristics for acquiring expertise. Two sources of expertise are differentiated: one relates to genetic (nature) meaning talent or innate characteristics and environmental (nurture) factors (on performance), also designated as nature and nurture (Cross, 1990). Talent or innate characteristics 'are given' by nature and cannot be changed, in contrast to the environmental factors that can be nurtured by experience and training. The nurture of expertise can be influenced by several factors in order to acquire expertise.

Acquiring expertise

Based on their investigations in chess, Simon and Chase (1973) discovered an average ten years' experience needed to become an expert in a cognitively demanding field. This proposed 'ten years rule' was postulated, based on research, to apply also to other domains because of similar factors influencing the acquisition of expertise in areas such as sport, language, and science (Simon & Chase, 1973). An individual must not only make an effort to gain expertise but must also strive to maintain the attained skills and knowledge. Therefore, experts must constantly practise to ensure that their level of performance remains high. This entails continuous improvement of their skills and knowledge. It is necessary for expert performers to continue learning to achieve a level of performance that is higher than their current level. For example, a typist must dedicate all their attention and engagement to active

learning to improve their typing speed (Book, 1925). Such engagement is designated as dedicated practice.

Moreover, the acquisition of superior performance not simply needs ten years of practice in a dedicated way but also deliberated practice. Investigating exceptional performance, researchers found out that it evidently takes at least ten years and dedicated and focused practice to win in international competitions (Ericsson, 2006; Simon & Chase, 1973).

Expert performance can be conceptualised as to be *'mediated by complex integrated systems of representations for the execution, monitoring, planning, and analyses of performance its acquisition requires an orderly and deliberate approach'* (Ericsson, 2004, p. 74). Furthermore, Ericsson stresses that *'improving integrated performance cannot be performed mindlessly or independent of the representative context for the target performance'.* In addition, to a form of mindfulness or awareness professionals in teaching and coaching is considered essential *'in guiding the future experts to acquire superior performance in a safe and effective manner'* (Ericsson, 2004, p. 74).
As described before, cognition is a main characteristic for acquiring expertise, because *'most types of expertise – even athletic performance – continue to be mediated by cognitive processes such as monitoring, planning, reasoning, and anticipating'* (Ericsson & Lehmann, 1996, p. 297). For example, elite marathon runners report that they continuously monitor their physiological state and the effectiveness of their running, whereas novice runners deliberately think about things unrelated to their running to minimise their experience of pain (Morgan & Pollock, 1977). The previous insights stressed the strong link of cognition with exceptional expertise.

A further cognitive aspect relevant for expertise is memory. The results from de Groots´ research stress the relevance of memory for remembering a large body of chess moves as a phenomenon of expertise (De Groot, 1946). The author reported that chess master train themselves in order to study chess games of other chess masters. To study chess games, seem to enlarge the image repository of the chess player who can recourse to these in a future chess game.

Ericsson et al. (1993) postulate the need for four hours a day of deliberate practice to achieve expertise, and this is the maximum that individuals can sustain for many years. Hence, to achieve, maintain, and exercise exceptional performance requires a daily practice of at least four hours over many years (Ericsson et al., 1993; Ericsson, 2004; Ericsson & Lehmann, 1996).

An additional factor for acquiring exceptional expertise, for example, are adaptions. Researchers adjusted maximal adaptations to domain-specific constraints*:*

> *'Acquired anticipatory skills circumvent general limits on reaction time, and distinctive memory skills allow a domain-specific expansion of working memory capacity to support planning, reasoning, and evaluation. Many of the mechanisms of superior expert performance serve the dual purpose of mediating experts' current performance and of allowing continued improvement of this performance in response to informative feedback during practice activities'* (Ericsson & Lehmann, 1996, p. 273).

Summary

Although expertise research has been conducted in the problem-solving context, we must consider that chess deals with different types of problems compared to design. Problems in chess are not complex problems, in contrast to design problems. The 'moves' to reach the goal of a design solution are per se unlimited. Nevertheless, some findings on expertise in chess are transferable and relevant for design, such as the impact of cognitive processes and other processes relevant for memory activities, planning, reflecting, and monitoring are relevant for design performance.

Various factors influence the acquisition of expertise concerning cognition among others memory for a large image repository to get access to knowledge experiences and precedents in the field, as well as monitoring oneself when practising in a dedicated and deliberated way. For exceptional performance this approach has to be practiced over at least over ten years and at least for four hours a day.

2.3.1 LEVELS OF EXPERTISE

Differences in behaviour can be observed across disciplines and related to different levels of expertise. Dreyfus (2002) investigated in the chess context how adults acquire skills by instruction. He differentiated and described adult skills acquisition into a model of five levels of expertise. The levels are hierarchically structured in five steps: novice, advanced beginner, competent, proficient, expert level. Each level corresponds to one of five ways individuals with different expertise levels perceive, structure, interpret, and solve tasks. Dreyfus based his model of research on chess. Even if chess and design are both problem-solving disciplines, there are pertinent differences and therefore the Dreyfus' mode requires adaptation to design.

Dreyfus' model (2004) is the basis for the development of a model of skill acquisition to the design field (Dorst & Reymen, 2004; Lawson & Dorst, 2005a). When aiming at improving design abilities and to transit e.g., design students to a higher level of expertise, first expertise has to be differentiated and described (Dorst & Reymen, 2004; Lawson & Dorst, 2005). The acquisition of design expertise 'is influenced by a complex array of factors' (Lawson & Dorst, 2005a, p. 98). Based on Dreyfus' five levels of expertise, the seven levels of design expertise were developed (Dorst & Reymen, 2004; Lawson & Dorst, 2005) and are introduced below.

Novice. The beginner receives from the instructor a task and rules for determining the task. The task is deconstructed in a such a way that the beginner can build on her/his previous experiences to follow the given rules.

Advanced Beginner. The advanced beginner experiences new situations that enable her/him to cope with real situations. The advanced beginner, after seeing a sufficient number of examples, learns to recognise these new aspects, which could be situational or non-situational features but are recognisable for the advanced beginner.

Competent. The competent performer 'seeks new rules and reasoning procedures' to cope with the 'overload of recognizable potential relevant elements and aspects that he/she is able to recognise (Dreyfus, 2002, p. 370).

Proficient. The proficient performer detaches more and more from rule following and this is approach is replaced by 'situational discriminations accompanied by associated responses' (Dreyfus, 2002, p. 370). Dreyfus stress that proficiency seem only to evolve if experience is integrated 'in this atheoretical

way and intuitive behaviour replaces reasoned responses' (Dreyfus, 2002, p. 370). In a moment of intuitively responding there cannot be doubt 'since doubt comes only with detached evaluation'. It is due to (limited) experiences of possible responses to each of the situations that the proficient performer can discriminate the situations and its important features; hence, he/she cannot intuitively respond but has to decide what to do and fall back into rule-following.

Expert. Due to a 'vast repertoire of situational discriminations', the expert 'can see how to achieve the goal'. The ability to make subtle and refined discriminations distinguishes the expert from the proficient performer. Moreover, a characteristic for an expert is 'the immediate and intuitive situational response' (Dreyfus, 2002, p. 372).

Master. The master level is situated above the expertise level. Masters are described as designers who have reached a level of innovation such that their own 'work is seen as 'representing new knowledge in the field' (Lawson & Dorst, 2005, p. 223). The master develops a set of founding principles to a level of innovation and offers innovative responses to situations that become examples for other designers to study.

Visionary. Here, the highest level is called visionary. The visionary designer questions, with new designs, the boundaries of the subject, despite the work might not always be realised. Visionary designs often enter exhibitions and competitions. A visionary is one 'who has become so interested in developing new ideas that the normally expected level of competence is no longer important' (Lawson & Dorst, 2005, p. 223).

In parallel to the before introduced levels Cross (Cross, 2001b, 2003) used and coined for reporting his research two terms for the high(est) level of expertise: exceptional and outstanding. Both terms are treated as equal in his publications and Cross uses both terms for the highest level of expertise (Cross, 2004a, pp. 437–438). In his work, Cross described findings from interviews with designers designated as exceptional (Cross, 1998) and outstanding (Cross, 2001b).

The before mentioned models of skill acquisition as well as the terms for high expertise in design are listed below (Table 1). The terms of 'outstanding' and 'exceptional' for designers are placed at the same level as masters as the made descriptions are more like the 'master' than to the 'visionary' level of expertise.

Table 1. Overview of terminology regarding the different levels of expertise.

	Levels of expertise Dreyfus & Dreyfus, 1980)	Levels of design expertise (Dorst & Reymen, 2004)	Terms for high design expertise (Cross, 2001b, 2004; Cross & Clayburn Cross, 1996)
		Naïve	
1	Novice	Novice	
2	Advanced Beginner	Advanced Beginner	
3	Competence	Competent	
4	Proficient	Proficient	
5	Expert	Expert	
6		Master	A) Exceptional; B) Outstanding (two terms for same phenomenon)
7		Visionary	

Referring to previous conceptualisation of expertise levels we decided to refer from now on to the terms of Proficient and Outstanding Designers. In this PhD study, we investigate designers of two different expertise levels (outstanding and proficient). Throughout this thesis, we refer to the term 'Outstanding Designers (ODs)' to address designers on the 6th level of expertise, which would also include the master level or exceptional designers.

In the following section we report what is known from the research literature about ODs and PDs.

2.3.2 OUTSTANDING DESIGNERS' EXPERTISE

Research on expertise in design is important for understanding the nature of design, and thus being able to nurture design abilities in young designers. Therefore, learning from exceptional performers in design is considered essential (Cross, 2004). Nevertheless, there has been little research on expertise at a high(est) level in design and was mainly conducted starting around 30 years ago and we give an overview of this research literature.

Lawson led eleven interviews and observational studies with outstanding architects to understand their design approach. Thus, some of these architects generated various of solution concepts in contrast to other outstanding architects who focus only on a few or just one concept (Lawson, 1994). Lawson concluded that 'one simple message' that recurred from his studies was 'the extremely demanding standards set by the designers themselves' (Cross & Lawson, 2005, p. 287).
Further contribution to the field is also based on interviews. Roy (1993) researched two exceptional designers and innovators and identified patterns of their design approaches. Hence, in order to design 'radical new products' the designers rely rather on personal need or direct experience and therefore, they neglect conventional market research. In addition, they tend to apply a 'solution-focused strategy with an initial idea' often derived from an accumulated repertoire of knowledge and experiences. Furthermore, both designers 'conceive and then develop their inventions and design' and therefore, they typically tend using a mix of sketching and physical modelling (Roy, 1993, p. 442). The choice which method to employ depends on the nature of the problem and individual preference. Roy also reported a tendency to move quickly from sketches to physical models and prototypes.

In the context of creative designers of high expertise, Candy and Edmonds reported a case study of the design of the 'LotusSport' bicycle. The focus of their investigation into characteristics of creative designers lies on knowledge and how the designer might be supported by software in the knowledge intensive aspects of design. The aim of the research is to gain knowledge for the development of support and the design of a future computer support system (Candy & Edmonds, 1996).

Cross investigated expertise through protocol analyses and interviews. In his research he found out that ODs structure, perceive, and solve problems differently than designers with lower expertise levels. He interpreted and attributed these differences to expertise. He concluded that, cognitive strategies may explain some important facets of the behaviour of ODs resulting in of quicker perception, pattern recognition, strategic knowledge, or visual memory (Cross, 2001b). Outstanding designers rely to a great extent on experience to synthesise a broad range of information to inform their decision-making and before selecting a concept for refinement. Furthermore, ODs seem to differ from non-ODs regarding the amount of their strategic knowledge in the design process (Cross, 2001).

Cross' research contributes to a better understanding of the highest level of design expertise. This focus led him to transfer insights from interviews with ODs into a general model of design strategies. Cross (2001) identified strategies in all three interviews with designers. Based on these insights deduced a model of the early stage of the design process. Of the three strategies, the first is a broad 'systems approach' to the problem. Going into more detail, the second strategy is referred to as 'framing.' Here, the ODs frame a problem in a specific often individual and experienced-based manner. The third emphasised strategy is to design and start from 'first principles'. For example, the OD selected and followed a triangular structure as a base for the desired solidity of the design for a bicycle rack (Cross, 2001). For investigating outstanding designers, we built on previous research to develop criteria as means for the identification of ODs.

Criteria for identification and selection of ODs

Lawson and Cross (2005) provide three means or identifying the sample of ODs for their research studies (Cross & Lawson, 2005). They stress 'a clearly acknowledged record of success', that includes an objectively comprehensible and externally recognised level of achievement (Cross & Lawson, 2005, p. 284). In this research project we opted for ODs as sample. To identify our sample for the interview study, we integrated the means of identification by Lawson and Cross (2005) and theoretical concepts from research literature. Based on the insights six criteria were defined for this research. These six criteria are juxtaposed to means and theoretical concepts from research literature (Table 2).

Criterion 1) Successful design: Outstanding designers are people who have successfully designed artefacts (products or services) that were realised and launched by rather prestigious companies and manufacturers with high reputation. Their designs are internationally prized with awards.

Criterion 2) International reputation among peers: ODs are recognised within and beyond their peers. This can be assumed when their work was published in design magazines, and/or books as well as in newspaper magazines. ODs are also invited to internally show and exhibit their work in commercial and non-commercial contexts.

Criterion 3) Designer as a role model: Individuals whose design has attracted (international) attention, which means been invited to speak about their work and to teach design. ODs are considered as inspiration, based on their design and person, not only for younger designers.

Criterion 4) Own signature/unique selling proposition (USP): Individuals who have developed a unique personal signature for their design in terms of aesthetics or approach in design work with societal relevance and/or use a specific design approach that can be based on very personal experiences. This approach of personal `framing´ is visible and recognisable in the design outcomes. Regarding marketing language, this framing could be called the 'USP' of a designer.

Criterion 5) Deliberate Practice: Deliberate practice plays a role in expert and exceptional performance. One part of deliberate practice is that more than 'ten years of deliberate practice' are necessary for expert performance (Ericsson & Lehmann, 2003, p. 1). Admittedly, this criterion is difficult to verify. Therefore, we consider the phenomenon of successful practice a result of deliberate practice. In addition, we built on the fact that training and coaching is needed to be supervised to improve the performance. Therefore, we link this criterion to an academical background and a degree in engineering or design. Furthermore, we expect that the designers incorporated a habit of to constantly monitor themselves and thus learned to improve their doing and practice.

Criterion 6) Primarily involved in design and dedicated practice:

We assume that studios with more than ten employees, have a head to be mainly involved in managing rather than designing. So, the designer is still deeply involved and dedicated in the creative work and to offer guidance for the designs. In this setting, ODs primarily focus on design work rather than managing the studio or spending time on representational tasks. Based on these criteria we identified the ODs for the interview study (Chapter 4). We selected designers for our sample when there was a match of at least five of the six criteria.

Table 2. Criteria for Selection of Outstanding designers.

Means and concepts	Criteria for ODs	Description
(Cross & Lawson, 2005) Acknowledged record of success (awards & level of achievement)	1 Successful and multiple-award winning' design	Individuals whose artefacts (products or services) realised and launched with prestigious companies and manufacturers. A range of successful designs that won awards.
Peer-group recognition (Cross & Lawson, 2005)	2 International reputation among peer, as well as with a world-wide following	The designs are published, shown, and exhibited internationally.
	3 Designer as role model	Individuals who have been invited to teach design and/or have been invited to speak about their work. Design(er) is considered as inspiration by other designers.
	4 Own signature/ UPS	Individuals who developed a unique personal approach and/or signature for their design
Deliberate practice (Ericsson, 2008; Ericsson et al., 1993)	5 Deliberate practice	Individuals with more than ten years of deliberate practice.
Dedicated practice of four hours/day (Ericsson & Lehmann, 1996)	6 Primarily involved in design practice	Individuals involved constantly improving their design abilities and are involved in dedicated practice. They have primarily a focus on design work, therefore, the studio runs with a small size of employees (up to 10 individuals).

2.3.3 PROFICIENT DESIGNERS' EXPERTISE

A Proficient Designer can be described as one who graduated and has little experiences in professional practice. The term 'proficient' designer relates to 'graduates with some small degree of professional experience' (Lawson & Dorst, 2005, p. 221). Moreover, such graduates can solve routine problems for clients and users: 'This level is probably a fairly comfortable experience that presents few challenges either in the development of a design or to the approach itself' (Lawson & Dorst, 2005, p. 9). In design research, few studies have explored Proficient Designers (Chevalier & Chevalier, 2009) or mentioned the Proficient Designers as educational aim (Albers & Burkardt, 1999). Less investigations were done in PDs' sketching and prototyping activities. Thus, investigating PDs to learn about their design activities is relevant. A reason for few insights from proficient design research might be that in research often the group of professionals are not divided into expertise levels. Thus, there are limited possibilities to relate with proficient design research. Examples from research with or about Proficient Designers and a model to support proficiency as educational aim are introduced below.

In a web design study with ten PDs and eleven novices the influence of proficiency on viewpoint switching was investigated. According to Chevalier and Chevalier, the usability quality of websites may be proportional to designers' ability to switch between the client's and the user's viewpoint. The ability of switching back and forth seem to be influenced by designers' proficiency' and 'a significant relation between viewpoint switching and the usability quality (of e-mockups) was found' (Chevalier & Chevalier, 2009, p. 126).

In the paper 'Proficient Designers a challenge to academical education' the authors present the educational model 'Integrated Product Development' in machine design. The model consists of three units Competence in Fundamentals, Social Competence, and Methodological Competence. The aim is to educate and thus develop designers' proficiency in a way that the designer can face the challenges of nowadays (Albers & Burkardt, 1999).
To identify designers for our research we derived criteria for our sample, the Proficient Designers. The criteria for identifying Proficient Designers are listed in Table 3.

Table 3. Criteria for Selection of Proficient Designers.

Means for identification	Criteria	Description
Graduate (Dorst & Reymen, 2004; Lawson & Dorst, 2005)	1 Graduated in a design discipline	Academically trained and graduated in design.
First professional experience	2 Professional practice	First professional experiences in design and practice (up to five years)

Criterion 1)

A PD is academically trained and has a degree in design. A PD has less than ten years of deliberate practice (unlike the ODs)

Criterion 2)

Graduated with first professional experiences from three months up to five years. The sample of PDs was selected for insights into how academically trained designers use sketching and prototyping after having recently finished their studies.

Summary

Although the concept of expertise has a common basis and shares some characteristics across domains, it is generally domain specific and must be investigated as such (Ericsson et al., 2018). Therefore, findings from research in expertise from other domains, such as chess or sports, can only be used in a limited way and transferred as an unverified hypothesis to the domain of design. In this PhD thesis, we investigated the behaviour of designers of different design expertise levels (Dorst & Reymen, 2004). Our samples are PDs and ODs and knowledge regarding design expertise, especially about PDs and ODs, is scarce. This research project aims to bridge this knowledge gap with the contribution of research results about PDs and ODs.

2.4 DESIGN PROBLEMS

In the previous part, we described designer behaviour and how it is influenced by motivation, emotion, and cognition. In addition, we reported results from research in design expertise. To investigate designer behaviour, we described the designer's environment, which involves complex design problems and coping with them (Dörner & Funke, 2017). According to Funke (2010), complex problem-solving aims to reduce the barriers between a start state and an intended goal state. Complex problems are not static, may not be transparent, and/or are, to some extent, unknown (Funke, 2010). A complex problem is attributed to multiple 'involved variables like connectivity, mutual dependencies between involved variables and dynamics of the situation'. These are reflecting 'the role of time and developments within a system'. Furthermore, 'intransparency (in part or full) about the involved variables and their current values' and lastly ' reekly' meaning many goals. (Dörner & Funke, 2017, p. 2). For this research complex problems are used equally to design problems. Hence, the designer must cope with complexity as an inherent part of design and the design process.

Behind a background of complexity there is a need for designers at the beginning of a design process to analyse and understand the problem and to develop a standpoint towards the problem and its solution. This process is termed, according to Cross (2001a), a 'problem formulation'. Problem formulation covers the (premature) initial assumptions about the requirements and constraints that must be considered. Based on the problem formulation, the designer can develop a design frame to deduce a solution. The task of design can be to develop a solution (Simon, 1995), or, as suggested by Dorst (2019), a system transformation.

To describe the process of coping with complex design problems, a wide range of process models have been developed. These models might differ in focus, content, structure, or graphical representation, but the essence of design process stages seems stable across decades (Bobbe et al., 2010): 'One of the most detailed and widely referenced prescriptive models of designing is the systematic approach developed by Pahl and Beitz' (Kannengiesser & Gero, 2017, p. 2). This model is based on the experience of Pahl and Beitz and their observations of professional designers and presented as a stepwise procedure used as a

prescriptive approach. In this research, we refer to the design process model of the systematic approach (Pahl et al., 2007) as one out of many existing models. As this model is often used and referenced, it is used here for a common understanding of the design process.

Systematic approach

In the systematic approach model, the design development process is subdivided into four main phases: 'clarification of the task', 'conceptual design phase', `embodiment phase', and 'detail design phase' (Pahl et al., 2007a). In the first phase, the problem was analysed and understood, and the task is (re)defined. In this process step, the task is to analyse and understand the included design problems before a designer develop ideas or solution approaches. In the 'conceptual design phase', ideas are generated to find solution approaches and concepts for the final design. The step to generate ideas is called ideation (Ehrlenspiel, 2007). Many researchers have focused on this phase because of its relevance to a successful outcome of the process. When weak ideas are chosen and developed late in the process, it becomes very expensive because, to correct these ideas, the designer must restart the process and choose a better idea or find a solution to correct the weak idea. To find innovative and novel ideas is a core goal of design creativity techniques by using e.g., brainstorming (Osborn, 1953), TRIZ (Altshuller, 1999), to generate a numerous different ideas. After generating a pool of ideas, these ideas must be further developed. At the end of this phase, designers evaluate a concept by the team or client or have individuals testing the design. Concepts must be evaluated before starting the `embodiment phase'. During the embodiment design phase, the concept and design idea are developed, and solution proposals and representations are realised. Designers use visual representations to find answers and solutions about aesthetics, form, material, surface, and/or functionalities. In the fourth and final phase, 'detail design', the final design is developed. By using visual representations, it becomes possible to test, to provoke feedback, and to enhance communication between the designer and e.g., the client, the user, the manufacturer. In this phase the presentations are detailed and display a design as basis for decision-making.

Summary

Part of an ODs characteristic is a successful design outcome. Successful designs are of great economic importance. Design problems are the 'environment' of a designer. This environment is characterised by complexity. To meet the requirements of demanding the complex problem-solving activities of the design process are of great interest not only for designers. It is therefore relevant to understand how sketching and prototyping can be used to advantage so that the designer can meet these requirements.

2.5 DESIGN ACTIVITIES: SKETCHING, AND PROTOTYPING

In this thesis, two specific design activities are emphasised to support complex design problem solving: sketching and prototyping. In the following section, results from research literature are presented, to better understand the impact of sketching and prototyping on the process, the outcome, and the designer.

Sketching and Prototyping

Research insights from sketching and prototyping are introduced, which are part of design representations. In general, sketching and prototyping support complex problem-solving processes in which the gathering and storing of information, communicating, and deriving knowledge from design representations are addressed (Cross & Dorst, 1998; Dorst et al., 1996). Design representations externalise thoughts (Larkin & Simon, 1987). Other researchers (Goldschmidt, 1997a; Görg et al., 2007) believe that, during the design process, design representations are most commonly used to express ideas. Design representations support thinking and reflecting (Ferguson, 1994; Suwa, Gero, et al., 1998a) to derive new ideas.

Design representations are also related to 'information recording', as it functions as a storage mechanism, avoiding the need to memorise data (Do, 2005). In this context, design representations can be an extension tool for short-term memory (Lipson & Shpitalni, 2000) and support for cognitive facilitation (Ehrlenspiel & Dylla, 1993).

One challenge of visual representation is that it should be realised in an understandable way and should be well externalised when used for shared understanding (Goldschmidt, 1997b; Pipes, 2007). Design representations play the role of a messenger communicating the essential features of the visualised data (Do, 2005) and are a persuasive aid for e.g., clients (Menezes & Lawson, 2006). By using sketching and prototyping, team members may see a design problem at the same level and create a shared mental image of the problem (Goldschmidt 2007). Another aspect is 'information processing', in which design representations are used to derive knowledge from data. During the design process, designers examine their designs in several ways (e.g., through different types of the sketches, notes, and models; (Goel, 1995a; Görg et al., 2007).

For this research we decided for two – out of many possible – activities to realise design representations, sketching, and prototyping. We defined for this research the outcome of sketching and prototyping, thus, sketches, and prototypes in the next sections.

2.5.1 SKETCHING

For this PhD project, we define sketching as an activity executed by hand that differs in the degree of detailing to visualise an idea, process, or real objects. We further consider sketching as a design activity and visual language. We postulate that designers use sketching as their second language, in addition to their (verbatim) mother tongue. Our view implies a certain aspiration of the designer attaining fluency and legacy in (speaking) the visual language of sketching.

Sketching is a characteristic design ability of designers. Moreover, sketching is a design activity and visual language as it makes visible what the mind's eye sees (Ferguson, 1994). Sketching has several functions in the design process. Sketching supports the exploration of the problem and solution space (Cross 200). On a cognitive level, sketching minimises the cognitive load, facilitates the working memory, and offers mnemonic help (Bilda & Gero, 2005; Sachse et al., 2014; Suwa, Purcell, et al., 1998).

However, there are different ways to approach sketching, with its different aspects. Research has found that many aspects of sketching are related to design outcome (Häggman et al., 2015; B. M. Kudrowitz & Wallace, 2013; Sachse et al., 2004; 2009). The basic aspects of sketching are mechanical qualities, such as proportion, accuracy, level of detail (high resolution, low fidelity), and type of sketch (thinking, talking, reminder etc.). Sketches contribute to achieving a certain (set) goal of the designers. Various types of sketches address different aims and how they impact the design process. The 'thinking' sketch supports the designer to clarify the design concept (Ferguson, 1994). Sketches are used to support thinking processes early in design processes and are considered a thinking aid (Goel, 1995b; Tversky, 2002). Goldschmidt (2014) provided evidence for the role of sketching as thinking aid. She conceptualised a sketch as an external representation and sketching as a way to quickly externalise an internal representation. These two representations 'work as a tandem' and support and complete each other (Goldschmidt, 2014, p. 433). Therefore, she designated sketching as a strategic design skill and highly recommends the mastery of sketching (Goldschmidt, 2014).
In addition, there is also the 'talking sketch', which aims at communicating the design idea (Ferguson, 1994). There is also the 'reminder sketch' supportive to store information to prevent being forgotten (Schenk, 1991). Sketches created for presentations are complex, often in full colour, and illustrate what the final product or service would look like. This sketch is called a 'persuasive sketch' and is used as a selling tool to help stakeholders and clients evaluate a design proposal (Menezes & Lawson, 2006; Pei et al., 2011).

Generally, sketching is considered an intuitive technique to support the flow of ideas (Visser, 2006). Exploratory sketching, often executed in a rough and vague way, is especially used for creating ideas and is called an 'idea sketch' (Pei et al., 2011). A further characteristic of a (hand) sketch is the degree of detailing, often designated as resolution or fidelity. The range of detail is from a quickly scribbled sketch, to a dimensioned sketch, and up to a highly detailed and coloured sketch. Sketches can be extremely accurate, and these are referred to as high resolution or high fidelity. The level of detail relates to the aim of the sketch. A sketch used for communication is designed for understandability to achieve a shared mental model. A sketch for communicating has to be executed in a higher level of resolution compared to a sketch that supports ideation, which can be done in low resolution and is rather quick and roughly done.

Sketching, according to McKim (1972), is performed quickly and is concerned with broad features rather than details (van der Lugt, 2005). A quickly performed sketch has many incomplete and imprecise lines, and this refers to what Goel (1995) calls 'ambiguity' or 'indeterminacy'. Ambiguous or indeterminate sketches are rarely realistic, not very detailed, and are open to reinterpretation, which is linked to creative ideas (Goldschmidt, 1991, 2002). Especially for ideation the form of a sketch is mentioned to be a more appropriate (form) than the 'polished drawn image' (Sturdee & Lindley, 2019, p. 6).

In general sketches are less detailed than drawings (e.g., technical drawings, renderings, etc.). We postulate the boundary between when the sketch ends, and the drawing begins is fluid. In the engineering context the sketch is described as rough picture with proportions and lengths which are simply judged by eye and realised by a pen or pencil. Whereas drawing aims at 'standardised drawings'. These drawings are characterised by 'proportions and lengths (that) follow a specific scale' (Alias et al., 2002, p. 165). In addition to the level of detailing, sketches have a mechanical quality. There is a correlation between sketch quality and the assessed creativity of the sketched idea (Kudrowitz et al., 2012). The two mechanical qualities of sketch smoothness/line quality and overall accuracy/proportionality have also been researched (Das & Yang, 2022; Hammond et al., 2018; Hilton et al., 2016; Kudrowitz et al., 2012). Research of Das and Yang (2022) indicates that maximum sketch quality (smoothness/line quality) scores correlate with overall design outcomes. In addition, the quality of sketches correlates with design outcomes for novices.

Moreover, there is a correlation between overall design outcomes and novices who have a higher maximum sketch quality score (i.e., at least one excellent) and who sketched extensively. Regarding 'understandability', two characteristics are especially relevant: 'line smoothness' and 'proportion/accuracy' of sketches (Das & Yang, 2022, p. 9). Many qualitative aspects of sketching matter not only for the design process, but also for the quantity of sketching. There is also a correlation between quantity of ideas sketched and eventual design outcome (B. M. Kudrowitz & Wallace, 2013). The technical execution of the designers' sketching skills matter, and the number of produced sketches offers an opportunity for sketching training. This point suggests opportunities for novices to practise and train in these sketching techniques, which may help them when creating sketches (Das & Yang, 2022).

This aspect applies not only to novices, but also to design education in general. A further argument for emphasising hand sketching in design education is supported by research that hand sketches help avoid fixation. According to Robertson and Radcliffe (2009), for novice engineer designers, it is more fruitful to develop expertise in sketching than immediately engaging in Computer Aided Design (CAD) for design skills to avoid premature fixation on a single design (Goldschmidt, 2017; Robertson & Radcliffe, 2009). Design fixation is defined as 'blind adherence to a set of ideas or concepts limiting the output of a conceptual design' (Jansson & Smith, 1991, p. 3).

Fixation concerns not only novices or students even 'practitioners can have difficulties to release from an idea' and seem to be faced to fixation and to deal with a premature commitment to a solution to a design problem (Purcell & Gero, 1996, p. 363). In problem solving 'this effect is called functional fixedness or fixation'. For example, a person cannot 'see new ways of using objects which could lead to the innovative solution required, because they are blocked or fixated on well learnt uses or properties of the object.'(Purcell & Gero, 1996, p. 363). Sketching is used during the entire design process and, depending on the process phase, different sketches are used. In the early phases, idea sketches or thinking sketches are relevant, and in later phases the sketches are primarily used to support communication via the talking sketch or persuasive sketch for presentation. Research has stressed the relevance of sketching for the early phases of the design process. In the early phase, sketching is relevant for analysing the problem, ideation, and conceptualisation. In the ideation phase, there is a correlation between quantity of ideas sketched and eventual design outcome (Das & Yang, 2022; Kudrowitz & Wallace, 2013). Sketching supports the design process, impacts outcome, and affects the designer, although the effect of sketching on designers has rarely been investigated. The effect on the design can be at a cognitive level (Das & Yang, 2022; Sachse et al., 2004; Schütze et al., 2003) or at an emotional motivation level. Traditionally, in the design field, there is a tendency to use sketching first, and then prototyping. In the next section, we introduce prototyping.

2.5.2 PROTOTYPING

For this research, we define the term 'prototyping' as an activity for creating tangible artefact(s) to visualise an idea or object or part of an object in different degrees of detail. In this thesis, the term 'prototype' includes virtual, e.g., CAD, intangible (role play) and physical (mockup) forms. In addition, we designate prototyping as the third language of a designer. A prototype is often described a three-dimensional (3D) and tangible visualisation of a design idea.

Researchers have suggested classifying prototypes according to their level of detail, and these levels are designated as high- or low resolution or fidelity (Buchenau & Suri, 2000) or are differentiated into models and prototypes (Evans, 1992). Non-functional objects are called models and are used to describe the appearance of a design proposal (Holmquist, 2005).

Another approach is to define such objects as impromptu prototype(s) (Radcliffe, 1998), which are 'quick and dirty' prototypes (Brown & Wyatt, 2010) that physically express an idea, a dimension, or a detail in a quick and rough way. In contrast to prototypes with a high level of detail which are often full-scaled physical representations that incorporate functional components.

Furthermore, prototypes are differentiated in having a physical or virtual form. (Best, 2006). However, the relevance of how intangible prototypes can be realised is a relevant topic (Thoring & Mueller, 2012). An intangible prototype is e.g., a role play (Svanaes & Seland, 2004) and a virtual form have e.g., CAD models or a video.

Physical prototypes are relevant for the concept design phases and have limitations when it comes to design in large scales (as needed e.g., for airplanes). Consequently, in such conceptualisation contexts further prototyping approaches are used. Using Virtual Reality Prototyping allows the immersion of the users for grasping their opinion on the design proposition (M. Li et al., 2022). However, in this project we focus on physical prototypes and disregard Virtual Reality Prototyping.

Furthermore, there is a need for prototyping tools communicating intangible and tangible elements of e.g., smart products (Wang et al., 2022). However, this question lies outside the scope of this thesis.Different types of prototypes (ergonomic, functional, empathy prototypes) address different aspects of a design to test (Houde & Hill, 1997a; Y.-K. Lim et al., 2008). It is up to the designer to decide for the most appropriate type of prototype in the current process phase. The selection of the best prototype for the current situation is a relevant topic.

Designers use impromptu prototypes to clarify or test their own thoughts and to communicate and share understanding among design teams, users, or clients. Impromptu prototyping is mostly used in the early phase of a design process but can be used later in the process as well, visualising and testing a new idea. In the context of service design it is relevant to develop creative ways of user involvement to anticipate the service proposition (Snelders & Vervloed, 2015).

Peng (1994) argues that the 3D properties of a model or prototype enable to develop, reflect, and communicate ideas with others. Prototyping supports a shared mental model with a team or a client. The activity can also be used for a specific communication method to persuade other stakeholders, the team, users, or clients (Pei et al., 2011).

A prototype not only transfers information, but also incorporates knowledge and documents previous decisions. Various low-fidelity prototypes can be used to interact with users to obtain feedback and information that indicate the way how to proceed.

Prototypes are frequently used as visual and tangible tools for communicating ideas, especially during the problem analysis, definition, and ideation phases (Goldschmidt, 1997). On the opposite side of the prototyping range, there are high-end prototypes that can test and simulate the latest product or process with all the elements, qualities, and features the final design will have: for example, the preproduction prototype, blueprint, and beta software version will all be in the end of the process.

The concept of building prototypes in the preliminary stage is supported in the research and in the design-thinking approach (make the idea tangible), in which it is considered an important mindset for the designer. The benefits of applying prototyping have been widely discussed in the literature, and the reasoning is multifaceted. It is important to choose the right prototype to generate knowledge to answer any (design) questions (Evans, 1992; Houde & Hill, 1997). The inherent questions that occur when designing is different regarding the process phases, the object itself, and the context of the object.

2.5.3 INTERRELATIONS BETWEEN SKETCHING AND PROTOTYPING

In the previous part we reported research that investigated sketching and prototyping separately. In this section results from the research literature on the interplay between sketching and prototyping and the comparison of the two activities are presented.

Comparison of sketching and prototyping

Research that was done to compare sketching with prototyping mostly addressed the early phases of the design process (Bao et al., 2018; Häggman et al., 2013; Vidal et al., 2004b; Viswanathan & Linsey, 2013). A prominent method in the early phase to generate ideas is Brainstorming (Osborn, 1953). Researchers found that design teams who brainstormed on functional design problems and used sketching created more diverse ideas compared to when they use prototyping. In contrast to the use of sketching in a Brainstorming the use of prototyping led to create more valid ideas (Vidal et al., 2004).

In general, the prototypes that are built in the early phase to generate ideas and concepts are rather low fidelity prototypes and that to build prototype is in general perceived as being a rather time-consuming activity even if the amount of time to build prototypes differ.

Interestingly, research has shown that designers working individually on a product design task sometimes realise a simple prototype faster than a sketch. Furthermore, these designs created by prototyping were perceived as being more novel, more aesthetically attractive, and offering more comfort in their use (Häggman et al., 2015). A further comparison was done focusing on sketching with sketching compared to sketching with prototyping. Results showed that to build prototypes was related to higher quality of ideas compared to the use of sketches only (Viswanathan & Linsey, 2012). The reported research focused on the comparison of sketching and prototyping and did not investigate e.g., its role in the early phase of the design process nor the impact on the designer. More research is needed to gain a better understanding of sketching's and prototyping's role in the design process and the impact of these on the designer.

Interplay of sketching and prototyping

There is few research done on the interplay of sketching and prototyping and their way they effect e.g., design outcome or/and people. One study researched the interplay of sketching and prototyping in engineering design (Faas et al., 2014). The results suggest that, for a simpler mechanism task, the influence of sketching and prototyping are interchangeable regarding their influence on idea quantity and quality (Faas et al., 2014).

In a follow-up study (Bao et al., 2018), the interplay of sketching and prototyping was researched in a design context with a complex task. This time the participants of the study were design students. According to the results of the study, sketching supported the generation of more ideas, the exploration of a broader design space, and the development of more novel final designs. Moreover, the design students who were only allowed to prototype developed designs were evaluated as more aesthetic and functional compared to designs of students who were only allowed to sketch. In the reported study, the interplay of both, as well as individuals allowed to use sketching and prototyping, explored the design space in more depth compared to the other group who were only allowed to sketch or prototype and had final ideas that were assessed as being more creative (Bao et al., 2018).

Building on the few studies that compare sketching and prototyping or focus on the interplay of both on e.g., designers, we are optimistic that the exploration of sketching and prototyping and design expertise enables valuable insights for design research and education.

Summary: The interrelation's impact on the designer

In the focus of this research is the expertise of designers and their use of sketching and prototyping activities. As design activities are conscious actions of designers, therefore relevant elements such as cognition, motivation, and emotion were previously introduced. The sketching and prototyping activities impact not only the design process and its outcome but also impact the designer on various levels. Sketching and prototyping have impact on a cognitive level, to support memory relieve and for thinking processes, on a motivational-emotional level to gain certainty, to increase self-efficacy, that can result in higher motivation to use sketching and prototyping even more.

The contradictory variables of complex problems challenge cognitive resources, such as information processing. Meaning it is relevant to support working memory in order to facilitate thinking and reflection in design processes. Central for supporting thinking is the working memory and can be supported by visualisation. Sachse and Hacker (2012) found that experienced engineering designers reported using sketching and (impromptu-) prototyping (for externalisation) to relieve their memory.

Building on the insights from research literature sketching and prototyping can be considered as a learning opportunity. This approach offers a further perspective of supporting the designer and the use of sketching and prototyping towards learning barriers and enablers.
Thus, Dweck (2008) demonstrated that people's belief in whether intelligence is mostly fixed or mostly shaped by practice significantly impacts whether they seek learning opportunities. Dodgson and Wood (1998) found that, with high self-esteem, people respond less negatively to failure and focus on strengths rather than weaknesses. Both results address designers who must meet high requirements of design problems.

Research results indicated evidence that one source – among others –for self-esteem and self-efficacy can be engaging in sketching and especially in prototyping. One beneficial prototyping approach is successive prototyping during the design process that enhances the self-efficacy belief of the designer (Dow et al., 2009, 2011).

In addition a successful interaction with low-fidelity prototypes relates to a positive learning experience and can be considered a small win, leading to a gain of certainty (Gerber, 2009): 'By taking frequent action on manageable tasks, practitioners profit small wins by experiencing and by observing their impact and attributing success to their actions' (Gerber, 2009, p. 333). Gerber (2009) frames the approach of using low-fidelity prototypes as a learning process that 'reduces uncertainty'. Certainty, or the sense of control, is one of the basic human needs, according to Maslow (1943).
Humans need to feel control to be able to master their environment. The mastery experience is, in addition to vicarious experiences, verbal persuasion, and emotional and physiological states, one of four sources of self-efficacy, according to Bandura (1982). Self-efficacy is a concept of a personal judgement concerning 'how well one can execute courses of action required to deal with prospective situations' (Bandura, 1982, p. 122).
An individual with strong perceived self-efficacy regarding an activity or skill has high motivation to approach and fulfil a challenge and invests great effort to achieve their aim.

Thus, a designer with high self-efficacy will approach a more challenging or complex design problem and put more effort into accomplishing the task than a designer with low self-efficacy. Building multiple prototypes in parallel to the design process not only results in a better outcome of the solution's quality, but also enhances self-efficacy (Dow et al., 2011). Self-efficacy grows over time and by achieving various mastery experiences. Based on the concept of self-efficacy a designer with high self-efficacy belief in own complex-problem solving abilities is convinced to master and control the process. Moreover, the designer is certain, motivated and will activate all resources needed to overcome obstacles to attain the set goal (Bandura, 1993).

This chapter provided the theoretical basis for this PhD research. In the following chapter the set-up, conduct and the results of the first study are presented.

Parts of this chapter have been published in:
Jobst, B. (2020, August 6). *The Bonding Gap Between Proficient Designers and Their Prototypes* [Conference Presentation]. 23rd DMI: Academic Design Management Conference, Toronto, Canada.

3 STUDY 1: PROFICIENT DESIGNERS

The survey study's aim is to explore PDs' use of sketching and prototyping activities. The sample of the study are designers at a proficient level, designated as graduates with some professional experiences (Lawson & Dorst, 2005).
The survey study's aim is to explore PDs' use of sketching and prototyping activities. The sample of the study are designers who have 'some small degree of professional experience and solve routine problems for clients and users' (Lawson & Dorst, 2005, p. 9). This level of expertise is described as 'probably a fairly comfortable experience that presents few challenges either in the development of a design or to the approach itself' (Lawson & Dorst, 2005, p. 9). To investigate PDs' awareness for the value of sketching and prototyping activities, a survey study was set up to answer the first research question:

> *RQ1: How do Proficient Designers use sketching and prototyping in the design process?*

Through the survey study, qualitative and quantitative data were collected using an online questionnaire. Answers to closed questions and scale were analysed quantitatively, whereas a coding scheme was developed to analyse the qualitative data derived from open questions. The responses from the PDs were used to generate a status quo regarding their use of sketching and prototyping activities. The results of this study are the first step towards achieving our overall research aim to learn from ODs'.

3.1 THEORETICAL CONCEPTS

This survey study's aim is to reveal PDs sketching and prototyping activities being phenomena of their design expertise. Consequently, we employed an open, exploratory approach that enabled us to understand better:
1) the PDs' use of sketching and prototyping activities, and 2) the strengths and weaknesses therein, as well as 3) PDs' perceptions of characteristics of sketches and prototypes.

Furthermore, we decided for a retrospective approach and relates to the methodological approach from other researchers (Cross, 2001b; Deininger et al., 2017) for data collection.

Moreover, we built on the assumption that activities practised frequently are generally nearer to a person's consciousness and were mentioned more often than activities rarely executed (Reason, 1990). Thus, the responses from the PDs offered insights regarding frequently performed sketching and prototyping activities, motivation for the use, and assessed relevance. Our first study's aim is to understand PDs' use of sketching and prototyping activities.

Therefore, we conducted a survey with open and closed questions. A coding system was developed for the analysis of the answers to the open questions. The development of the coding system is based on the identified patterns, trends, and relationships between the collected data.

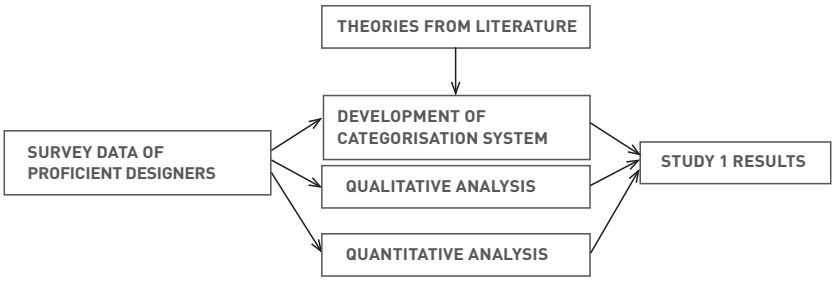


Figure 3. Overview of Study 1.

3.2 DATA COLLECTION

This survey study is based on a questionnaire containing closed questions (on scales and checklists) for quantifiability of answers. Moreover, as we targeted a larger number of respondents, the decision for a questionnaire is appropriate (Blessing & Chakrabarti, 2009).
In addition, we integrated open questions in the questionnaire. Open questions are used by other researchers, for its aid to a better understanding of, for example, implicit motivation (Cross, 2001b; Cross & Clayburn Cross, 1996).

3.2.1 SAMPLE

The sample of Proficient Designers was selected to gain insights into graduates who have completed their design studies and are now gaining their first experience in professional practice. The study' s sample consists of PDs (n=54), with backgrounds in design. The sample involves designers with initial professional experiences (from one year up to five years) and thus matches the description of the proficient level of expertise (see Chapter 2). Table 4 gives an overview of the study sample.

Table 4. Sample of the Study: Proficient Designers.

Gender		Professional Experience (in years)		
Female	Male	Mean (in years)	Std. Deviation	Range
33	21	M = 2.69	1.195	1–5

3.2.2 PROCEDURE

The developed questions were discussed with experienced researchers in the fields of design methodology and design research, and we conducted pilot surveys before soliciting participants for the final questionnaire.

These pilot surveys were distributed to seven probands, five master design students and two experienced professional designers, and after analysing feedback, confusing questions were revised to their current versions.
For the distribution of the questionnaire, we preferred an online survey to a printed one, since experience indicates that online surveys tend to result in more feedback. Online surveys also make distribution and collection easier, prevent data-entry errors, and allow respondents to decide when to complete the questionnaire. The collected data are then available immediately for download and processing. The questionnaire we used was only accessible through a web link and could be processed and edited with a browser (www.qualtrics.com).

3.2.3 SURVEY DEVELOPMENT

The questions for the questionnaire were deduced from concepts stemming from the research literature, the teaching experiences of the author, and from design methodology (see further details on data collection 3.1.1). For the survey study, we used a questionnaire with in total 22 questions/items. The questionnaire was developed and divided into three thematic sections: Personal Data, Sketching and Prototyping as Design Activities, and Sketching and Prototyping in Practice. In the following, we introduce the three parts of the questionnaire and provide example items.

Type of questions

The questionnaire collected qualitative and quantitative data. For the quantitative data collection, we decided to use two types of closed questions: check boxes and scales. Rating scales represent an evaluation continuum (e.g., agreement, intensity, frequency, satisfaction), which allows different characteristics and phenomena to be studied. The respondents could rate the content of questions and statements (items) by choosing a suitable category of the rating scale.

We decided for checkboxes and a five-point Likert scale because of the odd number of points allowed for the expression of uncertainty via the 'neither nor' option in the middle of the scale. In addition, to these scales with five scale anchors (see the questionnaire in the appendix), check boxes were incorporated for the questionnaire. A question to be answered on a checkbox is e.g., *Is there a moment when you can´t do without sketching? Yes, no, I don´t know).* The participants of the survey study were asked in the questionnaire about the characteristics of sketches and prototypes. Therefore, we used a rating scale ranging from 1 (*I don't agree at all)* up to 5 (*I agree completely)* and an example item is: *What do you think about prototypes in your daily work?* The participants are asked to indicate the level of agreement on a scale (please, assess the following claim from 1 to 5): *A prototype should have degrees of freedom to allow (re-)interpretation and/or spark new ideas, new concepts, etc*. In addition to closed questions, there was a variety of open questions. These questions allowed us to move from the general (e.g., *What is sketching for you?)* to the specific *(e.g., Can you describe a moment when you cannot do without sketching?).*

Thematic Parts

A Personal Data. In this section, the participants were asked about personal data (e.g., gender) and professional background (e.g., educational background, experiences in practice).

B Sketching and Prototyping as Design Activities. In this part the respondents were asked about their perceptions of sketching and prototyping, the important functions of sketches and prototypes, and the typical and core situations for using sketching and prototyping (e.g., *In your opinion, what is the most important function (or use) of a sketch in your design work or process?).* They were asked about the characteristics of sketches and prototypes using a rating scale ranging from 1 (*I don't agree at all)* to 5 (*I agree completely*). For example, *What do you think about prototypes in your daily work? A prototype should have degrees of freedom to allow (re-)interpretation and/or spark new ideas, new concepts, etc.*

C Sketching and Prototyping in Practice. In this part of the survey, the participants were asked about the value of sketching and prototyping (among other things) for different design phases using a five-point scale, in which 1 meant not important at all and 5 meant very important. An example question is: *How important is sketching for you in the following design phase? Clarification of the task?* The participants were also asked for a core moment of using sketching and prototyping; exemplary item: *Is there a core moment when you can't do without prototyping? If, yes please describe this moment!*

Closed questions: Seven characteristics measured by Likert Scales

Within the three different thematic parts of the questionnaire, we used five-point Likert Scales (see Table 5). These items of the questionnaire are concerned with process phase characteristics based on the concept of the design process model of Pahl et al. (1996). The 'characteristics of sketches and prototypes' are based in part on the concepts discussed in research literature (Das & Yang, 2022; Pei et al., 2011). These items are the foundation for variables derived from the survey. For seven items of the questionnaire seven characteristics were conceptualised based on theoretical constructs derived from research literature concerning 'Basic Characteristics' of sketches and prototypes (1-3) and 'Design Phase Characteristics' (4-7) relating to different phases in the design process with sketching and prototyping. The seven characteristics

are used as items for the Likert scales. The characteristics are introduced in the following part.

The first study aims to understand how PDs use sketching and prototyping.

To aid this understanding, the designers were asked how they perceive the characteristics of sketches and prototypes, as well as the relevance of sketching for different phases of the design process. We derived seven characteristics sketching and prototyping types corresponding to seven items (on Likert scales). These characteristics (previously described) are not only part of the preparation and construction of the questionnaire itself (also relevant to data analysis and used as research scheme). The seven characteristics of sketching and prototyping (a research scheme) are introduced in the following: three Basic Characteristics and four Design phase Characteristics, as well as their requirements for the problem-solving process.

Table 5. Research scheme with seven characteristics.

Basic characteristics	
1	A sketch/prototype should be open to reinterpretation
2	A sketch/prototype should be realistic
3	A sketch/prototype should support the communication of the design idea
Design phase characteristics	
4	Sketching/prototyping is important to the clarification of the task phase
5	Sketching/prototyping is important to the concept design phase
6	Sketching/prototyping important to the embodiment design phase
7	Sketching/prototyping is important to the detail design phase

After introducing the topics and structure of the questionnaire, we present the background concepts for selected items relevant to the subsequent data analysis of the responses to the quantitative questions. We introduced three items concerning the characteristics of sketches and prototypes and four items addressing sketching and prototyping activities in different design phases.

Basic Characteristics (1–3). We aim to understand better which characteristics PDs perceive as relevant for their design process. For the items addressing the 'characteristics', we assume the responses relate to the same resolution of their design process. For each design phase, we assume the same degree of resolution.

Basic Characteristic 1. To describe and categorise types of sketches and prototypes, the levels of low and high fidelity are appropriate and have been used by other researchers (Rudd et al., 1996; Sauer et al., 2010; Virzi et al., 1996). Low fidelity concerns the level of detailing or precision regarding all possible aspects of a design representation and can be related to visual refinement, functionality, and interactivity. A sketch or prototype described as having 'low fidelity' is fuzzy enough to be open to different understandings and interpretations. These rough and often-imprecise design representations are mainly used to support ideation and thinking processes. An imprecise design representation can also serve as a reminder of an idea and aid its discussion (Sachse, 2007). The development of low-fidelity prototypes is usually associated with the use of material different from the final product, such as paper or other impromptu prototypes (Radcliffe, 1998) or quick and dirty prototypes (material collages). Simple low-cost externalisations (manual sketching and impromptu prototyping) are perceived to offer the most support for communication (Sachse & Hacker, 2012, p. 603). The use of early and mostly roughly executed prototypes opens the design space to new alternatives (Rudd et al., 1996). (Example item: *A sketch or prototype should: have degrees of freedom to allow (re-) interpretation and/or spark new ideas, new concepts, etc.)*

Basic Characteristic 2. Sketches and prototypes can provide a high degree of fidelity regarding appearance, aesthetics, dimensions, functionalities, and other aspects. High-fidelity design representations are intended to serve as documentation and presentation, as well as the evaluation and selection of concepts, ideas, functionalities, etc. (Sachse, 2009). Similarly, research involving expert engineer designers has found that 'sophisticated' externalisation (e.g., manufactured prototypes) offer the most perceived support for evaluating solutions (Sachse & Hacker, 2012, p. 603). (Example item: *A sketch or prototype should be realistic (e.g., in terms of shape, proportion, surface).*

Basic Characteristic 3. A sketch or prototype allows different aspects of a design to be conveyed, for example, the design idea. When interacting with a team, users, or clients, the sketch or prototype can assist communication of the design idea. The sketch or prototype can be used to gain feedback and

attain a shared understanding with others. (Example item: *A sketch or prototype should 'support the communication of the design idea, including the underlying design considerations. Meaning, the process and reasoning that led to the current design proposal.*')

Design Process Phase Characteristics (4-7)

PDs were asked to assess the relevance of sketching and prototyping at different stages of the design process. Based on results from case studies, Pahl and Beitz (2007a) developed the 'systematic approach' and structured the design process into four process phases. In the systematic approach, the authors describe the requirements that the designer has to fulfil in each of the four phases. These requirements are explored in more detail in the following and for each design phase, the same degree of resolution is assumed.

Design phase Characteristic 4. The Clarification of a task phase involves several steps, such as analysing the problem, developing a problem frame, and elaborating the specification. The analysis of a problem influences both solution quality and the outcome of the process (Römer et al., 2000). Mental resources, and working memory especially, are challenged during problem-solving; therefore, the release of the working memory is necessary. The working memory has been described as the 'needle's eye of thinking´ (Sachse et al., 2014, p. 339), and sketching and prototyping can aid release (Sachse & Hacker, 2012): 'The higher the mental resources are loaded during the analysis of the given problem, the higher the probability of inappropriate or incorrect representations, as well as incorrect operations on them' (Anderson & Jeffries, 1985; Dörner, 1976; Klauer, 1993). External aids as sketching and prototyping are described as supporting problem analysis among others by facilitating the working memory (Römer et al., 2000; Sachse & Hacker, 1997). Some researchers have argued that, 'the process of sketching has been shown to enhance the construction of a mental representation, and thus the sketch has improved analysis of the problem' (Leinert et al., 1999, p. 30). Not only sketching, but also prototyping benefits the process. In engineering design contexts, early low-fidelity prototyping is emphasised during the first design phase to prevent more costly faults at later stages (Ehrlenspiel 1995): 'Low-fidelity prototypes have great value in the requirements gathering and analysis phase of product development' (Rudd et al., 1996, p. 79). (Example item: *Sketching and prototyping are important for the clarification of the task phase.)*

Design phase Characteristic 5. The concept of design phase is possibly the most important phase due to its links with creativity and innovation (Goldschmidt, 1991; Purcell & Gero, 1998b; Suwa, Gero, et al., 1998b). The main steps in this phase are framing and the development of ideas based on prior problem analysis. A concept is developed based on possible solutions, and sketching supports this key moment in the process in various ways: 'Sketching in a design context serves not only as a visual aid to store and retrieve conceptualizations but also as a medium to facilitate more ideas, and to revise and refine them' (Bilda & Gero, 2006, p. 1020). Similarly, the relevance of prototyping in this phase is stressed by researchers. Early and parallel prototyping leads to better outcomes (Dow et al., 2011; Yang, 2005). In addition, early prototyping also supports enhanced certainty (Gerber, 2009) and self-efficacy (Dow et al., 2011). The use of early and rough prototyping is stressed and taught in the design-thinking context, and even formulated with a rule intended to be absorbed within the designer's mindset: 'Fail early, fail often!' The focus here is early verification of hypotheses and determining what will and will not work. To apply this attitude, aim to prevent fixation in designers and avoid the embrace of premature ideas. (Example item: *Sketching and prototyping are important for the concept design phase).*

Design phase Characteristic 6. The embodiment design is relevant for evaluating and selecting ideas and concepts and for developing the concept, functionalities, ergonomics and other aspects of a design further (Ehrlenspiel et al., 1998; Pahl & Beitz, 2013). Tasks in the embodiment phase include the generation of a preliminary layout, the definition of the construction structure, the elimination of weak elements, and the identification of errors, disturbing influences, and base costs (Pahl & Beitz, 1996). (Example item: *Sketching and prototyping are important for the embodiment phase)*.

Design phase Characteristic 7. For the designer, the relevant steps in the planning and design process (Pahl & Beitz, 1996) in this phase include the development of a definitive layout, detailed drawing, and completing production, assembly, transport, and operating instructions. Sketches, and especially prototypes, are intended to support these steps and to form the basis for testing, evaluation, and final decisions. (Example item: *Sketching and prototyping are important for the detail design phase).*

3.3 DATA ANALYSIS

Since we employed both open and closed questions, the collected data were analysed using both qualitative and quantitative analysis. The responses to open questions from PDs were qualitatively analysed, and therefore a coding system was developed. The responses to the questions measured by Likert scales were quantitatively analysed.

Translation

The questions of the questionnaires are in English, as they were distributed at TU Delft and Anhalt University of Applied Sciences. Therefore, the answers were mainly given in English and only a few designers answered in German. The German answers were translated into English. The responses given in English, have been modified regarding the spelling and/or grammar – when necessary for comprehensibility. In some instances, the author added parenthetical dots to indicate the quotations were shortened or added a word in parenthesis to facilitate the understanding.

Analysis of Quantitative Data

The data collected through the survey described above were analysed using a quantitative approach. The questionnaire responses from the PDs provided data regarding the use of sketching and prototyping in practice. The answers to the questions measured with Likert scales were analysed quantitatively. For analysing the answers, we used the seven characteristics applied on the scales to deduce a research scheme. The research scheme of seven Characteristics was already introduced in the previous part. Since all PDs' answers were at the extremes of the five-point Likert scale and no answers were given in the middle of the scale, we summarised the answers and divided them into '(very) important' and 'not important (at all)'.

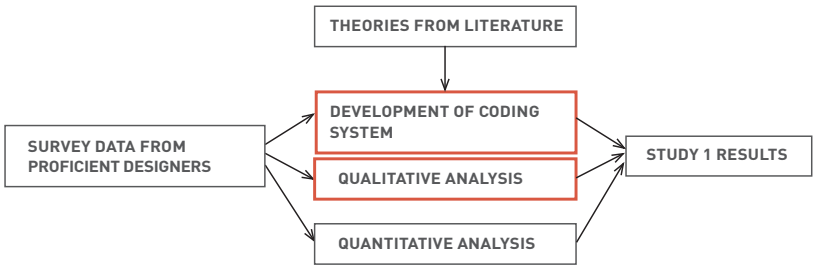


Figure 4. Qualitative Research Approach.

3.3.1 CODING SYSTEM

To analyse the PDs' responses to the open-ended questions qualitatively, we developed a coding system based on empirical and theoretical concepts from the research literature. All derived codes, categories and subcategories of this coding system are theoretical assumptions.

Two types of coding approaches were used: inductive (Boyatzis, 1998; Creswell, 2013; Patton, 2014) and deductive (Crabtree & Miller, 1992) coding. Inductive coding is an iterative analysis of a dataset, in which patterns, themes, and codes may emerge from the data (Boyatzis, 1998; Creswell, 2013; Patton, 2014). In addition, to the inductive coding analysis, we also employed deductive coding. This approach leveraged theoretical concepts from the research literature to contextualise our findings about designers' sketching and prototyping usage and activities. The approach also supported identifying additional patterns and gaps in the data that were not captured by the inductive codes (e.g., gain of certainty). For the coding, the software Atlas Ti (www.atlasti.com) was used. We began by analysing participants' responses through the development of codes from emerging patterns and topics relevant to our guiding research question as described in research methodology (Blessing & Chakrabarti, 2009). The selection and development of codes, categories, and subcategories, to allow all responses to be classified together, was repeated until no further changes were necessary, and any overlap of subcategories and codes was eliminated. The corresponding codes of sketching and prototyping were compared to see if any might be interchangeable. After several repetitive coding processes, the saturation of codes was attained. The author examined all the questionnaire responses in various cycles of coding to ensure that critical information was covered. Through this process, 16 subcategories and descriptions were developed, which captured trends and patterns. This data analysis was again analysed by a second experienced researcher, and the interrater reliability was tested (interrater agreement). An important outcome of the analysis procedure was, in parallel to results, the development of a measure – a coding system – that is presented in the following section.

Three categories of activities

The developed coding system is characterised by three substantial overarching categories of sketching and prototyping activities. Following our analysis of activities as outlined in Chapter 2, we formulated a function for activity.
Hence, activity (A) is a function (f) of the task (T), the person (P), and the interaction (I):

$$A = f(T, P, I)$$

Consequently, our coding system consists of three categories: task-, person-, and interaction-related activities. We now introduce the deduced categories and subcategories of the coding system, covering the activities of sketching and prototyping in the design context. The three categories of sketching and prototyping are relevant to the design process and, like all activities, are central components of human behaviour. At the centre of every activity is a person, who is motivated to act. There are various theories about human action and motivation, and twentieth-century researchers have differentiated the motivations that guide action in various ways (Bartl & Dörner, 1998). Maslow's hierarchy of needs (Maslow, 1943), for example, differentiates five needs (self-fulfilment, and two basic and two psychological needs) and posits three central information needs at the cognitive level (esteem, belonging and love-needs) that influence daily life. We postulate that sketching and prototyping activities form part of daily practice of designers.
In this research we focus on activities related to sketching and prototyping. We referred for the analyses of responses to the three categories of sketching and prototyping activities – already introduced (in Chapter 2) – and used these in the coding system. The three categories of activities in the coding system are: task-related, person-related, and interaction related activities of sketching and prototyping.

Task-related activities. Exemplary activities (and subcategories) in the system are 'allowing ambiguity' (2.2) and 'gaining certainty' (2.1). The latter category contains all activities related to sketching and prototyping that are executed to solve complex problems in the design context. These mentioned activities are designated as 'task-related activities of sketching and prototyping'. Exemplary forms of these activities are 'generating ideas' (1.1) and 'reflecting' (1.3). The two mentioned categories address the single designer.

Person-related activities. Activities that are impacted by motivations and/or emotions are designated as 'person-related activities of sketching and prototyping'.

Table 6. Coding System of Study 1.

Categories		Subcategories	Definition / Description
1 Task-related activities			
	1.1	Generating ideas	Ideation, generating ideas, further development
	1.2	Conceptualising	Developing a concept, detailing an idea in alignment with solution criteria
	1.3	Reflecting	Higher level thinking and reasoning. For the definition of reflection activities, see Chapter 2.
	1.4	Being aware of reflection on sketches and prototypes	Awareness that reflection upon sketches and prototypes is relevant for the designer, actively initiating moments of reflection.
	1.5	Reducing complexity	Narrowing problems to reduce complexity.
	1.6	Accelerating decision-making	Creating and using sketches and prototypes to enable decision-making.
	1.7	Facilitating cognition	Strategies to support the working memory and to liberate the mind for the preparation of new ideas.
2 Person-related activities			
	2.1	Gaining certainty	Adopting preventative measures to avoid fear of failure, nonworking solutions, or wrong decisions.
	2.2	Allowing ambiguity	Aspects that are new or not yet perceived appear in a sketch or prototype and are considered in the process.
	2.3	Facilitating the continuation of the process	Aiming to facilitating the (creative) design process
	2.4	Displaying expertise	Forms a characteristic unit; forms how people aim to be seen
	2.5	Self-expression	The intent to express oneself; artistic ambition
3 Interaction-related activities			
	3.1	Search for information	Support the search for information in books, online, or other places (excludes information gained from experts).
	3.2	Transfer of information	Aiming to transfer information
	3.3	Transfer of information addressing the user	Using sketching and/or prototyping to interact with users.
	3.4	Developing a shared mental model	To gain an ideal, shared understanding

Interaction-related activities. The third category, 'interaction-related activities of sketching and prototyping', focuses on interaction with the designer's social environment. Humans act and interact within a given context and environment, and these activities inform the 'interaction-related activities of sketching and prototyping'. Exemplary activities of an interactive situation are 'transferring information' (3.2) and 'developing a shared mental model' (3.4) based on sketching and/or prototyping.

These three categories of sketching and prototyping activities are overarching 16 subcategories, described in the coding system in Table 6. The coding system was introduced and visualised to the subcategory level. In Chapter 4, the coding system will also be used to analyse the responses from the ODs in Study 2.

3.4 RESULTS

The PDs' sketching and prototyping are explored based on responses to a questionnaire. The following quotes in this section are selected because they are prevalent in the data. In addition, this explorative approach is a qualitative one and we refrained to transfer qualitative data into quantitative ones. Results from quantitative and qualitative data sets provided valuable insights into the

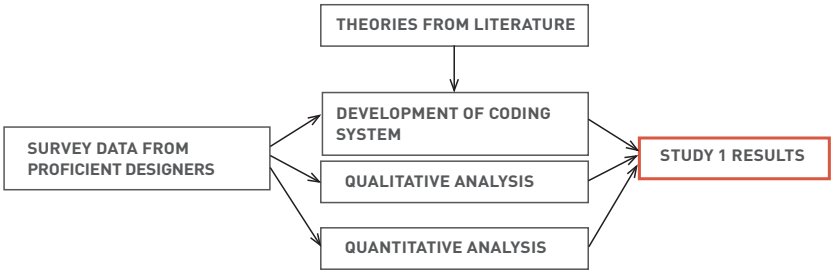


Figure 5. Results of the study.

PDs' use of sketching and prototyping activities in order to answer the first research question. The results were structured into quantitative and qualitative ones.

Procedure. Responses from PDs will be reported in the sections sketching activities (3.4.2) and prototyping activities (3.4.4). In sections 3.4.2 and 3.4.4, we report the results from the qualitative analysis approach (see Figure 5). We present PDs quotes in order to answer how they respectively use sketching and

prototyping activities. Exemplary and selected quotes were structured for more precise answers to the research question, according to the three task-, person-, and interaction-related activities of sketching and prototyping (as described and employed in the coding system, see Table 6).

Labelling of quotes. We report exemplary responses/quotes from PDs. For reasons of anonymity, we consecutively numbered the 54 PDs (PD1 to PD54) and labelled each quote with the number belonging to the corresponding respondent to identify multiple responses from the same person. Furthermore, we labelled each quote based on a certain pattern for reason of connectivity and transparency. Therefore, we have started to mark the quotations with a 'PD' for sample, followed by an 'S' (sketching) or 'P' (prototyping) for the corresponding activity and a 'Q' for quotation, followed by a sequential number for the quotation (e.g., PDSQ1). In the following we present exemplary quotes from the PDs, focusing first on sketching and then on prototyping.

Structure of presented quotes. Quotes can relate to various categories of activities or subcategories. Thus, one quote explicitly or implicitly addressed foremost various activities. The addressed activities are commented on after each quote.

3.4.1 RESULTS OF SKETCHING

Sketching results from quantitative data

In the following, we report the results from the Likert-scale portion of the questionnaire regarding the relevance of sketching to PDs in their design process. The results refer to the relevance of Basic Characteristics of sketches (in Table 7) and the relevance of sketching in different design phases –the Design Phase Characteristics (in Table 8).

Basic Characteristics

In Table 7 the results are presented regarding 'Basic Characteristics of Sketches'. More than half of the PDs expressed relevance for all three types of sketches (n_s 28-35/54). The claim assessed as most frequent is that 'a sketch should be open to reinterpretation' (n_s =35/54). Such sketch can also be designated as having a low fidelity or resolution.

The statement rated as the second most frequently mentioned characteristic of a sketch is that 'a sketch should be realistic' (n_s =29/54). The difference to the least assessed sketch is small and differs only in one answer from a PD, referring that 'a sketch should support communicating the design idea' (n_s =28/54).

Table 7. Results of the Basic Characteristics of Sketches.

Basic Characteristics
A sketch should be open to reinterpretation (n_s =35/54)
A sketch should be realistic (n_s =29/54)
A sketch should support the communication of the design idea (n_s =28/54)

Design phase Characteristics

The results from the Likert-scales are reported regarding the relevance of using sketching in different design phases of the design process. As already mentioned in Chapter 2; the design process can be divided into four phases into the phase of: clarification, concept design, embodiment, and detail design (Pahl et al., 2007a). The PDs were asked about their assessed relevance of sketching for each phase in their design process. For the majority of all the PDs (48/54) sketching in the concept design phase was considered as being relevant (Goldschmidt, 1991; Schütze et al., 2003; Scrivener et al., 2000; Verstijnen et al., 1998). The PDs second most highly assessed design phase that saw the relevance of sketching is the embodiment design phase (40/54). As the third most assessed design phase there were 33 PDs (33/54) who replied that sketching is important for clarifying the task phase a phase where one main aim is to analyse and understand the task. 28 of the PDs claimed that sketching is relevant to them for the detail design phase (28/54).

Table 8. Results of the Design Phase Characteristics of Sketching.

Design phase Characteristics
Sketching is important for the phase: Clarification of task n_S=33/54)
Sketching is important for phase: Concept design n_S=48/54)
Sketching is important for phase: Embodiment design n_S=40/54)
Sketching is important for phase: Detail design n_S=28/54)

The results from the Likert scales, are related to results from PDs responses to open questions and are discussed in section 3.5.

3.4.2 SKETCHING ACTIVITIES

Results of the qualitative data

The previously reported results from scales contribute to answering the first research question. This section includes sample quotes to underpin our findings, taken from prevalent responses from the PDs. The findings are divided into the three categories of sketching activities. Often the reported sketching activity of the quote not only address one but various activities. In this case we decided to structure the quote according to the most obvious of the three sketching activities.

Task-related sketching Activities

Exemplary PDs quotes from the category task-related activities of sketching are reported below.

Insight: Generating Ideas

> *PDSQ1: 'It allows the mind to move on, ideas flow better. (...) For me it's all about the hand–brain connection.' (PD41)*

PD41 used sketching to support ideation, and in this context stressed the hand – brain connection (PDSQ1).

PDSQ2: 'Sketching is the time to let the ideas flow, without being concerned about aesthetics, feasibility, or complexity. It is the time to have as many ideas as possible, and the important thing is to catch the main goal of any idea.' (PD46)

In PDSQ2 the PD described the use of sketching to generate ideas and as being a joyful activity rather than directed and goal-orientated process.

Cognitive Facilitation

PDSQ3: 'Sketching for conceptualisation to support cognitive facilitation.' (PD51)

PD51 mentioned the use of sketching for conceptualisation and facilitating cognition (PDSQ3)

PDSQ4: 'First step in creation. Absolutely necessary. Can only think with a pen in my hand.' (PD4)

The quote PDSQ5 expresses PD4's attachment to sketching, with sketching being a precondition for idea generation and facilitating cognition.

Reflection

PDSQ5: (...) 'it is a form of communication with others, a sketch is a first prototype, it is a reflection tool.' (PD54)

The PDs used sketching to generate ideas, a diverging activity that opens space for ideas and solutions. In order to converge this large amount of information and ideas the designer has to decide which of the ideas is most appropriate. PD54 described the use of sketching for reflection and considered a sketch to be a 'reflection tool' and a 'first prototype'. (PDSQ5)

PDSQ6: 'To clarify my way to proceed.' (PD50)

PD50 mentioned the use of sketching for clarification, which is (only) one aspect of reflection (PDSQ6)

PDSQ7: 'You can't communicate, you can't get things done your way, you can't even begin with a creative process, also, no-one has the time to read big text articles, and most people lack the brain capacity/feature for visualisation (...) without using sketches.' (PD51)

Person-Related Sketching Activities

Exemplary responses from the PDs regarding person-related sketching activities are reported.

Insight: Continuation of the process

Sketching seems to ease the complexity of information and provides a feeling of cognitive facilitation (PDSQ7).

> *PDSQ8: 'I am comfortable using it in my design process. It helps me generate ideas and avoid a creative block.' (PD8)*

Sketching was deemed to support the continuation of the design process, and even to prevent creative blocks by PD8 in quote PDSQ8.

Insight: Attachment with sketching

> *PDSQ9: 'I start sketching, as the process itself has some effect on the mind, that somehow, I feel my hand is doing the thinking. I don´t know how to explain it!!! But I think it's another mindset and context see ideas shape on paper, so different.' (PD30)*

In PDSQ9, the designer described sketching as 'another' mindset and assessed it positively. This mindset seems to facilitate thinking and cognition. The quote refers also to allow ambiguity in sketches and to unexpected discoveries. In addition, the use of sketching seems to facilitate thinking and cognition.

> *PDSQ10: 'I also use sketches if I need to understand the physical relations of physical properties or objects.' (PD6)*

The use of sketching for the search for certainty and information was expressed in PDSQ10.

> *PDSQ11: [I use sketching] 'For all design projects, I simply cannot hold the required volume of information in my head simultaneously.' (PD22)*

Sketching was used to facilitate cognition, reported in PDSQ11 by PD22.

> *PDSQ12: 'Sorting out the thoughts in my head to get ideas out that I haven't "pictured".' (PD14)*

In PDSQ12 is expressed the use of sketching to support cognition, and to transform ideas into images, which only happens when beginning to sketch on paper (not before).

Insight: Self-Expression

> *PDSQ13: 'It has a good hand feeling for me. And the outcomes always have great expressive force.' (PD24)*

The expressive force of the sketching outcome might aim to display expertise. Furthermore, PD24 reported positive emotions when sketching and attributing expressive force to the outcome (PDSQ13).

> *PDSQ14: 'I am mostly sceptical about things I like to open the door for changes unless it's more a self-expression thing, then I am not open changing it.' (PD30)*

The quote from PD30 reveals their use of sketching for reflection, allowing for ambiguity and self-expression (PDSQ14).

> *PDSQ15: 'It's a way of expressing oneself and of describing a picture that only exists in your imagination. Without sketching, it would not be possible to explain a shape, function, or concept in a similarly precise manner, regardless of whether the sketched idea is presented to oneself or someone else'. (PD17)*

PD17 described in PDSQ15 the use of sketching for self-expression and precise explanation. The PDs perspective stress the use of sketching to gain certainty and to develop a shared mental model.

In the responses, the PDs use of sketching for personal related activities are reported, which are among others the use of sketching, allowing ambiguity self-expression or gaining certainty. In two quotes PDs expressed a joyful approach to sketching (PD8/PDSQ15, PD24/PDSQ5), where one reported positive physiological feedback when sketching (PD24/PDSQ5). We detect a tendency towards an emotional attachment to sketching.

Interaction-Related Sketching Activities

The activities that pivot on interaction were conceptualised as 'interaction-related activities of sketching', and we report some related quotes.

Insight: Search for Information

> *PDSQ16: 'It is a quick way to explore many routes of a design. It is relaxing, it is liberating (putting thoughts out of your head).' (PD54)*

PD54 uses sketching for cognitive facilitation and the search for information. They expressed positive emotions during sketching and a tendency to prefer a playful approach (PDSQ16).

> *PDSQ17: 'Visual thinking, presentation of ideas to clients, communication within teams and vendors.' (PD51)*

> *PDSQ18: 'Communicating ideas within a design team, and (communication) sometimes works for the client as well.' (PD37)*

PD51 and PD37 referred to using sketching for information transfer (PDSQ17, PDSQ18).

> *PDSQ19: 'Sketching can complete words and express the "ineffable" to visualise things that cannot be explained by words or use it to complete words.' (PD43)*

PD43 believed sketching supports the development of a shared mental model (PDSQ19).

> *PDSQ20: 'If you don't sketch, you can't transfer the picture in your head to other people's heads effectively, as some people are really bad at visualisation and visual thinking, so you need to show them the picture on paper.' (PD51)*

PD51 mentioned that sketching supports the transfer of information by developing a shared mental model (PDSQ20).

Summary of sketching insights

Sketching is reported to be used foremost for generating ideas. In the answers we found rather a divergent approach to sketching. Few uses of sketching to reduce complexity or to reflection (in a structured way) e.g., constraints, own standards or criteria were not mentioned by the PDs.

In the quotes there is a clear tendency of a positive and emotional attachment for sketching (PDPSQ15, PDPSQ 5). There is a notion in the responses that the designer can 'rely' on sketching. The use of sketching for self-expression seems to be relevant for the PDs too. The PDs in our study expressed being aware of the use of sketching to search and transfer information. PDs mentioned the relevance of using sketching to develop a shared mental model

(Badke-Schaub et al., 2007) within a team, user, and clients. One of the PDs considered that some people are bad at visual thinking. Having reported the results related to PDs' use of sketching, the results regarding prototyping activities are presented in the following section.

3.4.3 RESULTS OF PROTOTYPING

In this section, we report the results of how PDs assessed the relevance of different Basic Characteristics of prototypes and the relevance of prototyping for different design phases (Design Phases Characteristics).

Prototyping Results from quantitative data

The results from the responses to the Likert-scale portion of the questionnaire regarding the relevance of prototyping to 54 PDs are reported. The results relate to the Basic Characteristics of prototypes in Table 9 and Design Phase Characteristics in Table 10 are presented below.

Basic Characteristics of prototypes

The most frequently ticked statement by PDs is that 'a prototype should support the communication of the design idea' (n_p =31/54). The second most mentioned statement is that 'a prototype should be realistic' (n_p =29/54). The prototype that was assessed being important for less than half of the PDs from 26 PDs is the statement that 'a prototype should be open to reinterpretation' (n_p =26/54).

Table 9. Results of the Basic Characteristics of Prototypes.

Basic Characteristics
A prototype should be open to reinterpretation (n_p =26/54)
A prototype should be realistic (n_p =29/54)
A prototype should support the communication of the design idea (n_p =31/54)

Design Phase Characteristics of Prototyping

In the questionnaire, the designers were asked about the relevance of the use of prototyping for different design phases. The results are presented in Table 10. Based on the data, the majority of PDs (45/54) considered prototyping to be important to a later design process phase (embodiment phase) rather than earlier phases. Furthermore, most of the PDs considered prototyping to be relevant during the later phases of the design process, specifically the embodiment phase (45/54) and the detail design phase (38/54). In contrast, the PDs did not highlight the relevance of prototyping for the early phases of the design process and thus less than half of the PDs assessed relevance for the early phases. Hence, 18 PDs agreed that 'prototyping is important for the clarification phase' (18/54). In addition, 24 of the PDs concurred that 'prototyping is important for the concept design phase' (24/54).

Table 10. Results of the Design Phase Characteristics of Prototyping.

Design Phase Characteristics
Prototyping is important for the phase: Clarification of task n_p=18/54)
Prototyping is important for phase: Concept design n_p=24/54)
Prototyping is important for phase: Embodiment design n_p=45/54)
Prototyping is important for phase: Detail design n_p=38/54)

Prototyping Results from qualitative data

As in the previous sketching part, selected quotes are reported and labelled starting with a 'PD' for the sample, followed by a 'P' for the related prototyping activity, and a 'Q' with a successively augmenting number for the quote (e.g., PDPQ8).

3.4.4 PROTOTYPING ACTIVITIES

The PDs' quotes related to prototyping are structured into person-, interaction- and task-related activities of prototyping. Often one quote addresses more than one activity. This overlap of activities was considered and then structured into the more obvious category.

Task-Related Prototyping Activities

PDPQ1: [...] 'to prototype! develop ideas, try and test ideas and concept.' (PD24)

PD24 mentioned prototyping activities for the early design process phase. Hence, the designer was aware of prototyping's benefit for the generation of ideas as well as for testing of ideas and concepts (PDPQ1).

Insight: Cognitive facilitation

PDPQ2: 'When things become too complicated to keep them all connected.' (PD17)

In quote PDPQ2 the PD reported using prototyping in order to reduce complexity and to use it for cognitive facilitation.

PDPQ3: 'If you don't prototype a new product, you are half blind because you can't guess how the volume, the materials, and the interface will interact with end users and context.' (PD21)

PD21 was aware of prototyping's benefits to gain certainty and to transfer information to the user. Further motif is reducing complexity and accelerating the decision-making (PDPQ3).

PDPQ4: 'It works as an extension of the sketch; it allows us to store more information in a physical object, so that we don't need to keep the sketch in our head. It allows us to think in three dimensions (even if the object is not a product)'. (PD22)

In PDPQ4 the designer expressed, awareness for the prototype's ability to store and transfer information, which also supports the working memory and facilitates cognition.

Insight: Reflection

PDPQ5: 'Prototyping (is important) for evaluating a design.' (PD9)

PD9 mentioned in the quote (PDPQ5) the use of prototyping for evaluation purposes is related to reflection.

PDPQ6: 'Finding the real practical problems in the final steps.' (PD32)

PD 32 reported in PDPQ6 relevance for to use the prototype rather in the later phases of the design process and to use it for analysing in order to find problems.

Nevertheless, the designer did not explicitly mention using prototyping for reflection or related activities such as analysing, structuring, or selecting.

Person-Related Prototyping Activities

In this section, we present quotes from the PDs about prototyping activities related to the person-related principle they emphasise.

Insight: Gaining certainty based on feedback

> *PDPQ7: 'When I need to find reactions to my work. (Prototyping) 'helps u to find results and reactions you did not predict.' (PD 43)*

PD43 aims to gain certainty by using the prototype to get reactions from others to forecast results. Further effect might be to facilitate the process (PDPQ7).

> *PDPQ8: 'Some ideas might not work in the end. If client can already know he doesn't want it's better to not waste time on extra details.' (PD39)*

PD39 uses prototyping for a shared understanding and to gain certainty to accelerate decision making and to facilitate the process continuation (PDPQ8).

> *PDPQ9: 'The importance is that with the prototype we can see how our product will interact with the user, the context, and the world. Also, we are going to feel the product in its physical characteristics.' (PD21)*

PD21 stress the relevance of prototypes tangibility and use prototyping to gain information based on interaction with the user (PDPQ9).

Insight: Cognitive facilitation

> *PDPQ10: (...) it's good for you to have a general picture on how the project will look like in the end.' (PD28)*

PD28 mentioned to use for to gain certainty and can thereby facilitate the process (PDPQ10).

Insight: Displaying expertise

> *PDPQ11: 'With prototyping, you show your capability to make things real.' (PD16)*

PD16 considered prototyping to be supportive and beneficial for the presentation own competencies and show expertise, as well as know-how regarding feasibility (PDPQ11).

Insight: Reflection

> *PDPQ12: 'Prototypes provide the ability to test and analyse previously visualised ideas, testing handling and functional aspects.'(PD52)*

In the quote the use of prototyping for analysing and testing. Furthermore, there is also a tendency of using prototyping for gaining certainty (PDPQ12).

> *PDPQ13: 'Prototyping has also helped me to raise questions about details I forget to consider while planning an experience only in my head or in a text. It is an excellent way of finding out what specific information we are missing.' (PD13)*

PD13 recognised prototyping's benefits regarding searching for information, evaluation and gaining certainty. Prototyping is used to facilitate cognition.

Interaction related activity

Insight: Relevance of testing with the user

> *PDPQ14: 'To see how the product looks like and how it works and test it with the users.' (PD27)*

PD27 uses prototyping to interact with the user to gain feedback (PDPQ14).

> *PDPQ15: 'Prototypes are a perfect tool to make a sketch more tangible so the client can imagine how it will look like and work once it's finishe(d)s' (PD49).*

In the answer was mentioned using prototyping in order to gain a shared understanding and to create a shared mental model. Prototyping is used for involving tangibility's and functionality of a prototype into evaluation for the client (PDPQ15).

> *PDPQ16: 'The most important function of a prototype is to allow the user to interact with a design idea or a design proposal. After the interaction, the user will be able to provide feedback to the designer, or the designer himself/herself will learn something about it.' (PD33)*

PD33 was conscious of the benefit of prototyping for transferring information to users in order to interact with the prototype and for gaining information. Stress the relevance of prototypes for interacting with the user and is considered being a learning opportunity (PDPQ6).

Insight: Late use of prototyping in the process

> *PDPQ17: 'Prototyping is one of the last steps in the design process. It gives you the possibility to see the problems, the functions, and how the audience perceive the design.' (PD20)*

PD20 appreciated prototyping, especially in the later phases of the process. The Designer was aware of both prototyping's importance for the product's audience and its use for identifying problem (PDPQ17).

> *PDPQ18: 'To develop ideas with others.' (PD12)*

To interact with other individuals in order to develop ideas further was the mentioned prototyping activity by PD12 in (PDPQ18).

> *PDPQ19: 'to show it to potential users and evaluate it' (PD6).*

PD6 uses prototypes for interaction with user. Prototyping is used for evaluation and is related to reflection (PDPQ19).

> *PDPQ20: 'Making sense of a solution, gathering critique from the team etc. A quick prototype for the client never hurts.' (PD37)*

PD37 considered prototyping to be an (expected) part of client work for information transfer. According to PD 37, the prototype seems being more relevant for the client than for the designer's own use for reflection and exploration (PDPQ20).

Summary of prototyping insights

The PDs employed prototyping activities for solving design problems for evaluating a design. Therefore, one PD stressed the benefits of the tangible and functional side of a prototype. Another PD was aware of facilitating cognition or supporting the working memory. Also, we see a tendency to use prototyping to facilitate the continuation of the design process. The PDs expressed using prototyping to forecast how a project might evolve. The interaction with others and reactions to the prototype seem to be considered as being supportive, insightful and a gain of certainty.

Evaluation and reflection tend to be related to interactive situations. The PDs might apply a trial and error approach, and to reflect retrospectively and think backward (Ahmed et al., 2003). A further tendency of the PDs' use of prototyping is to display expertise. The possibility of storing information and knowledge in a prototype. Some of the PDs in our study emphasised interaction to receive reactions (PDPQ3, PD21, PDPQ6, PD20) and feedback (PDPQ6, PD33) from users. Therefore, the cited PDs seem to engage with users, the team, and clients in order to get reactions. We assume that this interaction is motivated to gain feedback and to enter a reflective conversation. The external reflection approach supports the designer in reducing complexity and gaining certainty. Quantitative and qualitative sketching and prototyping results are summed up in the following.

Summary

The presented quotations are exemplary excerpts from the PDs' questionnaire responses. In the quotes the PDs mentioned a range of sketching activities and purposes and especially emphasised the use of sketching for ideation. Furthermore, they expressed an emotional attachment to sketching and seem to rely on sketching during the design process (allowing to express themselves and to communicate with others). The PDs expressed few emotional attachments compared to sketching. In the quotes an emotional attachment regarding sketching was expressed.

There is a tendency for PDs to have little motivation to use their prototypes to reflect and gain certainty. Moreover, it seems that their reflection is not self-initiated and rather externally motivated or supported by reflective conversations with others. The PDs tend to use of prototyping especially to communicate and interact with user, team, and clients to learn from their reactions to the prototype. It might be that a side effect of prototypes is to trigger own reflection activity. However, in their responses, only few PDs expressed relevance to use prototyping for evaluating or reflecting. It is possible that PDs seek feedback on their prototypes but do not consider it as a form of reflection. It may also be that they do not yet perceive or name the concrete and relevant function of evaluation and reflection using prototypes. This could be a kind of lack of awareness of the value of prototyping for reflection. It is also possible that the PDs have the attitude of defending the prototype they have worked long and

hard on, rather than reconsidering it and discarding it if necessary, this might be due to the phenomenon of the sunk cost effect (Viswanathan & Linsey, 2013). The PDs may avoid reflecting about it in order not to have to discard something they have already invested a lot. In particular, the PDs with low prototyping skills require a high cognitive effort in prototyping, which could explain their lower prototyping activity.

All in all, in the answers there was little expressed emotion or emphasis for using prototyping. Based on the quotes only small indices for awareness for reflection were found. In the PDs answers there was also an absence of perceived relevance for using sketching and prototyping for reflection, reducing complexity, and gaining certainty.

Summary of insights from sketching and prototyping activities

Based on our findings, we postulate that PDs emphasised the following use of sketching OR prototyping:

Sketching in the early phase

- Positive emotion and attachment regarding sketching and rather few positive emotions regarding prototyping
- sketching is especially used to generate ideas.
- prototyping is used for user testing.
- prototyping is used for gaining feedback from the team and clients.
- prototyping is used for evaluation.

PDs neglected the following use of sketching and/or prototyping:

- little awareness for reflection.
- to gain certainty.
- little awareness of the benefit to a structured approach to reflection. based on sketches and prototypes.
- no expressed awareness for constraints, framing or derived criteria.
- little awareness of cues of uncertainty
- little prototyping in the early phases of the process.
- a tendency to compensate reflection activities with team discussion.
- early phase of the design process.

In the following section, we discuss the study results.

3.5 DISCUSSION

The results of the study are underpinned by theoretical constructs from the research literature and discussed. These insights were synthesised and flowed into the deduction of two explanatory models. The abstraction of a process in the form of a model facilitates the development of recommendations for the improvement of the identified neglected or overemphasised activities.

Models

The variables involved in such interplay are many, and to investigate each would add too much complexity for detailed research. Therefore, we chose an abstraction and decided on models. The explanatory mode to visualise the relation of design expertise and sketching respectively, prototyping. Each of the models, is not intended to represent the complete array of factors involved in the relation. Instead, we focus on the essential influences from our findings that are relevant to the real process, and we represent these via an abstract, explanatory model, focusing on a specific part of the relation to integrate our findings. These complex relations are visualised in two models, the relation between the PD's design expertise level with sketching (Figure 6) and in the model PD's expertise with prototyping (Figure 7).

In the model the 'plus signs' mean an increasing effect and the 'minus signs' mean a decreasing effect. Each causal relationship between two concepts is considered separately, so that a preceding negative influence reverses the entire subsequent loop. The relationships were defined based on (a) insights from studies and (b) based on literature and were described in the following sections.

3.5.1 THE RELATION BETWEEN PROFICIENT DESIGNERS' EXPERTISE AND SKETCHING

In PDs responses we not only identified their use of sketching activities but also gained insights about their motivations, emotions, and aims. Based on these insights, the motivations for PDs sketching behaviour were derived.

In the PDs' answers, we could identify an emphasis and emotional attachment towards the use of sketching in their design process. We postulate that one

reason for this emphasis relates to the use of sketching in the early phases of the design process and is supported by 48 PDs (out of the 54) who assessed relevance for the use of sketching in the Concept Design phase. This expressed relevance further supports our assumption that the PDs emphasis on the use of sketching for ideation. Furthermore, this assumption is supported by the PDs' quotations (PD41; PD46) mentioning the use of sketching for idea generation and can be related to PDs (highest) assessed statement (of a sketch characteristic) that 'a sketch should be open to reinterpretation' (35/54). The use of sketching for ideation is congruent and postulated to be the activity with the most impact for the design process (Goldschmidt, 1991a). The benefit of sketching, in particular for the early phases of the design process, has been reported in various research results (Goldschmidt, 1991; Schütze et al., 2003; Scrivener et al., 2000; Verstijnen et al., 1998).

More than half of the PDs stated that a sketch should be realistic (33/54) and this might be a hint that they value or even have good sketching skills. We cannot make any statement about the mechanical sketching skills of the PDs despite good sketching skills might explain the PDs' preference for sketching. Moreover, good sketching skills might explain the assessed relevance by PDs to use sketching in the Embodiment Design Phase (40/54) and in the Detail Design phase (28/54).
Another explication for the PDs' emotional emphasis on sketching could be that sketching costs cognitively 'less' than prototyping. The cognitive costs of sketching in ideation seem to be lower compared to prototyping (Calpin & Menold, 2023).

Based on the findings it is assumed that the PDs' focus lays on the approach to diverge and to generate as much ideas as possible, and this relates to the concept of fluency. Fluency is related to creativity (Torrance, 1969). In the quotes we found indices that the PDs relate their sketching to creativity. This could lead to self-efficacy beliefs in sketching fluently ideas and could explain the PDs' emotional attachment to sketching.

Sketching is basically beneficial, powerful, and relevant, especially – although not only – for generating ideas.
The designers have not only to generate ideas but also to cope with the resulting complexity. Despite in the PDs' answers few indices for conceptualisation

and for the reduction of complexity was identified the PDs might rather focus on additional ideas than developing ideas thoroughly further. This assumption is in line to research claiming that during concept generation the novice designers are not able to 'configure out' their ideas (Chen & You, 2004, p. 8). This is a finding from novice designers and might also apply to PDs.
Based on the findings the PDs did not mention to use sketching for a structured reflection approach therefore, it is assumed that the complexity is insufficiently reduced. So how do the PDs cope with the complexity?
An interpretation is that the PDs sketch a lot in order to generate ideas to approach the solution until it is matched. Thus, the PDs might apply a trial-and-error approach. The use of trial and error pattern was observed in a study with novice design engineers (Ahmed et al., 2003) and might also apply to PDs.

In their answers, the PDs rarely mentioned that they use sketching for thinking OR reflecting. Moreover, we could not find in the responses any explicitly methodological, systematic, or structured approach to reflection. Further statement that was noted by 33 PDs is that sketching is important for the Clarification of task phase (33/54). In this phase researchers stress the relevance of analysing the problem and of creating representations of the problem in order to create a better understanding that is beneficial for the quality of the outcome (Sachse et al., 2004). Although more than half of the participating PDs gave importance to these activities, the PDs did not explicitly mention these activities in their responses.
Based on these insights relevant sketching activities such as analysing, reducing complexity and reflection might not be applied in a sufficient and structured way. Therefore, an unstructured approach to reflection which only insufficiently reduces complexity and result in uncertainty, is assumed.
The reduction of complexity is essential for coping with design problems because of the effect that certainty has on the quality of the outcomes (Bartl & Dörner, 1998). We identified some weaknesses in this approach of insufficiently reducing complexity (on the part of the PDs) and posit that it results in uncertainty.
Our definition of certainty has two aspects. First, it refers to perfect knowledge that is free from error, and second, to a mental state that is free from doubt. The search for certainty is part of basic human motivation and serves to avoid the experience of uncertainty (Dörner et al., 1994). Designers can reduce uncertainty through speculative attempts aimed at understanding and solving the

design problem (Buchanan, 1982; Cross, 2011). According to Bandura (1997), the experience of uncertainty depends on the perceived ability to control the uncertainty of a situation. An individual who is in an uncertain condition and is able to exercise high control will experience certainty and feel self-efficacious. A person who feels able to control a certain situation experiences: more intrinsic motivation, greater interest, less pressure and tension, more cognitive flexibility, more creativity, greater persistence (Deci & Ryan, 1987; Seligman, 1990), and there is evidence that all these aspects also impact the quality of outcomes.

The question arises as to why PDs continue to sketch in the face of great divergence, high complexity, and great uncertainty? PDs might ignore or not perceive the uncertainty that comes with many novel and divergent ideas.

Despite the assumed uncertainty there is indication in PDs' answers that they feel supported and can 'rely' on sketching. Based on the results, we interpret the observed behaviour as an overemphasis on sketching and relate it to the concept of self-efficacy. The more PDs sketch, and the greater the divergence of ideas, the more the designer has mastery experiences in sketching novel ideas. According to Bandura (1982), mastery experiences over time enhance self-efficacy beliefs and influence motivation, cognition, and emotion. Thus, the more the PDs produce divergent ideas, the more they feel self-efficacious in using sketching to generate fluently novel and diverse ideas. The more PDs are self-efficacious, the more they are motivated to generate more ideas. The more novel the ideas are, the more the designers have positive emotions and become emotionally attached to sketching.

One reason for the abundance of sketches could be the educational background of the PDs and that they were trained to sketch many different and novel ideas to avoid a premature fixation on one early idea.

This attitude may result in PDs sketching overflow, which might itself be a form of functional fixation on sketching. Functional fixation can impact design and design features, as well as methodological approaches. According to Cross (2001a), who investigated industrial designers and engineers, the designers' fixation on generating as many novel ideas as possible might stem from their training in design educational programmes. One reason for this approach to ideation might be the aim to 'be different' (Purcell & Gero, 1996, p. 300). Cross (2001a) interprets this behaviour as a positive form of fixation.

Based on our findings, we consider the PDs' strong attachment to sketching to be a form of fixation at a cognitive and emotional-motivational level.

Model of the Relation between Proficient Designers' expertise and sketching

In the following, we link our findings on PDs' sketching activities to theoretical concepts and findings from the research literature to interpret their strong attachment to sketching. The preliminary explanatory model is described from the top down. The model begins with the 'sketching activity' step. There is evidence, based on Research Literature, that the more sketching that occurs, the more ideas will diverge. This divergence of ideas results in the enhanced complexity of a design situation. The more the divergence, the more the complexity. However, a high degree of complexity leads to uncertainty and humans have a strong tendency to avoid uncertainty and seek certainty (Dörner, 2002). Thus, complexity needs to be reduced to gain certainty. In the responses from the PDs, we detected no awareness of the need to reduce complexity. Furthermore, we found no indication of structured reflection in the answers.

Therefore, we assume an unstructured approach and moreover, that this approach cannot entirely reduce complexity. As such, the complexity is not sufficiently reduced to gain certainty.

It seems the PDs are unaware of this uncertainty. They might perceive uncertainty at an emotional level, which is why they sketch to dissolve the complexity, since they can rely on sketching and even generate more ideas. The results indicate that the designers use sketching for their idea generation and at the same time show high emotionality when using sketching. Therefore, excessive sketching behaviour is assumed which we call the 'PDs sketching overflow'. Based on insights we consider the 'sketching overflow' as an approach to dissolve uncertainty and problematic situations via the generation of many ideas. This approach is of questionable use for the design process, because a 'sketching overflow' leads to even more divergence, more complexity, and thus greater uncertainty. We postulate the need to combine the use of sketching with a structured approach to reflection in order to reduce complexity and avoid the vicious circle of 'PDs' sketching overflow' (see Figure 6).

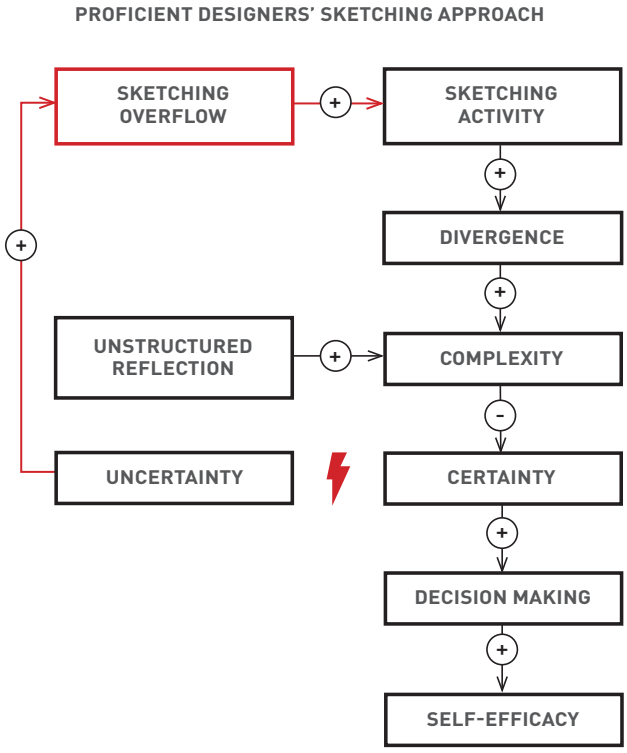


Figure 6. Relation between Proficient Designers' expertise and sketching.

3.5.2 THE RELATION BETWEEN PROFICIENT DESIGNERS' EXPERTISE AND PROTOTYPING

As in the previous part the insights are discussed and form the basis for the synthesis of a model. Our results indicate that PDs are aware of the several benefits despite – we postulate – not fully exploring them. Moreover, only few emotional attachments towards prototyping have been identified in the answers. Based on our data, less than half of the participating PDs mentioned the relevance of prototyping in the early phases, namely 18 (from 54) for the Clarification Phase and 24 (out of 54) for the Concept Design Phase in their design process. Few of the PDs mentioned relevance for prototyping activities in the early phases such as generating ideas, representation of the problem when they replied to the open-ended questions. As mentioned earlier, we assume, that mainly activities that were considered relevant and mentioned by the PDs will be selected and carried out. Given the majority of PDs who assessed that prototyping is not relevant in the early phase, we assume that they will follow their assessment and rather not build prototypes early in the process. Protypes are known to be relevant thinking aids, especially early physical models complement 'designers' erroneous mental models, leading to higher quality ideas' (Viswanathan & Linsey, 2013, p. 1). It is well known in the research literature that the early phases of the design process are of great importance for the whole subsequent design process and have an impact on the quality of the outcome (Dow et al., 2011; Yang, 2005). Thus, a design idea that is not thought through sufficiently can increase costs later in the process if expensive corrections are necessary (Ehrlenspiel et al., 1998). In the early phase it is recommended to build several low-fidelity prototypes in parallel in order to produce many divergent ideas (Yang, 2005), which leads to an increase in complexity.
We postulate that the PDs who do not use early prototyping might not be able to reduce the complexity of the prototype(s). Therefore, they may feel uncertain, unsupported, did not have a good experience with (early) prototyping which leads to little emotional attachment. This assumption is supported by the fact that PDs did not emphasise the use of prototypes for reflection in their responses. It seems that PDs are not getting the full benefit of their prototypes.
This approach might not be fully beneficial nevertheless, human beings often do not fully analyse situations before they make complex decisions (Dörner, 1996), instead, they decide based on rules of thumb or personal feeling rather than rational analysis (Kahneman & Tversky, 1972, 2013).

Another explanation for the neglect of prototyping and the low emotional attachment to prototyping may be due to the costs associated with it - in terms of effort, time, or money. These costs may be too high compared to the expected outcome. Therefore, the PDs might not build prototypes if the ratio between the cost of building prototypes and the benefit from the outcome is at least equal.
This can be related to the assumption that these PDs might be more used to routine tasks than complex design problems, so they might not need to build prototypes in the early phases.
The estimation of the cost benefit could lead the PDs to continue sketching at moments when reflecting and prototyping would be the better choice. They may prefer sketching because they are simply 'better' at sketching than at prototyping. This preference for sketching may be due to lack of prototyping skills, lack of access to facilities, lack of knowledge, among other causes, or may also have individual reasons. Design education and training can also have an influence on the preference.

Another reason for the preference could be the cognitive load that occurs during prototyping. Sketching might be experienced as less cognitively demanding and thus more attractive for the PDs. Calpin and Menold's (2023) findings suggest that there is a significant difference in the way designers experience cognitive load during ideation and prototyping, and that they experience prototyping as more cognitively demanding. Therefore, the PDs may prefer sketching to a rather cognitively demanding structured reflection approach OR early prototyping.

The PDs who ignore early prototyping might prefer prototyping at a late stage of the design process. Then, they decide on a single prototype to focus on, which might be less divergent and complex than building several prototypes in parallel. The approach of building rather high-resolution prototypes is related to high costs (time, effort, and money).

A possible disadvantage of this focus on only one high-resolution prototype may be that the prototype, which has been worked on long and hard, is defended instead of being reconsidered and, if necessary, discarded. (Viswanathan & Linsey, 2013). This attitude would relate to the concept of sunk costs. Sunk costs are costs that have been incurred and can no longer be reversed

(such as effort and time). A sunk cost fallacy occurs when a person convinces themselves that they should keep doing something because they have already put a lot of time OR effort when in return they will gain very little from it (Thaler, 1980).

It might be that the PDs use other approaches instead of a structured approach. In contrast to a high number of PDs who did not assess the relevance for the early design phase there were nevertheless, 24 out of 54 PDs who attributed relevance to the early phase. PDs of this group mentioned in their answers using prototyping early in the process for communication e.g., with the team, user, OR client. The PDs did not explicitly mention drawing benefits from dialogical interaction based on prototyping. Nevertheless, some of the PDs mentioned the motivation for interacting with e.g., the user not only to exchange ideas, but rather to provoke feedback. The involvement of the user not only provides information about the prototype, moreover a question-based dialog facilitates reflection (Wetzstein & Hacker, 2004). But none of the PDs related the dialogues with e.g., team members to the reduction of complexity or reflection. Therefore, this approach to reflection could be beneficial, but seems to be an unstructured approach to reflection. There might be good reasons for exceptions but in general not integrating prototyping early in the process is a finding that is problematic because of neglecting essential benefits of prototyping.

Model of the Relation of Proficient Designers' expertise and prototyping

We integrated our research findings underpinned with results from the research literature to develop a model that illustrates the relation of PDs' expertise with prototyping. The model (see Figure 7) is described from top to bottom. The more prototyping activity that occurs, the more the divergence (Dow et al., 2011; Yang, 2005). The more the divergence, the more the complexity and the less certainty there is.

Based on our results, we postulate that PDs use an unstructured and rather unconscious approach to dealing with divergence and coping with complexity. Complexity creates uncertainty, and uncertainty generates fear. Humans want to protect themselves from this fear. Therefore, the brain tends to block out all that is complicated, intransparent, and that can predict weaknesses and failure (Dörner, 1996).

Based on PDs answers it is assumed that the PDs use an unstructured and rather unconscious approach to cope with the complexity despite this approach may not sufficiently reduce complexity, meaning uncertainty remains. The PDs might not perceive and experience prototyping as helpful in this context and therefore no strong emotional attachment results from it. Therefore, they are not motivated to prototype. We call this behaviour the 'PDs' bonding gap with prototyping'.

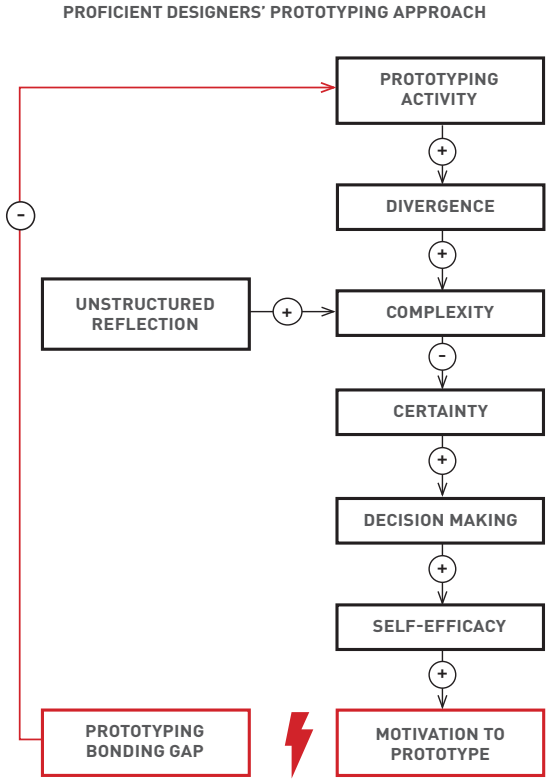


Figure 7. Relation between Proficient Designers' expertise and prototyping.

3.6 CONCLUSIONS

This survey study's aim was to explore the PDs' use of sketching and prototyping activities in the design process in order to answer the first research question:

> *RQ 1: How do Proficient Designers use sketching and prototyping in the design process?*

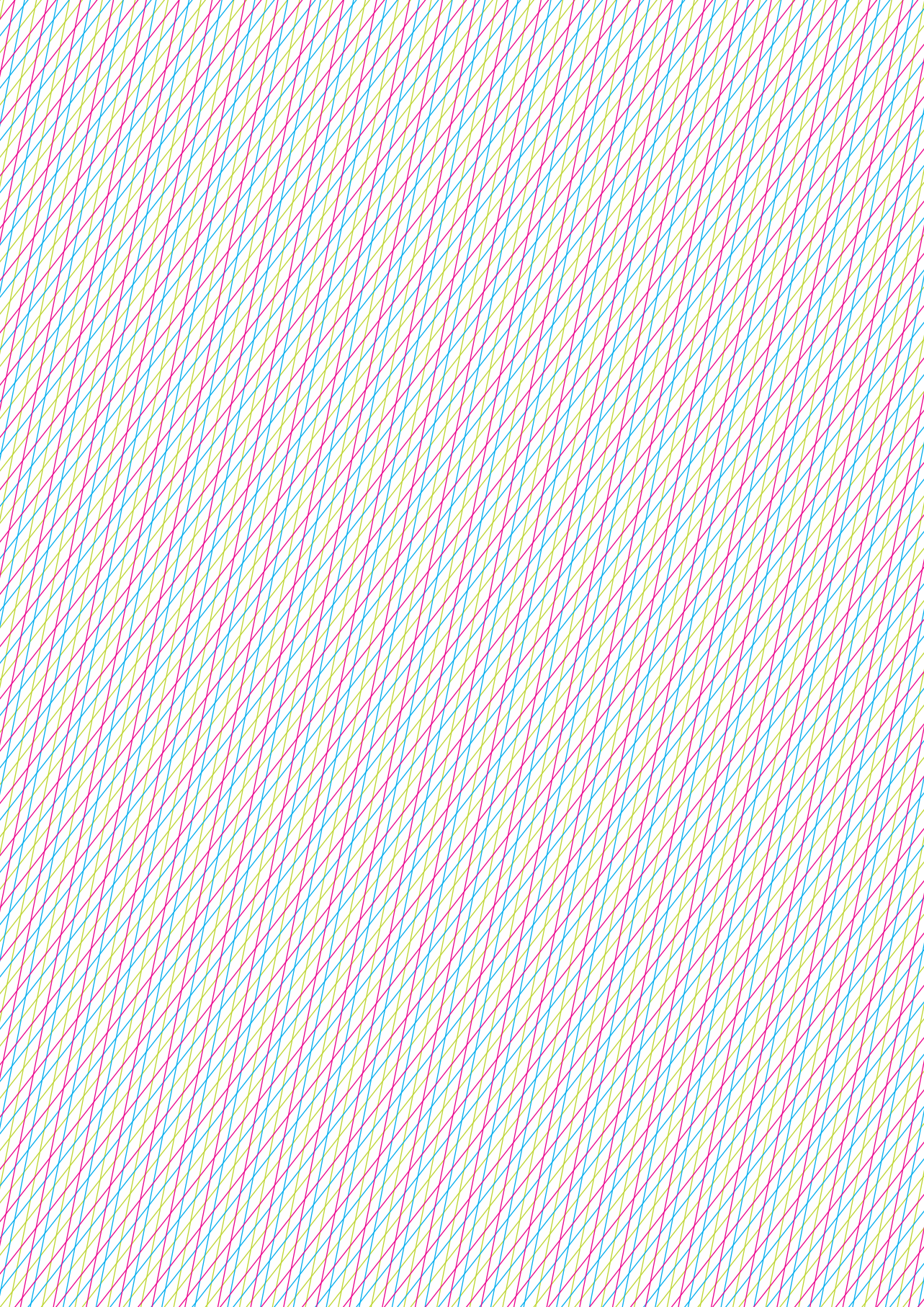
Through this study with 54 PDs, we determined the status quo of PDs' use of sketching and prototyping. Main insight from the responses to the survey is that the PDs are emotionally attached to sketching and that they can rely on sketching. This attachment results from the use of fluently sketching for ideation. As few reflection activities were reported from the PDs, it is assumed that the complexity of the design process is insufficiently reduced.
Therefore, the unstructured reflection approach might result in uncertainty. Moreover, it seems that, the PDs ignore the complexity OR produce even more sketches to approach a design solution until matched. This unstructured approach to reflection results in a behaviour that we call the 'PDs' sketching overflow'.

Based on responses on Likert scales a high number of the PDs did not express relevance for prototyping early in the process. This might be due that the PDs did not have experience the building of early prototypes as helpful. We assume this is because they cannot sufficiently reduce the complexity of the prototypes. Thus, they avoid using prototyping in the early phases and might prefer other approaches such as to build one single prototype in the end of the process OR use prototypes to provoke feedback. Some of the PDs emphasised to use prototyping for interaction with e.g., the user. We assume that the PDs are not fully aware of the benefits of a structured approach to reflection because they did not mention it. Therefore, the PDs seem to involve the user for gathering information and entering in a reflective conversation about the prototypes to learn from. Based on the insights that most of the PDs neglect early prototyping and show little emotional attachments to prototyping we label this behaviour as the 'PDs' bonding gap with prototyping'.

The predominant responses of the PDs and also those not mentioned were taken into account to interpret the PDs' behaviour. The assumed behaviour of PDs has to be further investigated in future research.

Based on the study results, a facet of the overall research objective was provided. In order to make the results and our theoretical assumptions more accessible and illustrative, the results were synthesised and flowed into the deduction of two explanatory models. These models represent the relation between PDs' expertise with sketching (Figure 6) and with prototyping (Figure 7). The explanatory models are preliminary and must be verified in future work.

In the following chapter, the second study is reported. The study results contribute to a status quo of ODs sketching and prototyping activities. This is the second step on the way to achieve the research goal of exploring the interplay of design expertise, sketching, and prototyping – in order to learn from the ODs.



4 STUDY 2: OUTSTANDING DESIGNERS

The interview study's aim is to explore Outstanding Designers' use of sketching and prototyping activities. In this study we present a closer look at designers with a high level of design expertise: the Outstanding Designers (ODs). This research is guided by the following research question.

RQ 2: How do Outstanding Designers use sketching and prototyping in the design process?

The results from the interviews with seven ODs not only answered the research question but contributed also to the overall research aim: exploring the interplay of design expertise, sketching and prototyping in order to learn from ODs. In addition, the findings were synthesised and flowed into the development of two explanatory models. The models facilitate the deduction of recommendations for improving the use of sketching and prototyping to learn from the ODs.

4.1 THEORETICAL CONCEPTS

This research aims to learn from ODs. Outstanding people are – as the term describes – rare. In addition, to the small number of ODs, it is often difficult to involve them in a study. This behaviour is the reason for few research: 'Most studies of designer behaviour have been based on novices (e.g., students) or, at best, designers of relatively modest talents' (Cross, 1998, p. 141). The reason for this approach is obvious – it is easier to recruit such people as subjects for a study. Moreover, Lawson and Cross (Cross & Lawson, 2005) described that designers with high expertise tend to be open only being involved in a single research approach: interviews.

Nevertheless, case studies also enable conclusions to be drawn based on a smaller number of participants. The obtained datasets were rich and offer a good impression of the use of sketching and prototyping and their value for ODs. Consequently, we applied an explorative approach based on interviews to investigate ODs use of sketching and prototyping activities. Therefore, interviews with seven ODs were held using the same set of questions as in the questionnaire for the PDs in Study 1. We decided for a semi-structured interview method. For ensuring that the 'same basic lines of inquiry' can be conducted

for each participant interviewed (Patton, 2002, p. 343) an interview guideline was prepared.

The interview guideline of questions enabled the same topics to be covered across interviews and ensured even coverage. As we aimed also at an explorative approach and as 'unstructured interviews are more suitable for an exploratory study' (Blessing & Chakrabarti, 2009, p. 272) we therefore, opted for a semi-structured interview based on a guideline and space for emerging topics. The guideline with a list of questions to ensure that the interviews were (to some extent) comparable, and at the same time this approach would be flexible enough to allow for reaction if new topics emerged. Any issues that appeared were explored further during the interview. As similar questions were asked in the survey and in the interview study, the same coding system was used to analyse the ODs' responses.

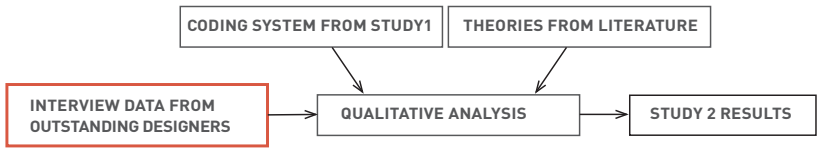


Figure 8. Research approach.

4.2 DATA COLLECTION

The study followed an exploratory approach and thus the data was collected through seven interviews.

4.2.1 SAMPLE

The sample of this study are ODs. The term 'Outstanding Designers' was coined by Cross (2001b), who greatly contributed to the research on design expertise. Cross describes ODs as 'highly creative or talented individuals who have become successful and highly regarded designers, with international reputations both within and beyond their professional peer groups.' (Cross, 2004, pp. 437–438). For identifying designers as sample for this study we built on concepts and descriptions from other researchers in the field of (design) expertise (described in Chapter 2).

Based on these concepts we developed criteria used as a means for the identification of ODs. In Table 11 we juxtapose the criteria to the designers and an 'x' means they do meet the criteria.

Table 11. Means of ODs Identification: Criteria.

	OD1	OD2	OD3	OD4	OD5	OD6	OD7
Criterion 1: Practice	x	x	x	X	x	x	x
Criterion 2: Success	x	x	x	x	x	-	x
Criterion 3: Reputation	x	x	x	x	x	x	x
Criterion 4: USP	x	x	x	x	x	x	x
Criterion 5: Design Focus	x	x	x	x	x	x	x
Criterion 6: Role Model	x	x	x	x	x	x	-

Designers with diverse backgrounds were selected for the interviews to obtain insights from differently elaborated expertise due to different fields of design. The designers differed in their mother tongue, the interviews were conducted with native Dutch and German-speaking designers.

Professional background of the sample

In Table 12, the interviewees are listed anonymously. The ODs are described by their background and the focus of their work, which are the reasons for their selection for the interview.

Table 12. Professional Background of Interviewees.

	Discipline	Field of expertise
OD1	Industrial Designer (Male)	Consumer goods
OD2	Furniture design (Female)	Furniture and consumer goods
OD3	Product Designer (Female)	Consumer goods
OD4	Fashion Designer (Female)	Furniture
OD5	Industrial Designer (Male)	Furniture
OD6	Industrial Designer (Male)	Consumer goods
OD7	Engineering Designer (Male)	Office furniture

4.2.2 PROCEDURE

To test the understanding and the flow of the questions for the guideline two pilot interviews were conducted.

Participants were an expert product designer (female), and a male expert glass designer (male). The insights were used to improve the intelligibility of the selected questions. In this case the order of questions was changed and transitions to the next focal point were added to the guideline. All seven ODs were met in their working context, in their studio or in one case in an office at university to conduct the interview. Each of the interview was led by the author. The interviews were audio recorded and took around 120 minutes on average. In two cases an interview was split into two interview appointments.

Survey Development

In total 15 items were developed for the guideline. The items are foremost based on the survey questionnaire from study 1. In addition, some items were developed and added based on concepts from the research literature (Ehrlenspiel, 1995) and design methodology (Blessing & Chakrabarti, 2009; Pahl et al., 2007c).

1 Personal Data: In this section, participants were asked about personal data and professional background (example question: educational background).
2 Sketching and Prototyping as Design Activities: Here, the respondents were asked about their perceptions of sketching and prototyping, the important functions of sketches and prototypes, and typical and core situations for using sketching and prototyping (example question: *What is sketching for y*ou?).
3 Sketching and Prototyping in Practice: This question asked the participants about the value of sketching and prototyping in their work. They were also asked for a core moment of using sketching and prototyping (example question*: Is there a moment when you cannot do without prototyping?).* If yes, please describe this moment.

4.3 DATA ANALYSIS

Before analysing the data, the interviews had to be transcribed. Two interviews were led in English and three interviews were led in German.
Among the group of interviewees were two native Dutch-speaking designers who switched sometimes between English and German in the interview.

Transcription

Interviews transcribed in German were translated into English. Sometimes, the designers were not concise in expressing their thoughts thus their statement remained ambiguous. Furthermore, in parts the grammar of the ODs' quotes in English has been improved. To support comprehensibility in some cases, notes from the authors were added to the quotes in parenthesis.

The interviews were coded in the same manner as the responses from PDs in Study 1. The Coding system was developed to analyse the answers from the PDs and was adapted for the answers of the ODs. For the data analysis, an inductive and deductive coding approach was applied. As soon as more codes appeared, they were added to the Coding system. For completeness, five subcategories were added to the existing Coding system, developed in Study 1. The additional subcategories identified in the answers of the ODs are presented (in Table 13) and were described in detail in the following.

Table 13. Further identified subcategories deduced from interviews.

Categories		Subcategories
Task-related activities	1.4	Being aware of reflection
	1.8	Implementing best practice prototyping routines
Person-related activities	2.6	Striving for success
	2.7	Bonding with prototyping
Interaction-related activities	3.5	Cooperating

Being Aware of Reflection: Awareness of reflection is defined as a combination of knowledge, expectation, and motivation (Jobst et al., 2020a). Knowledge can be differentiated into declarative knowledge (e.g., information) or procedural knowledge (based on e.g., experiences). Expectation is related to a mental model about how a certain e.g., object or situation should be. Motivation results in activity, in this context, reflection activities. Therefore, awareness of reflection can be described as a mental state of activity. Especially when a plan that normally works fails, such awareness sets in. This awareness describes not only the activity of the mind, but also implies the intention to act (see definition in Chapter 2). In this context, to begin a structured process of reflection to act and, for example, apply a method to gather more information is a relevant step in the design process. Awareness of reflection is activated (within another activity) when internal or external stimuli causes uncertainty.

A cue of uncertainty can be understood/interpreted as a signal to interrupt the current activity and to start reflection activities in a structured way. This described awareness for reflection can be related to the concept of monitoring that was described by Ericsson and Lehman (1996). They found out that exceptional performers monitor themselves during their activity in order to perform it perfectly or to improve it. This finding was derived in the field of elite sport. Nevertheless, the 'monitoring approach' is promising also for the design field and for attaining exceptional performance.

Implementing Best Practice Routines regarding Prototyping: We identified different intentions for implementing routines to support prototyping. These intentions concerned, among other aspects, specific staff, equipment, workshops, and even a culture (e.g., of showing early prototypes) to team members to support prototyping routines. These routines are dedicated to implementing prototyping best practice routines. Some of the Outstanding Designers (OD1; OD7) expressed not only an attachment to prototyping, but also described ritualised activities such as 'demonstrate or die' meetings, own well-equipped workshops with special trained craft workers, CAD experts and other foci to contribute to best practice activities related to prototyping.

Striving for Success: Traditionally, success is defined as the degree to which project goals and expectations are met (Lim & Mohamed, 1999; Parfitt & Sanvido, 1993). The elements of success are defined by criteria that form the set of principles or standards by which judgement is made (Lim & Mohamed, 1999). Project success is the aim, and the objectives of budget, schedule, and quality are the three normally accepted criteria to achieve the goal. A main insight from research with outstanding architects is that they establish highly demanding standards (Lawson, 1994b). We consider a certain motivation as necessary for at least facilitating the time- and attention-consuming activities in the design process especially for a structured and regular reflection approach. Therefore, we see evidence that outstanding performance is related to a high personal engagement. Or to bring it to the point: outstanding expertise is to a high degree nurtured with personal commitment (Lawson, 1994).

Bonding with Prototyping: We identified a behaviour in the answers that we call 'bonding' by analogy. We chose the analogy of bonding regarding the emotional component of a (happy, sustainable, and supportive) mother-child

relationship of a designer to their prototype. Designers with more experience build more prototypes, and by doing so increase their self-efficacy. We distinguish the behaviour of bonding from the concept of self-efficacy. We now examine both concepts and distinguish them from each other. The concept of self-efficacy is related to a specific activity, for example, generating many and diverse ideas. We relate self-efficacy in this context with complex problem-solving. Enhanced self-efficacy is related to motivation and the persistence to achieve a (challenging) goal (Bandura, 1982). Enhanced self-efficacy also influences the selection of a more challenging goal than would be selected without enhanced self-efficacy beliefs (Bandura, 1983). We consider the difference between self-efficacy and 'bonding' as follows. We interpret bonding as the behaviour(expression) of an enhanced self-efficacy belief in design problem-solving (based on prototyping). This enhanced specific form of self-efficacy is fortified and driven by highly successful experiences in problem-solving based on prototyping. According to Bandura (1997) The concept of self-efficacy is based on the exercise of control. Dörner and colleague (Bartl & Dörner, 1998; Dörner, 2008) also introduced a concept of control and certainty as basic human needs. Human beings aim to experience and exercise control (Bandura 1997). Regarding Dörner (2008) the level of control one person needs is individual. The need for certainty and uncertainty are opposed. You may say, on the one hand, there is curiosity and openness for uncertainty, and, on the other, there is certainty that can be related to boredom because it is known and controlled. The motivational process is the basis for control and allowing uncontrol. We describe uncontrol as related to allowing curiosity, discovering new things, seeking novelty, experimenting, and uncertainty. Whereas too much uncertainty can lead to insecurity and increased anxiety. Every person has a different degree of comfort with certainty and uncertainty. We expect that Outstanding Designers aim for control, to a high extent, but remain curious to follow the highest quality of design and can switch between both poles. We assume that ODs are simultaneously highly curious for information and at the same time have high certainty regarding controlling a situation. Thus, the ODs might be able to control certain elements they are certain and satisfied with while accepting uncertainty in order to allow search for alternatives for unsatisfying and central design aspects. We assume that the use of prototyping can support a divergent and convergent approach in the design process. A process that swings between divergence and convergence is described as an 'ideal approach' and is attributed to expertise (Chen & You, 2004).

Cooperating: At various times in the design process, designers involve other people, especially team, users, and clients. A typical situation for cooperating using sketching and prototyping is in meetings and presentations, in which not only information is shared and transferred, but also emotions. Parallel to transferring information, there is also the intent to make the counterpart (the client) certain that the design idea or solution is relevant. The designer is conscious about the relevance of cooperating with the client or manufacturer. Some of the ODs expressed the relevance of offering certainty to their counterpart (e.g., in a pitch or in an acquisition talk situation).

The above-described five activities were identified based on the ODs' answers and added as subcategories to the introduced coding system developed in the first study. We added the five activities to the Coding system, which resulted in a total of 21 subcategories to analyse the answers from the interviews with the ODs. The results and insights regarding the use of sketching and prototyping activities are presented in the next section.

4.4 RESULTS

The use of sketching and prototyping activities by seven ODs was identified through their interview responses. Similarly, as in Chapter 3, we allocated each participant a label for reasons of anonymity (to feel free to express their perspective). We consecutively numbered the seven ODs –with the labels OD1 to OD7– to enable the identification of responses from the same person, (see Table 12). The quotes are designated with a code-ID that consists of the prefix 'OD' for Outstanding Designer, followed by an 'S' for sketching or 'P' for prototyping, and a consecutive number of the quote (e.g., ODSQ3). The respective author of each quote is identified by a label and listed after the quote in parenthesis.

The results from the second study are presented based on selected quotes and are structured into task-, person-, and interaction related activities of sketching and prototyping. These three activities stem from the coding system and are used in the following to structure and present the results.
In addition, insights considered as being strong and characteristic indices of expertise were underpinned by quotes.

4.4.1 RESULTS OF SKETCHING

Task-related activity of sketching

Insight: Being aware of reflection

In the quotes an awareness of using sketching for reflection is expressed.

> *ODSQ1: 'You have ideas, and then you sketch. Then you reflect on this idea and then you go on. You empty your head by sketching and you start again, that is the way (...). And this reflection that starts again, to look critically at it and repeat [to sketch] again. This is a process with distinct steps. I do quite a lot of steps, yes. I do so! The same is true for prototyping.' (OD1)*

> *ODSQ2: 'A lot of things are still emerging in the process. And a lot of ideas come up in the process. And I don't see it as something rigid, but rather as all these means to check the concept again and again, if necessary, to adapt it, or, in the worst case, to discard it. (OD5)*

> *ODSQ3: 'Sketching it's actually a ping-pong between heart and hand, head and hand. And you can almost get into such a trance that you puzzle your way through it and go on.' (OD2)*

> *ODSQ4: 'Even when we're building some prototypes or something, they actually accompany the process, the sketches, in order to clarify things, because of course it's somehow the easiest way to express yourself, it's also the quickest, because you need so little equipment for it.' (OD3)*

In the quote sketching is used for reflection in order to gain certainty. Sketching is also considered being the quickest way of self-expression (ODSQ4).

Insight: Relating sketching and verbalising

> *ODSQ5: 'First of all, [sketching] it's just a quick way to capture thoughts, but I also often write something. So, it's a closeness of sketching and writing.' (OD5).*

Sketching is used for reflection and idea generation and results in a switch of verbalisation (verbatim information), and visualisation. Here, the use of sketching is related to verbalisation to support the designers' ideation and reflection on the ideas (ODSQ5).

> *ODSQ6: 'Oh yes, no, good. And then here again, like this, "How thick should that be then? Two millimetres, three?", "That will be 60", and then I have a table of, well, that's how it goes then, so also, ping-pong, but then between two people, so thoughts. [Sketching] That's also a way of quickly agreeing with each other what we're actually talking about here.' (OD2)*

Sketching is used and supported by verbalisation (question asking) to transfer information in order to develop a shared mental model (ODSQ6).

Person-related activity of sketching

Insight: Being attached with sketching

There is an emotional attachment to sketching expressed in the quotes (ODSQ7-9). The design expressed a reflection activity in their 'mind's eye' before they (have to) start to sketch. This activity can relate to previous experiences and the combination of already known solutions (ODSQ7+9).

> *ODSQ7: And then when it really comes to the design work and what it will look like. So, then the sketch is also totally important. Sometimes certainty is given before sketching!' (OD5)*

Reason for using sketching in this quote is the search for information and for gaining certainty (ODSQ7).

> *ODSQ8: 'Sketching is, yes, for myself!' (OD1).*

> *ODSQ9: 'Sketching (...) always happens on the side. And I don't think that [takes] much time. But something precedes that. I move it around in my head before I put it down on paper. And then it's always a back and forth.*

In percentage terms, it's certainly very little. But that's valuable time, isn't it?' (OD3)

The quote (ODSQ9) expresses an attachment to sketching and awareness for reflection in order to gain certainty. The reflection process is described as a movement of 'back and forth'.

Insight: Gaining certainty

Sketching is used to gain certainty and therefore, sketching with a sense of reality and based on experience and expertise is required (ODSQ10).

ODSQ10: 'For me, sketching is really something that is also very much linked to the reality of the material, that you also have experience and know how things really look, that you also take that into your sketches, otherwise they are totally useless, because they are then fantastic sketches. But you can't use these in reality.' (OD2)

ODSQ11: 'Actually, you already start with the right dimension. And it's always the war with the dimensions and the feeling. So, the sketches are a lot. So, at some points, and then I'm...then I already know, oh, that doesn't work, or I don't like that.' (OD1)

There is also awareness regarding the limits of sketching for certainty.

ODSQ12: '[Sketching] Actually, for the client very little. Mostly models are made, that you have to do the right consequence, and then the sketch doesn't tell you anything, when you make sketches (...)' (OD1)
In sketches I draw the dimensions. It doesn't say how heavy it is, what the surface of the materials is like. All this information is not in the sketches. And so, for me, that alone is a phase in this search but is not in the right part for communication.' (OD1)

Insight: Allowing ambiguity

In contrast to the use of sketching for certainty we found in the quotes also the use of sketching to allow ambiguity.

ODSQ13: 'To develop a new idea in the first place, because it comes about in the process and through visualisation.

What is always interesting about the sketch, I think, is that it can be interpreted, and then, when you go to team colleagues with my sketching, for example, they see something completely different in the sketching and then have an idea and make something out of it. And then a dynamic arises or develops that is not necessarily plannable. And that's why the sketch is different than if you were to work in 3D, for example, it has qualities that a 3D drawing simply doesn't have'. (OD5)

Allowing ambiguity can result in unexpected discoveries and new perspectives and is perceived as being beneficial by the OD. Especially in the interaction within the team the ambiguity of sketching compared to 3D drawings is seen as relevant and supportive (ODSQ13).

Insight: Striving for success

Use of sketching for striving for success.

In quote ODSQ14 sketching is used for reflection, for to gain certainty and for to strive for success. ODs have to be personally committed to fulfil their own standard and to evidently perform on an outstanding expertise level.

ODSQ14: '(...) if you realise that it doesn't really work that way. And yes, I see – well, for me, it's just this working in the sketch. That is quite relevant for me, so also to really come to an interesting or plausible result in the end.' (OD5)

Insight: Displaying expertise and 'good' sketching skills

ODSQ15: [A designer has] 'to sketch quickly and well. And if that's amateurish, then he's also an amateurish designer.' (OD1)

Use of 'good sketching skills' to display expertise and to strive for success.

ODSQ16: 'It also demands quite a bit of imagination when you go from a sketch to the finished product, so to speak. Not everyone can do that. And I understand that when you have to invest a lot of money in these developments, you want to be as sure as possible and would like to, first of all, you want to have realistic images and later also realistic prototypes, and so on. Yes, yes, it also underlines the professionalism. And it helps, so to speak, to feel certain with the person who must put money into it.' (OD4)

In the quote the designer described using sketching for displaying expertise. Therefore, also good sketching skills are needed. The 'good' sketching aims at

attaining a shared mental model to cooperate with the client. There is also an awareness of the limits of using sketching and to change to prototyping in order to cooperate, to convince and to strive for success (ODSQ16).

Interaction-related activity of sketching

Insight: Cooperating

> *ODSQ17: 'Sketching, yes, and that's also so impressive – if you can sketch it better, then they can hear it better. That makes an impression, sketching impresses.' (OD1)*

Sketching is used to cooperate, to develop a shared mental model and to impress the client (ODSQ17).

> *ODSQ18: [Sketching] 'it is actually needed, yes, in these, let's say, mediation, or, if you like, sales situations, it always needed a vivid, that is, a kind of photo-like, vivid presentation. And that has always been part of it. So, I, well, above all, yes, so to speak, in the more everyday contexts. Of course, if you have a long-established partnership with a company or if you have achieved a status that you say, the beer mat sketch is enough for us, we'll do everything else.' (OD5)*

Awareness to use good mechanical sketching skills for to cooperate with others to develop a shared mental model and to display expertise. A 'good' sketch can be sufficient in an affiliated cooperation with the client.

Summary of sketching insights

The main insights of the results are that the ODs are aware of the strengths of using sketching and therefore they are emotionally attached to sketching.
We assume that the main motivation for this attachment relates to ODs awareness of reflection based on sketching. In the quotes we found the use of sketching related with verbalisation in order to facilitate reflection. In the quotes ideation and reflection were mentioned to be supported by a loop of sketching, writing and question asking and vice versa. This process was described as follows: interrupting sketching to reflect, or to 'go back and forth' or to puzzle the way through the process. We consider the analogy of a 'puzzle' as reflection activities. Even if a puzzle or jigsaw is not a complex problem, in the game one analyses (pieces of the puzzle) to structure pieces regarding criteria (color,

shape) and to select the fitting piece. Based on their answers, there is a strong tendency for ODs to think and reflect about design problems and ideas before they begin to sketch, and they reflect on the sketch and then sketch again, continuously until there is certainty (ODPS7+9). One OD explicitly mentioned to start sketching when his working memory is challenged, and when there is a need for more control of the situation. The ODs described their use of sketching as being closely linked to a sense of reality. Therefore, sketching skills shall be 'good', meaning precise and realistic to support a gain of certainty. The reported reflection behaviour relates to a structured approach to reflection and seem to be part of ODs' routine. We postulate that reflection activities are attention- and time consuming and one need to be motivated to reflect in a structured way. In the quotes we found a tendency to use sketching to strive for success. This 'success' motivation can be a reason for applying reflection and gaining certainty when faced to high complexity. There is indication in the answers that the ODs also know the limits of sketching for gaining certainty and when to continue with prototyping (ODPQ12). In addition, to the strive for certainty there is also an ODs openness to the ambiguous side of sketching which is allowed and welcome.

A further insight is that the ODs use sketching for cooperation with the client. What we call the use of sketching for cooperation refers to the need for affiliation of being part of a group and for acceptance. Characteristic for using sketching for cooperation was to frame a sales situation as 'mediation' by the designer (ODPQ18). In the responses we also found expressed a self-conception of a designer and that he considers his' task is to transfer certainty to the client in order to facilitate the decision making for an investment. The cooperation motif was related to good – in a mechanical way – sketching skills (ODPQ15). The good sketching skills are relevant for designers' own certainty and the certainty of the client. Based on quotes the ODs are aware of using their good sketching for attaining a shared mental model with the client to transfer certainty. Furthermore, the ODs are also aware of using their good sketching as an expression of their expertise. There is evidence in the quotes that the ODs have their own standards they bring them in. In addition to the motivation to cooperate the ODs use sketching for striving for success. Nevertheless, sketching is also used to impress and convince the client. All in all, sketching is used in a goal-focused and purposeful way.

4.4.2 RESULTS OF PROTOTYPING

Task-related activity of prototyping

Insight: Being aware of reflection

The cited quote below described awareness for reflection. Three quotes – ODPQ1 to ODPQ3 – expressed that these ODs feel supported by their prototyping activity, that allows them to reflect at a deeper level. One OD described reading the 'questions' of a prototype. The designer mentioned that a 'prototype promotes questions' which speeds up decision-making. Thus, one must be aware of arising questions. However, awareness is needed to read the questions and to identify cues of uncertainty to make full use of the questioning potential of a prototype.

> *ODPQ1: 'I build, at least the first 3D sketches [e.g., in plaster], prototypes myself. This is really important that I do it myself. I consider it important to do it myself because from the prototype emerge a lot of questions, which must be answered, and there are permanent decisions to be made. As I want to decide myself, that is why I prefer prototyping myself.' (OD3)*

The designer also expressed an emotional attachment to prototyping and it seemed to be a routine (ODPQ1). In addition, there are indication that question asking that involves verbalisation is applied.

> *ODPQ2: 'You have ideas, and then you sketch [or prototype]. Then you reflect on this idea and then you go on. You empty your head by sketching [or prototyping] and you start again, that is the way (...). And this reflection that starts again, to look critically at it and repeat [to sketch/ prototype] again. This is a process with distinct steps. I do quite a lot of steps, yes. I do so! The same is true for prototyping.' (OD1)*

Awareness for the support of (sketching and) prototyping for reflection.

> *ODPQ3: 'You need an empty head. You have to sketch or prototype. If not, there will be like a traffic jam in your head.' (OD1)*

Human working memory was described as 'needle eye of thinking' (Sachse et al., 2014). The ODs' quote expresses an awareness of using prototyping (and sketching) for facilitating cognitive processes.

Insight: Implementing best practice routines of prototyping

ODPQ4: 'To hand it [the prototype] out to another workshop takes too long for me, four weeks or so. Then I have already forgotten the question and don't know why we did it now.' (OD3)

Implementing routines to build prototypes in order to get answers to questions and to facilitate and speed up the continuation of the design process. Prototypes are built to immerse, to reflect and for to gain certainty (ODPQ7).

ODPQ5: [You need to have an own workshop or you] 'don't have the thread, like that. That's when it breaks off. So, this immersion is obviously interrupted, [and], to some extent, this dynamic is important, yes.' (OD6)

ODPQ6: 'It happens often that in the morning we talk about a design idea, and we finish the meeting by agreeing to meet again at lunchtime, each one with his/her prototype. At lunchtime, we present the prototypes to other team members. Our attitude is: demonstrate or die! Meaning: if you want to convince us and the others of your idea, you have to demonstrate it [with something physical].' (OD7)

A best practice routine to build early, quick, and rough prototypes to transfer information and to attain a shared mental model. Moreover, the routine and 'ritual' to use prototyping for cooperating and convincing other team members. Further motif to implement prototyping routines is the use of prototyping to strive for best solution approaches and success (ODPQ6).

Person-related activity of prototyping

Insight: Gaining certainty

ODPQ7: [To prototype is] 'Like an essence, [there is] a good possibility to get the essence out of a solution. You will condense and wonder: is it really necessary? Can we kick it? To make it as simple as possible, however, not simpler. This a process which is iterative and requires many, many repetitions, and iterations.' (OD4)

ODPQ8: 'There is something that allows me to sort out well my thoughts. (...) the first is: to go in the model shop to stick things together and to say let's have a look at – what I have reflected before' (OD7)

OD7 perceived prototyping as essential for reflecting on activities and for gaining certainty. To transfer information is a precondition of receiving feedback on one's own mental model and developing a shared mental model (ODPQ8).

Insight: Allowing ambiguity

> *ODPQ9: 'Sometimes the prototype is different from what I thought, but I am open to this kind of hazard.' (OD1)*

The search for certainty is a reason to prototype. Nevertheless, there is also awareness of prototyping's benefits to allow ambiguity unexpected discoveries. We assume they were also aware of reflection on a presented prototype because they realised the deviation from the mental model (ODPQ9).

Insight: Striving for success

Prototyping is used to strive for success.

> *ODPQ10: [The client:] 'What now? Building a prototype for the pitch? More time? More money? This is not intended!" They accepted it and we won the pitch. This was definitively more convincing than a nice rendering that promises all but does not deliver what it suggests.' (OD7)*

In quote ODPQ10 the designer expressed the use of prototyping to develop a shared mental model and to cooperate with the clients.

> *ODPQ11: 'This internalised idea, that what I did today will be for sure in doubt tomorrow initially, we do have that approach, and I have it strongly. And I believe this is necessary in order to not be satisfied too early to avoid getting stuck in mediocrity.' (OD4)*

The use of prototyping to strive for success and supporting own high expectations and standards are expressed. In the quote ODPQ11. There is also an awareness of using prototyping for reflection to increase certainty in the quote (ODPQ11).

Insight: Bonding with prototyping

The quote ODPQ12 to ODPQ14 expresses a strong statement and emotional attachment -that we designate as bonding with prototyping.

> *ODPQ12: 'Prototypes are very important; I do not work without prototypes.' (OD1)*

Prototyping is implemented as routine. Prototypes in 1:1 dimension is considered being supportive for the search for information, for reflection and gaining certainty.

> *ODPQ13: 'To find out the dimensions. It is for testing it [a prototype of a chair] with the back and the bottom this is the same with the dimensions for finding the proportion and relationship to the body. Therefore, a 1:1 prototype is very important. And therefore, it is better not to make it out of paper but instead to realise it immediately with material. "Where can you feel it?" That allows you to sit and reflect on it.' (OD2)*

> *ODPQ14: 'Prototyping in our own workshops means we have shortcuts, and we spend less time in comparison to outsourcing the prototyping. We do prototypes on our own. We can get feedback quickly. By doing so, we are deeply involved.' (OD7)*

In the ODs quotes (ODPQ13; ODPQ14) they describe their attachment with prototyping resulting in routines or establishing a workshop supporting the use of prototyping.

Interaction-related activity of prototyping

Insight: Cooperating

The affiliation between client OR team/designer is relevant for a positive and constructive working situation. In the answers the use of prototyping for cooperation is stressed.

> *ODPQ15: '[prototypes] stress the professionalism. It supports and helps the person who will give the money – let's say that he can feel more certain.' (OD4)*

In quote ODPQ15 the client's affiliation is relevant for successful cooperation, and the designer displays expertise to strengthen this affiliation.
The interaction 'transfer of information' is relevant for a shared understanding and mental model in a selling or presentation context. The designers use prototyping displaying expertise and transferring certainty to the client (ODPQ15).

ODPQ16: 'We develop the prototype until the very end of the process in order to pass it onto engineers. We want to avoid having to accept "another five more screws" for the chair.' (OD7)

The quote ODPQ16 expresses the use of prototyping for cooperation, to search for information, to transfer information and to develop a shared mental model. In addition, the quote also reported a use of prototyping to master the design, and to gain certainty. Part of using prototyping is striving for success.

ODPQ17: 'Clients have an increasingly bad comprehension of sketches. Fifteen years ago, it was possible for me to present a design and talk about it based on sketches. Nowadays, it is no longer possible: you need at least a rendering or a [high-fidelity] prototype. You can no longer expect that a client has much imaginative power.' (OD3)

The designer´s prototype 'fills' the lack of imaginative power of the client. The quote ODQ17 stated that prototypes are relevant to transfer information and to develop a shared mental model with the client and expressed the intent to cooperate with the client on a prototyping level.

Insight: Attaining a shared mental model

ODPQ18: 'If you want to bring something into the world, people need to see something photo realistic to avoid uncertainties. That is the point. It demands quite an imaginative power to move from a sketch to a finished product.' (OD4)

To create a mental model from a sketch to a product need quite an 'imaginative power'. OD4 was aware that transferring information must support the imaginative power of clients, suppliers, and companies via prototypes. Prototyping is used for to transfer information, to support a shared mental model and for cooperation (ODPQ18)

ODPQ19: [to build rough prototypes in the model shop] 'Like this, it becomes vivid, and by doing so all the team can see what I mean. It becomes tangible. Parts might still be interpreted from another perspective. I think this is the best basis for a discussion.' (OD7)

In this quote the designer uses prototyping and allow ambiguity. In addition, prototypes are built to search for information, to transfer information, and to develop a shared mental model for cooperation and for receiving feedback on the own mental model (ODPQ19).

Summary of Prototyping Insights

The ODs emphasised the relevance of prototyping in their design process. In their quotes, (ODPQ2) the relevance of using prototyping for reflection and hence, an awareness for reflection is expressed. For facilitating their prototyping habits, the ODs are implementing best practice routines. This supports not only reflection in a structured but also in a systematic and regular way based on prototypes. Moreover, the ODs are entering in a circle of reflection and prototyping and vice versa. Another OD mentioned to align the concept with the prototype in order to develop an 'interesting' design. The ODs approach to reflection seems to be driven by precise analysis, the alignment with the design frame, the concept (and criteria). Reflection is an activity that can support the human need to master a situation. The ODs expressed a need to reflect, not only to gain certainty, but also to master the design by prototyping. In the ODs answers specific routines were reported to support the prototyping approach through workshops, well-equipped and used by specifically trained staff. Additionally, routines for prototyping were implemented e.g., to pitch ideas withing the team (ODPQ4). These mirrors evidence for a strong emotional attachment to prototyping. We use 'bonding' as an analogy for the 'relationship' between an OD with his/her prototypes. We chose the term because this connection is more emotional than rational and feels intuitively 'good' and 'reliable'.

4.5 DISCUSSION

The identified sketching and prototyping activities were underpinned with the research literature. The main findings regarding ODs expertise with sketching, respectively prototyping are synthesised into two models. The models were deduced to visualise, discuss, and argue our main assumptions. The description of the explanatory models moves from top to bottom, and from the left to right hand side.

4.5.1 THE RELATION BETWEEN OUTSTANDING DESIGNERS' EXPERTISE AND SKETCHING

We discuss intriguing insights from the quotes and ODs emphasised sketching activities to discuss the consequences of these for the design process. Based on quotes from the interviews, we assume that ODs, due to a large range of experiences and knowledge (from previous design projects) have a large repository of images, principles, concepts, and design solutions. There is evidence that the ODs, compared to designers with lower expertise, dispose a larger solution space. Based on their experience, ODs align their mental model of a solution with already known solutions. This is in line with research studies indicating that 'expert designers' solution space is obviously bigger than of the novice designers' (Chen & You, 2004, p. 8). The difference in the process of recalling data is attributed to expertise by the researchers.

Moreover, when the ODs do not have a solution, we assume that they continue to develop ideas internally in the mind's eye (Ferguson, 1994). Due to their experience, ODs can recognise elements of already known solutions and combine these to create a solution idea. When the process of combining known concepts and images becomes too complex the designer needs cognitive facilitation or more certainty, then the designer starts to sketch.

In the answers we found evidence that ODs are sketching in parallel while reflecting on the idea. OD1 described the approach of a loop, the use of sketching for reflection activities and structured reflection through sketching. The OD3 mentioned the use of sketching involving verbalisation. The OD4 linked writing to the reflection process. In the quotes some of the ODs related reflection with

verbalisation and asking questions. Verbalising in a question based way support a rational thinking style that is beneficial for the quality of the solution (Wetzstein & Hacker, 2004). In addition, the quotes support that ODs not only use sketching for a structured approach to reflection, but they are aware of initiating reflection activities and are aware of 'questions' that we call cues of uncertainty.

Despite of their focus on precision and converging activities, the ODs are open to exploration and allow ambiguity. In the process. In the answers there is indication that the ODs are flexible and aware of switching between diverging and converging activities and is supported by using sketching. This switch might support an outstanding design solution quality. The described switch between sketch – to explore and diverge – and reflect – to converge – relates to an 'ideal' approach in the design process. Hence, the description of an 'ideal' approach for the concept generation is characterised by the development of concepts based on repeatedly applying a divergent and convergent process. The described finding is similar to results from other researchers (Chen & You, 2004; Cross, 1994; Pugh, 1991).

There is a strong tendency of ODs being aware of using sketching for a structured approach to reflection. We argue that ODs' focus lies on sketching 'with a sense of reality'. Based on quotes it became evident that ODs' sketch to gain certainty. One OD emphasised the fantastic side of sketching and stated that sketching can be illusory and even appear 'nicer' than reality. The designer claims that there is a need of manifested expertise linked to 'a sense of reality in the sketches'. Despite a weight on precision the ODs also allow ambiguity. As a label we suggest calling this dominant sketching approach with focus on reflection and on the goal as 'sketching with purpose'.

Model of the relation between Outstanding Designers' expertise and sketching

The insights from the discussed results were synthesised into an explanatory and preliminary model (Figure 9). The model is described starting from top to bottom and from the left to the righthand side. Complexity leads to uncertainty (Dörner et al., 1994). The greater the complexity, the more the ODs use a structured approach to reflection to reduce the complexity to gain certainty.

The more structured reflection activity based on sketches in alignment with the concept criteria or mental model the more the complexity is reduced. The more reduced the complexity, the more certainty there is regarding the idea or artefact, and for activities as decision-making. We argue that ODs reduce complexity during the analysis of the problem, when they align the problem with already known solutions from their image repository of e.g., ideas, concepts, solutions. Thus, ODs sketch with an already reduced complexity, to gain certainty and to accelerate decision-making. The greater the certainty, the quicker the decision-making and the greater the quality of the decision. The greater the quality of the decision, the more the designer feels supported by sketching activities. The designer experiences being able to master complexity and, over time, increases self-efficacy regarding gaining certainty by using sketching (Bandura, 1989). The more self-efficacy applies to complex problem-solving based on sketching, the more there are positive emotions regarding sketching and the motivation to sketch. The described interplay of ODs expertise and sketching leads to a self-reinforcing process.

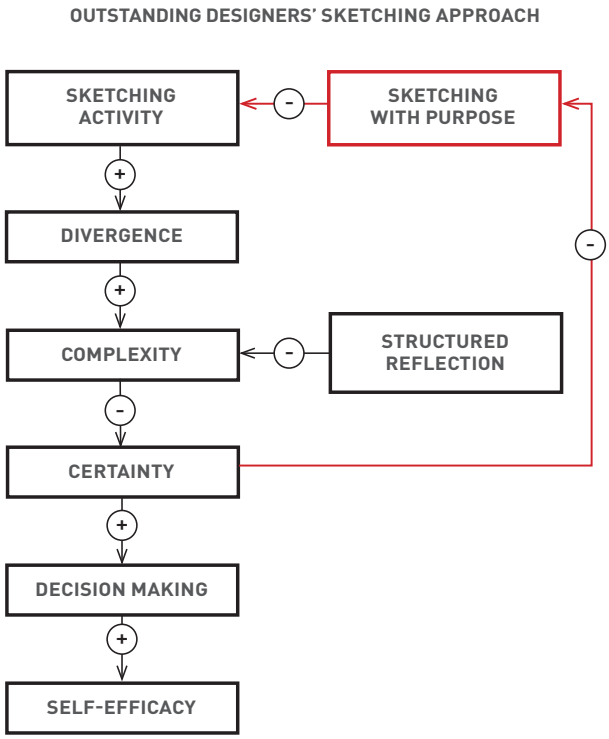


Figure 9. Relation between Outstanding Designers' expertise and sketching.

4.5.2 THE RELATION BETWEEN OUTSTANDING DESIGNERS' EXPERTISE AND PROTOTYPING

Main finding from the quotes is that the ODs are aware of prototyping strengths and can fully explore these. In sum, this leads to an emotional attachment with prototyping. Out of many activities used, the ODs highlight some important ones in their answers. The ODs emphasised using prototyping to reflect based on prototypes in order to gain certainty based on evidence on an emotional level. Several ODs used prototyping to develop and complete their designs to ensure they can master all details of the design. Some ODs also knew about the relevance of storing information in a prototype to support the working memory during the design process (Bilda & Gero, 2007; Sachse et al., 2014). Some of the ODs reported using prototyping to reduce complexity and they were aware of using prototypes to gain certainty and to accelerate their decision-making, and to speed up their design process.

To implement user tests in the design process is postulated and practised especially in the Design Thinking context and is a key factor for innovation (Kelley, 2005). The ODs had great experience and maxims for action, so why did they neglect to use prototypes for user testing? We assume ODs consider individual and personal experience as relevant as testing with users. The relevance of personal experiences as a basis for a 'problem frame' is postulated by research with ODs. Cross reports the case of an OD, who developed a sewing machine. The origins of the new design features were based on experience and some personal use of a sewing machine. Cross identified in his research strategic knowledge of ODs who applied three strategies in the early process phase. One of these three strategies is to develop a framing. The Outstanding Designers frame 'the problem in a distinctive and sometimes rather personal way' (Cross, 2001a, p. 4). We postulate that ODs prefer to build on personal experience rather than on user testing. This approach might become a gateway for limitation of relevant information and to take over only one personal perspective to a problem. Outstanding designers create positive experience with framings based on personal experience. If the design problem is outside the OD's, we wonder whether ODs question their (past) strategies. Are ODs open to taking a risk and trying a new strategy? We suggest conducting further research on this topic to discover why ODs do not use this opportunity to improve their design process. Pursuing this insight further is outside the scope of this thesis and an opportunity for future research.

Various ODs considered ambiguous prototypes as relevant. Ambiguous prototypes are open to interpretation and can support unexpected discoveries. In the responses was stressed the relevance of prototyping early and throughout the entire design process in an emotional and reliable way ('That is why I prefer prototyping myself'). Some ODs reported using specific prototypes (e.g., '3D (plaster) sketches', Q9) and implementing prototyping routines such as sharing prototypes at lunchtime.

Some of the ODs described an awareness for minor questions or cues indicating uncertainty that might arise during the prototyping process. We interpret this as one indication for awareness of reflection. These cues for uncertainty can signalise the designer to interrupt and start to reflect on the current situation. Part of Schön's (1992) description of a reflective practice is the designer having a conversation with the preliminary outcome of a design situation. In the reflective practice approach the designer reflects using sketches and prototypes. In the answers there is indication that the ODs are aware of using prototyping for reducing complexity. Furthermore, the ODs relate cues for uncertainty with reflection activities. We assume the ODs own standards, expectations, and criteria to reduce the uncertainty.

The ODs prototyping approach switches between allowing ambiguity and emphasis on reflection is in line with the research literature. This approach is described as 'ideal' for the concept generation, where concepts are developed based on repeatedly applying a divergent and convergent process. (Cross, 1994; Pugh, 1991).

We assume that the ODs have a powerful motivation to reflect efficiently because of previous, positive experiences. This insight can relate to research by Dörner (1994) that certainty positively influences the quality of the outcome. In their answers, a strong positive emotion was expressed regarding the use of prototyping. We use the term 'bonding' with prototypes to describe this strong relationship between the ODs and their prototyping activities ('I do not work without [them]'; 'demonstrate or die'). One possible advantage of bonding is a form of fixation on this activity that already –in the past– led to a successful outcome. Nevertheless, this approach might lead to reduced openness for other activities such as user involvement. The ODs fixation on prototyping might hinder selecting more appropriate activities for improving their design process.

The ODs' attachment to prototyping and towards their prototypes was evident in their answers and seem to result into a strong source of motivation for using prototyping. We designate the strong positive emotional attachment as 'bonding' (Lozoff et al., 1977). Bonding is a term that we define as being like a strong parent–child relationship which leads to an optimistic view for future projects.

Model of the relation between Outstanding Designers' expertise and prototyping

The main findings and theoretical assumptions of the relation between ODs' expertise and prototyping activities, are visualised in a model described in the following (in Figure 10). This model focuses on the visualisation of core insights and assumptions supported by theoretical concepts from the research literature. As in the previous model, we describe this model from the top down. The first step in the model is the ODs prototyping activity. The more prototyping activities, the more divergent ideas (Dow et al., 2011; Yang, 2005). The more divergent ideas, the greater complexity the designer must cope with. Research has linked high complexity to uncertainty and fear of failure (Dörner et al., 1994). Uncertainty can be accompanied by avoiding decision-making and being afraid to make mistakes. Thus, the complexity has to be reduced. The ODs reported to visualise the results of own reasoning and reflection activities direct into quick and rough prototypes. We see evidence in the responses that the ODs based on their experiences has more solutions and knowledge in their head. The ODs can combine these elements of solutions in their head before starting to prototype. That is one approach to avoid complexity.

In the model we focus on the prototyping activity as starting point. In the quotes were mentioned using a structured approach to reflection activities for gaining certainty. We gained the insights that an OD is aware of reflection based on prototypes. Moreover, the ODs described a switch between reflecting and prototyping. Another quote shows evidence that there is awareness for cues of uncertainties described as 'questions' that are popping up when building prototypes. Therefore, we see a tendency that verbalisation comes into play when ODs are talking about a reflective situation. ODs expressed a strong awareness of reflection activities related to prototyping.

Furthermore, the description of going back and forth expresses a struggle for evolving the design, this can relate to prioritising and structuring criteria to come to a selection and making decisions. Some of the ODs expressed a mind-set of striving for high quality of their design that we designated as 'striving for success'. Therefore, we postulate that the ODs reduce complexity in the design process by using reflective activities based on prototypes. We further assume that, through these activities, the ODs' gain certainty. Building on the answers, ODs align the framing and its criteria with the design idea. This alignment is part of a structured approach to reflective activities and results in quicker decision-making. Reflective decision-making reduces uncertainty and increases certainty. We assume that, based on the evidence, high certainty results in a high-quality outcome. We argue that mastery experiences, in this case, solving complex problems based on prototypes in the design process, result in a high-quality outcome.

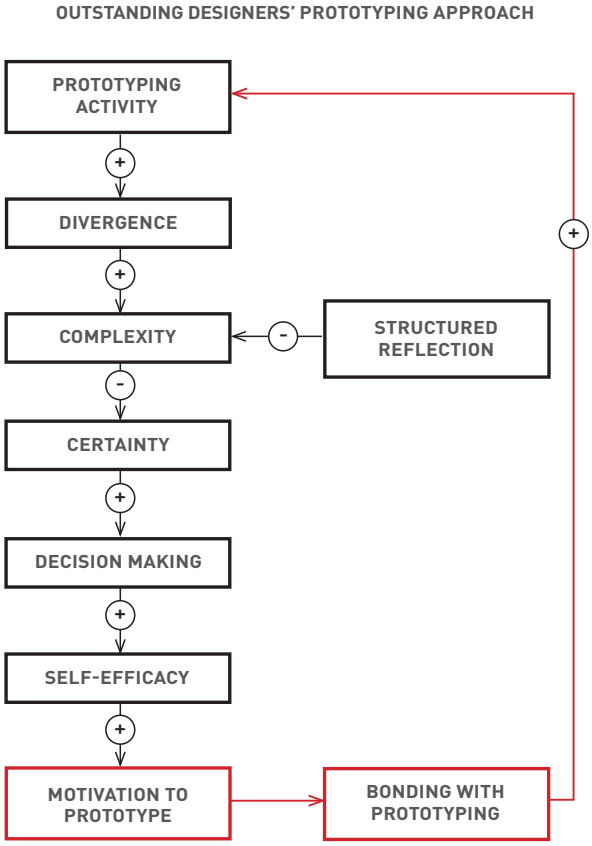


Figure 10. Relation between Outstanding Designers' expertise and prototyping.

These positive experiences lead, over time, to enhanced self-efficacy in solving complex problems based on prototypes. According to Bandura (1999), the greater the self-efficacy, the greater the motivation to select challenging tasks and complex problems. An increased self-efficacy impacts motivation, perseverance, and other behavioural elements beneficial for the quality of the design outcome. A strong attachment to prototyping supports the motivation to use prototyping more often. Experiences of high-quality outcomes emotionally reinforce this attachment. We refer to this behaviour as 'bonding with prototyping' and deduced an explanatory model of the relation between ODs and their prototyping activities. We postulate that the described relation is a positive and self-reinforcing cercle.

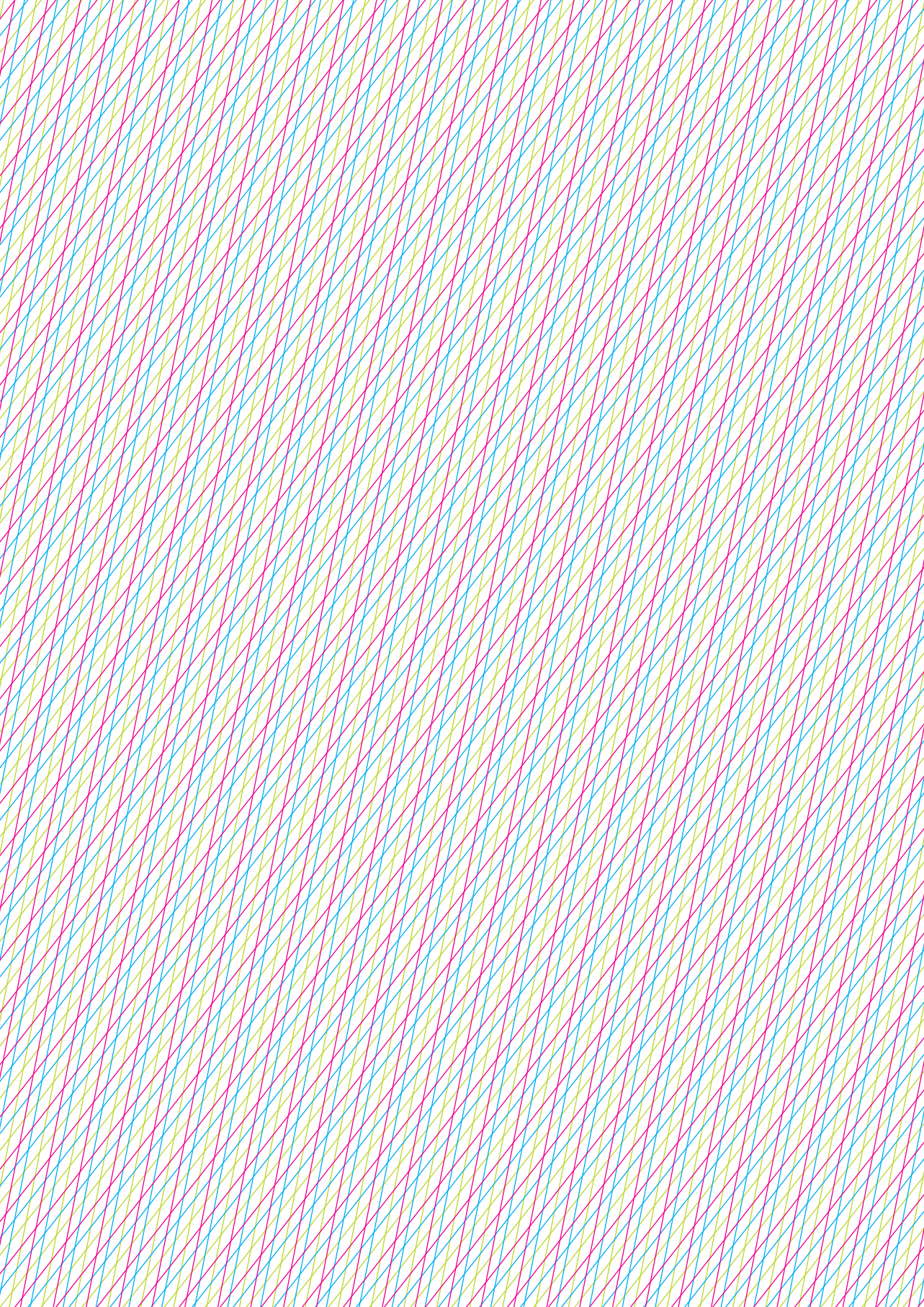
4.6 CONCLUSIONS

The interview study's aim is to explore the use of ODs' sketching and prototyping. Because of seven interviews with ODs, we determined the status quo of both design activities and answered the second research question:

> *RQ2: How do Outstanding Designers use sketching and prototyping in the design process?*

Based on the responses, we found indication that they are aware of the benefits and limits of using sketching and prototyping in their design process. Characteristic for their sketching, and prototyping activities is that these are pivoting around a structured reflection approach and the motivation to gain certainty. Gaining certainty requires reducing complexity which is time and attention consuming and needs effort. In the quotes we found indication that ODs are using sketching and prototyping to follow their own high standards, to persevere facing complexity in order to strive for success. The ODs sketching behaviour (that we assume based on answers) is goal-focused and applied for a structured reflection approach to support certainty. Therefore, the ODs emphasise good sketching skills for attaining a shared mental model and accelerating decision making with the client. Furthermore, the ODs use their good sketching skills for cooperating and impressing the client. This sketching behaviour is summed up as the ODs' 'purposeful sketching' approach.
Based on the quotes ODs expressed to experience prototyping as supportive for decision making and gaining certainty. This results in the positive emotional repeated use of prototyping.

Therefore, the ODs developed prototyping best practices and established prototyping environments for facilitation of prototyping. In sum, this behaviour is called the ODs' bonding with prototyping. The main findings and theoretical assumptions from this study were synthesised for the deduction of two models. The models illustrate the relation between ODs' expertise with sketching (Figure 9) and the relation between ODs' expertise with prototyping (Figure 10). Both explanatory models are preliminary and must be verified in the future. Nevertheless, the models contribute to the major interest of this PhD research to develop recommendations in order to learn from the ODs.



5 COMPARISON

The sketching and prototyping activities of Proficient and Outstanding designers were explored in two previous studies (Study 1and 2). In this chapter, these design activities were compared to answer the third research question.

> *RQ3: 'What are similarities and differences in the use of sketching and prototyping regarding designers with different design expertise levels?'*

The insights obtained from similarities and differences in PDs' and ODs' sketching, and prototyping behaviour are relevant to deduce strengths and weaknesses herein. The identification of strengths is the basis for the overall research aim to learn from ODs. Therefore, the main research findings are deduced into models that visualise the interplay between design expertise and sketching respectively with prototyping The interplay relates to how expertise affects sketching and prototyping activities and how designers with different levels of expertise can use these benefits in their design process. The explanatory models facilitate the deduction of recommendations and actionable advice.

5.1 CONCEPTS

A central assumption in this research is that ODs' sketching and prototyping activities are relevant to their outstanding performance and design outcome.
This research on the expertise of PDs and ODs aims to inform research, practice, and design education. As outlined in Chapter 2, we identified the following gaps in the literature:

- There is little research on PDs despite being interesting because of having finished their education and having less professional practice.
- There is little research on ODs despite them being interesting because of their success. There is evidence that sketching and prototyping activities emphasised by ODs in the design process contribute to the high-quality of design outcome.
- There is also little research on design expertise, sketching, prototyping and how these elements are related and interplay.

Based on the theoretical foundation of this PhD thesis, we identified relevance examining ODs' sketching and prototyping activities. We posit that ODs' sketching and prototyping are supportive to develop successful design outcomes. We discuss striking results from both groups of designers regarding their sketching and prototyping activities, see Figure 11.
Compared with the ODs, the PDs were obviously younger and had fewer years of experience. As they had finished their design education and had only a few years (maximum five) of experience in their design profession, PDs have less design domain-specific experience than ODs, such as knowledge about technology, design methods, and additional skills, as well as knowledge addressing administrative and financial topics and interacting within a network, etc. Less domain-specific experience also impacts a designer's individual perceptions, such as recognising information or problems as variants of each other or assessing on an emotional motivational level a situation as challenging.
PDs are used to being faced with rather defined tasks. We can assume projects and tasks in design education are mainly intended to be finished within weeks. Moreover, we assume that young professional designers are also working on less complex tasks, due to their lack of experience.

Therefore, we consider that the PDs compared to the ODs are more used to structured design tasks and less-complex problems. In addition, the PDs have also less experience than ODs in professional (business and administrative) contexts (e.g., concerning projects, planning, and the management of projects), in presentations, and in sales situations. These differences in the experience and knowledge of PDs and ODs are not the primary focus of this study; the focus is on the daily use of sketching and prototyping.

5.2 RESEARCH APPROACH

The main aim of this PhD project is to learn from the ODs**.** An explorative approach was selected using the same set of open questions in a survey study with PDs and in an interview study with ODs. For the study, we chose a retrospective research approach regarding the experience of PDs and ODs. The approach whereby we ask PDs and ODs about their experiences is self-referential and we postulate that it can be considered as self-reflection guided by instruction.

In this third study, PDs and ODs responses regarding sketching and prototyping activities are compared. Each of the designer's responses is considered as being representative of the sample. For a better overview, a table is provided with the categories juxtaposed to referenced quotes and designers. The table is not intended to transfer qualitative into quantitative data rather to give an overview of quotes from the results.

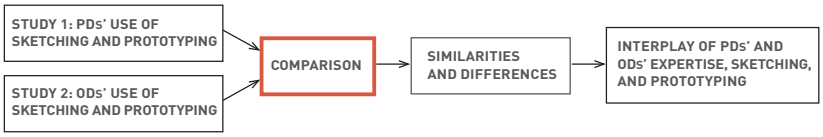


Figure 11. A comparison to identify similarities and differences.

The identified similarities and differences in PDs and ODs use of sketching and prototyping activities and the developed models support our understanding of the interplay of design expertise, sketching, and prototyping (Table 13).

5.3 DATA FROM TWO STUDIES

The data for the comparison was retrieved from Study 1 with PDs (Chapter 3) and Study 2 with ODs (Chapter 4). Results from both studies are compared to identify similarities and differences in PDs and ODS use of sketching and prototyping. Moreover, the previously deduced models were juxtaposed to identify strengths and weaknesses in the use of sketching and prototyping in the design process.

5.3.1 SAMPLE: PROFICIENT VERSUS OUTSTANDING DESIGNERS' EXPERTISE

We compared PDs, who have a design degree and have had their first professional experiences, with ODs, who have more than 15 years of professional experience. In addition, the ODs are already successful and esteemed in their profession (see criteria in Chapter 4). Comparisons of novices and experts are relatively common in design research (see Chapter 2).

Novices, who are only at the beginning of their design education, rarely have much experience with prototypes and sketches. In contrast, PDs are likely to be educated (graduate degree from design school or art school) and trained in sketching and prototyping methods and approaches. In addition, PDs have had their first professional experiences. Since RQ3 requires a comparison of prototyping and sketching activities, it made sense to conduct our research with PDs instead of novices, as the latter would not provide much data on prototyping and sketching. We compare PDs (and their first professional experiences) with ODs. Outstanding professionals work at a high level of expertise and have at least ten years of deliberated and dedicated practice. Outstanding designers not only differ from PDs regarding years of experience in practice, but also in the experience of having success they made in their profession. Outstanding designers are, among other criteria, acknowledged within and beyond their peers (see Chapter 4). Since PDs have fewer professional experiences and have less experience of success than ODs, we can assume they have not yet fully explored the use of sketching and prototyping. This lack might lead to deficits and become visible in different uses of sketching and prototyping compared with ODs. We aim at using the identified deficits and strengths to inform design education and practice.

5.3.2 PROCEDURE: SURVEY VERSUS INTERVIEW

First, we thought about issuing (part of) the questionnaire to the ODs also. As the first two ODs refused to answer using Likert scales and check boxes, the questionnaire was not employed. This is consistent with the difficulties reported by Cross and Lawson in studying designers using research approaches other than interviews (2005). Therefore, the ODs were interviewed using a guideline. Most of the questions of the guideline (<60%) were the same as the open questions in the questionnaire used in Study 1.

5.3.3 DATA ANALYSIS

The responses to open questions from, the survey, and interview study were analysed using inductive and deductive coding. The codes of both analysis procedures were integrated into one coding system, which is presented later in this chapter (Table 14). The coding system consists of three deduced categories

regarding activities of sketching and prototyping. Each category structures the activities of sketching and prototyping related to a different aim.
The development coding system was described in greater detail in Chapter 3 and Chapter 4. The codes, subcategories and categories and are all theoretical assumptions in alignment with the research literature.
The coding system developed for the analysis of the data from study 1 was also used for study 2. In study 2, additional codes were added to the coding system based on the responses and the coding system was expanded. The results from both studies are the basis for the comparison. In the following, PDs and ODs sketching and prototyping activities are compared to elaborate the similarities and differences in the use.

5.3.4 ACTIVITIES OF SKETCHING AND PROTOTYPING

Based on two studies the use of sketching and prototyping activities from PDs and ODs were explored. A coding system was developed and used to measure and examine the responses. The Coding system consists of three deduced categories regarding activities of sketching and prototyping. Each category structures the activities of sketching and prototyping related to a different aim that we described in greater detail (Chapter 3 and Chapter 4). All the sketching and prototyping activities can be summed up into three activities related to a specific aim, to person, task, and interaction.
At the center of every activity is a human being who makes decisions and acts. For the designer to behave and act, motivation is needed to start each activity. An activity can be accompanied by emotions and refers to the person-related activities of sketching and prototyping. An example of this activity is cooperating with the client to convince them in a sales situation.
The activities of sketching and/or prototyping that are executed to solve complex problems are designated a 'task-related activity' (e.g., reflecting). Some sketching and prototyping activities are used for their emotional-motivational impact and are 'person-related activities'. The described activities of sketching and prototyping concern individual designers. People behave within a context and interact with their environment and other people. The category addressing these activities of sketching and prototyping is designated as 'interaction-related activity' (e.g., searching for information).

Summing up this assumption of 'activity', we formulated the following function:

$$a = f(task, person, interaction)$$

The activity (a) is a function (f) of the task, the person, and the interaction.
For more detailed information about (the activities are also used for the developed coding system and) the description (and the conceptualisation) of these activities of sketching and prototyping, see Chapter 3 and 4. The results and insights from the comparison are presented in the following section.

5.4 RESULTS & DISCUSSION

The comparison of two studies resulted in the identification of similarities and differences in the use of PDs and ODs sketching and prototyping activities (Figure 12). The identified similarities and differences in the sketching behaviour of PDs and ODs are presented in the first section, and their prototyping behaviour in the second section. The insights from the comparison are related to the research literature and are the basis for the deduction of two explanatory models of the interplay between design expertise and sketching. Moreover, through the insight and the abstract models we identified benefits and weaknesses in using sketching and prototyping to inform design research, education, and practice.

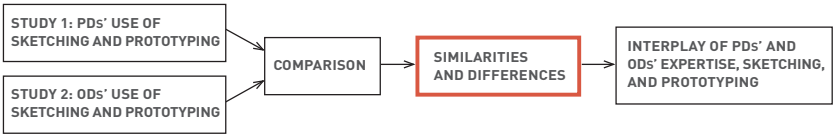


Figure 12. Results from two studies.

5.4.1 SKETCHING

Sketching – Similarities:

PDs and ODs mentioned using sketching early in the design process. ODs mentioned using sketching during the early phases for generating ideas and so did the PDs. Moreover, 48 out of 54 PDs assessed sketching as being relevant for the concept design phase. They expressed relevance for the use of sketching to generate ideas in their answers.

In their quotes the PDs tended to be attached emotionally to sketching (PDSQ8, ODSQ7), and the ODs also expressed an attachment to sketching, despite of we assume a different intensity and caused by different reasons. We found indices for an emotional attachment to sketching that emerges from the PDs' motivation to generate many diverse and novel ideas. The PDs seem to experience cognitive facilitation by sketching and expressed positive emotion during sketching. The PDs and ODs mentioned using sketching to transfer information, less for the search for information. For the PDs and the ODs using sketching to interact within a team and with the client is relevant. The main aim of this interaction is to develop a shared mental model. Using sketching for reflecting was expressed in the quotes by designers of both groups (e.g., PDSQ11, ODSQ2). There is also awareness for using sketching to facilitate cognition (e.g., PDSQ10, ODSQ1), to allow ambiguity, to facilitate the continuation of the process (e.g., PDSQ1, ODSQ13), to gain certainty (e.g., PDSQ7, ODSQ14). There is also a small tendency for self-expression in the quotes from ODs and PDs. Hence, there is evidence that their use differs in terms of number of designers who mentioned it, the frequency, the intensity of use and the awareness of this use. At first glance, we have found similarities, but we identified that the use and aim of sketching within such an interaction differs between the designer groups and has different foci.

Sketching – Differences:

In the quotes, it became evident that ODs in contrast to the PDs, are conscious to a high extent of the advantages and disadvantages in the use of sketching. Despite similarities in the quotes, we identified different motivations, aims, as well as frequency intensity of PDs and ODs using sketching. Therefore, we look closer to the sketching activities mentioned by ODs and PDs to also find smaller differences.

In the quotes, PDs stressed the use of sketching to generate ideas and described a playful, divergent, and less goal-focused approach. Compared to this divergent PDs' sketching approach, the ODs expressed an explorative but also a convergent and goal-oriented purposeful sketching activity.
The PDs' focus on sketching had a relatively playful aspect, and this might take more time especially in the concept design phase compared to the OD's sketching approach with a clear purpose. Building on research, the novices cannot configure their creative ideas compared to experts (Chen & You, 2004). Of course, this finding refers to novices and experts and may be applicable also on further expertise levels. The insights from the research literature can explain the use of overflowing sketching activity.
The PDs prioritised a divergent approach and we assume they tended to neglect the use of sketching for converging activities such as analysing, structuring, selecting and thus reflecting in a structured way. Few PDs expressed an awareness for reflection and none of them expressed valuing sketching as being supportive for a structured reflection approach. In their responses, the PDs did not mention relevance for reducing complexity or gaining certainty.

Whereas the ODs expressed awareness of the reflective use sketching to gain certainty and are aware of the danger of sketches 'to beautify' (ODSQ10). The reported PDs' use of sketching for thinking and clarification is related to reflection but executed in a less structured way compared to the ODs.

Moreover, the ODs are aware of their reflection and described a process of reflection before starting to sketch. The quotes suggest that the ODs build on their experiences from many projects and combine solutions in their head before they start to visualise their idea. Therefore, we assume that the number of sketches is lower compared to designers with less experience.

In addition, the ODs are aware of reflection process and described the need to switch between reflecting and sketching. Also, the relevance for involving verbalisation and visualisation for reasoning was reported (ODSQ5). Verbalisation is beneficial for the quality of outcome (Wetzstein & Hacker, 2004).
Indication was found that ODs follow high standards set by themselves for their work**.** They expressed a high motivation to strive for success. The insight that the ODs follow a high standard of requirements for their design relates to findings from research with Outstanding Designers from Lawson and Cross (2005).

The ODs – compared to the PDs – used sketching to transfer information precisely because they target a shared mental model with the client. Moreover, the ODs use sketching to cooperate with the client to show their expertise and to impress. In their quotes, the ODs were aware of sketching limitations and would then change to prototyping. Two different behaviors were identified based on the PDs' and ODs' sketching results: the PDs sketching overflow and the ODs sketching with purpose.

Our main finding from the comparison of results is that the PDs and ODs differ regarding their reflection activity. This insight is supported by the research literature comparing novice and expert designers. In generally, the design experts engage in more reflection compared to novice designers (Crakett, 2004; Petre, 2004; D. Schön, 1983). This relevant finding to attribute more reflection activity to a higher expertise level is visualised as PDs sketching overflow and ODs' sketching with purpose in a model.

5.4.2 PROTOTYPING

Prototyping – Similarities:

At a cursory glance, there are similar prototyping activities of PDs and ODs. On closer inspection, the similar PDs' and ODs' prototyping behaviour differ most in the areas of intensity, frequency, and intention. In their answers, the PDs and ODs mentioned their use of prototyping as searching for information, transferring, and sharing information, and as attaining a shared mental model. Both groups, PDs and ODs mentioned using prototyping for interacting with the team and with clients. Designers of both expertise levels expressed consciousness about the opportunity to display their expertise through their prototypes. In contrast to the PDs' approach, more ODs expressed the relevance of using prototyping to display expertise to clients to convince the client. In the answers of the PDs were mentioned using prototyping to prove the capability of realisation. Based on insights from PDs and the ODs, we posit that both groups of designers searched for certainty through prototyping. Both, the PDs and the ODs mentioned relevance to gaining certainty. The PDs mentioned little relevance for using prototyping gaining certainty whereas the ODs emphasised relevance for using prototyping to gaining certainty. PDs mentioned the use of prototyping for evaluation and thinking that relates to reflection. Whereas the reflection approach of the ODs is notably more detailed, structured, and emphasised compared to the PDs reflection approach.

Prototyping – Differences:

There is a clear tendency that the ODs, compared to the PDs, are fully aware of the advantages of using prototyping in the design process. In the responses, only few PDs reported using prototyping for thinking and reflecting. Their reported approach to reflection was described as rather unstructured. Similarly, in their answers the PDs did not seem to be aware of cues of uncertainty when using prototypes, nor expressed awareness for the relevance of initiating moments of reflection.

In contrast to the PDs, the ODs expressed in their answers a need for using prototyping for a structured approach to reflection (OD1, OD3, OD5). They also emphasised the use of prototyping for mastering the design, attaining a feeling of control, and gaining certainty.
The PDs assessed the relevance of using prototyping for different design phases. Most of the Proficient Designers surveyed rated prototyping as primarily relevant for the later phases, the embodiment and detail design phase.

Thus, less than half the PDs (24/54) did not express relevance for prototyping in the early phases. Thus, they might not use prototyping early in the design process despite being relevant for the process outcome (Dow et al., 2011; Ehrlenspiel & Dylla, 1993; Sachse & Hacker, 1995).

In contrast to the PDs, the ODs emphasised the relevance of early prototyping, mentioning specific types of early prototypes such as a 'first 3D sketch' (ODPQ1). In the quotes, the ODs expressed the use of prototyping during the whole process and in the later phases of the process. The ODs mentioned using high resolution prototypes to gain certainty for themselves (and to transfer certainty to the client).

Some of the PDs reported the relevance of prototyping for gaining feedback in testing with the user. We assume (that) to gain certainty the PDs use interactive situations with the team, the user, and the client for externally initiated reflection. We assume the PDs use this interaction as a learning opportunity and reflective conversation. This relates to findings from Deiniger (2018) that Novice designers tend to underutilise their prototypes and that they can explore the benefits of their prototypes only when requested.

Gerber (2009) stressed that each prototype (early in the process and with low fidelity) can be considered as a learning opportunity in professional practice. Consequently, the PDs mentioned the relevance of prototyping for user testing whereas the ODs did not mention user tests or user involvement. It is a surprising finding that ODs neglect user involvement because human-centeredness and user testing are considered as supporting innovation and are promoted by the Design Thinking approach (Kelley & Littman, 2001).

The ODs used prototyping to transfer information to the client and develop a shared mental model for cooperation with the client.
The ODs also used prototyping to display their expertise by impressing and convincing in a pitch, or by giving certainty to the client in a sales situation (ODPQ15). Similarly, some ODs displayed expertise to convey certainty to the client (OD1, OD4, OD7). We assume this approach is successful and supports high affiliation between client and designers that leads to certainty, positive emotion. In their responses we found a high personal commitment of using prototyping to follow high standards set by the ODs themselves. The insights that ODs follow their own high standard and that they are highly personally committed can be attributed to ODs' expertise (Cross & Lawson, 2005). We describe the resulting prototyping activity as the 'strive for successes'. This underlying motivation is obvious in ODs' use of prototyping for gaining certainty and for cooperating with the client (e.g., in order to win a competition). Therefore, ODs implement prototyping routines to create the condition needed for their design approach and their strive for success. These prototyping routines aresupporting a workflow. Moreover, the routines are accompanied by facilities and sometimes staff. Several ODs emphasised having established own workshop, and that they hired specific workshop staff for implementing their prototyping routines (OD7, ODPQ13). In contrast to the PDs, the ODs implemented best practice prototyping routines.

The ODs are aware of prototyping benefits and that is why they developed best practice prototyping routines. There is an emphasis in ODs answers for individual prototyping activity, e.g., building the first prototypes themselves (ODPQ13). Consequently, the ODs installed workshops and sometimes even employed specifically trained staff for realising the prototypes. Routines and workshops facilitate the continuation of the process and speed up the decision making.

These routines express an obvious need to involve prototyping in their design process. Compared to the ODs, none of the PDs reported any specific routine linked to prototyping.

One additional finding is that ODs expressed strong positive emotions and attachment regarding prototyping. Whereas the PDs did not express an emotional attachment regarding the use of prototyping and seemed to be more externally motivated to prototype. Based on the insights from PDs responses there is a lack of attachment regarding the use of prototyping, and we call this behaviour the bonding gap with prototyping. Compared to the PDs, the ODs expressed a strong emotional attachment with prototyping that is called 'ODs' bonding with prototyping' (Jobst, 2020).

Results: Overview of quotes

The overview is organised as a table (Table 14) including two sub-tables side by side. The results on sketching are presented on the left-hand side, and the results for prototyping are on the right-hand side. In the table, the reported quotes were related to the identified subcategories. The IDs for identifying the quotes are the same as described already in Study 1 (Chapter 3) and Study 2 (Chapter 4). All cited quotes in the table were already introduced and commented on in previous chapters (see Chapters 3 and 4). Some quotes, as mentioned before, address not only one but various subcategories (e.g., ODPQ1). The table is not for statistical analysis but summarises the emerged patterns from the answers that were conceptualised as codes, subcategories and structured into three main categories. The table's overview makes evident that most of the identified sketching and prototyping activities were relevant for both groups. Though some subcategories were only addressed by the ODs (e.g., 1.4, 1.8., 2.6., 2.7, 3.5), and one subcategory was only relevant for the PDs (3.3).

Table 14. Overview of the Coding system, with quotes from Proficient and Outstanding Designers related to sketching and prototyping – continued on the next page.

	Subcategories	Supported by PDs regarding sketching	Exemplary quote	Supported by ODs	Exemplary quote	Supported by PDs regarding prototyping	Exemplary quote	Supported by ODs	Exemplary quote
1 Task-related activities									
1.1	Generating ideas	PD41, PD46 PD54, PD4, PD24	PDSQ8, PDSQ9, PDSQ11, PDSQ12, PDSQ1	OD1, OD5, OD5	ODSQ1, ODSQ5, DSQ513	PD24	PDPQ1	OD3, OD4, OD7, OD7, OD7	ODPQ1, ODPQ3, ODPQ4, ODPQ8, ODPQ13
1.2	Conceptual-ising	PD51	PDSQ10	OD5	ODSQ2			OD4, OD4, OD7	ODPQ3, ODPQ6, ODPQ18
1.3	Reflecting	PD54, PD50	PDSQ11, PDSQ13	OD5, OD2, OD3, OD3, OD2, OD1	ODSQ2, ODSQ3, ODSQ13, ODSQ9, ODSQ2, ODSQ1	PD9, PD33, PD32, PD52, PD6, PD37	PDPQ5, PDPQ7, PDPQ6, PDPQ12, PPQ19D, PDPQ20	OD3, OD1, OD1, OD4, OD4, OD7	ODPQ1, ODPQ2, ODPQ3, ODPQ4, ODPQ6, ODPQ5
1.4	Being aware of reflection on sketches and prototypes	PD50, PD50, PD54	PDSQ4, PDSQ5, PDSQ1	OD1, OD3, OD2, OD3	ODSQ1, ODSQ4, ODSQ4, ODSQ9	PD13	PDPQ13	OD3, OD1, OD2, OD7, OD4, OD1, OD4, OD7, OD3	ODPQ1, ODPQ2, ODPQ9, ODPQ11, ODPQ6, ODPQ7, ODPQ4, ODPQ5, ODPQ6
1.5	Reducing Complexity	PD51	PDSQ14			PD17	PDPQ2	OD4	ODPQ4
1.6	Accelerating decision-making	PD51, PD54	PDSQ6	OD1, OD2	ODSQ3, ODSQ6	PD21	PDPQ3	OD7, OD3, OD7, OD7	ODPQ4, ODPQ1, ODPQ13, ODPQ14
1.7	Facilitating cognition	PD54, PD22, PD14, PD51, PD31, PD4	PDSQ16, PDSQ3, PDSQ4, PDSQ10, PDSQ14, PDSQ12	OD1	ODSQ1	PD17, PD22	PDPQ2, PDPQ4	OD1, OD1, OD1	ODPQ2, ODPQ3, ODPQ8
1.8	Implementing best practice routines of prototyping							OD6, OD1, OD7, OD7, OD7, OD3, OD3	ODPQ7, ODPQ10, ODPQ5, ODPQ8, ODPQ13, ODPQ1, ODPQ6

Table 14. Overview of the Coding system, with quotes from Proficient and Outstanding Designers related to sketching and prototyping.

	Subcategories	Supported by PDs regarding sketching	Exemplary quote	Supported by ODs	Exemplary quote	Supported by PDs regarding prototyping	Exemplary quote	Supported by ODs	Exemplary quote
2 Person-related activities									
2.1	Gaining certainty	PD6, PD17	PDSQ11, PDSQ7	OD3, OD5, OD1, OD2, OD5, OD5, OD3	ODSQ4, ODSQ2, ODSQ11, ODSQ10, ODSQ14, ODSQ7, ODSQ9	PD21, PD13, PD39, PD43, PD28	PDPQ3, PDPQ8, PDPQ8, PDPQ7, PDPQ10	OD4, OD4, OD4, OD7, OD7, OD3, OD1, OD7	ODPQ4, ODPQ17, ODPQ6, ODPQ15, ODPQ4, ODPQ1, ODPQ2, ODPQ8
2.2	Allowing ambiguity	PD6, PD30	PDSQ2, PDSQ1	OD5	ODSQ13			OD1, OD7	ODPQ7, ODPQ18
2.3	Facilitating the continuation of the process	PD8, PD51	PDSQ15, PDSQ10	OD2	ODSQ6	PD28	PDPQ10	OD7, OD7, OD6, OD3, OD7	ODPQ4, ODPQ11, ODPQ7, ODPQ6, ODPQ13
2.4	Expressing oneself/self-expression	PD30, PD17	PDSQ6, PDSQ7	OD3	ODSQ4				
2.5	Displaying expertise	PD24	PDSQ5	OD1, OD4, OD1	ODSQ15, ODSQ16, ODSQ7	PD16	PDPQ11	OD4, OD7	Q18
2.6	Striving for success			OD1, OD5, OD4	ODSQ15, ODSQ14, ODSQ16			OD7, OD4	ODPQ5, ODPQ6
2.7	Bonding with prototyping							OD3, OD1, OD7	ODPQ1, ODPQ10, ODPQ13
3 Interaction-related activities									
3.1	Search for information	PD54	PDSQ16	OD1, OD1, OD5	ODSQ3, ODSQ7, ODSQ5	PD13, PD33	PDPQ13, PDPQ16,	OD2, OD1, OD7	ODPQ9, ODPQ3, ODPQ4
3.2	Transfer of information	PD51, PD37, PD20, PD6, PD51	PDSQ17, PDSQ18, PDSQ1, PDSQ2, PDSQ20	OD5, OD4, OD4, OD2	ODSQ5, ODSQ8, ODSQ9, ODSQ6	PD27 PD20, PD16, PD22, PD17, PD43	PDPQ14, PDPQ7, PDPQ5, PDPQ3, PDPQ2, PDPQ	OD7	ODPQ13
3.3	Transfer of information addressing the user					PD21, PD33, PD37, PD24, PD6	PDPQ3, PDPQ6, PDPQ20, PDPQ1, PDPQ19		
3.4	Developing a shared mental model	PD43, PD51, PD17	PDSQ19, PDSQ20, PDSQ7	OD1, OD2, OD4	ODSQ17, ODSQ6, ODSQ16	PD12, PD49, PD39	PDPQ18, PDPQ15, PDPQ8	OD1, OD2	ODPQ10, ODPQ11
3.5	Cooperating			OD1, OD4, OD4, OD5	ODSQ17, ODSQ8, ODSQ14, ODSQ16, ODSQ18			OD7, OD4, OD3	ODPQ13, ODPQ5, ODPQ18

Models of the interplay

The main insights from two studies are underpinned with concepts from the research literature and synthesised into explanatory models. We compare not only the results but also juxtapose the models presented in Study 1 and 2 to visualise the relation between PDs/ODs regarding sketching in one model: the model of the interplay of design expertise and sketching (Figure 13). A second model was deduced visualising the relation between PDs/ODs with prototyping: the model of the interplay of design expertise with prototyping (Figure 14). The models illustrate the differences in the use of sketching and prototyping, so that strengths and weaknesses of these approaches can become visible at the same time.

5.4.3 SKETCHING: OVERFLOW VERSUS PURPOSE

In this section we discuss the main research findings that have been deduced into a model. The model illustrates two sketching approaches by designers with different levels of expertise. In the answers of the PDs and ODs we found that they share similar positive emotion about sketching, despite that the motivations and aims for using sketching are different.
Therefore, we discuss the underlying motivation, emotion, and reasons for the different sketching behaviour.

The PDs expressed positive emotion towards sketching and that they could rely on sketching and that they feel self-efficacious. Based on insights from PDs' answers we assume that they sketch a lot especially for generating ideas. In their responses we found hints that the PDs might link their flow of ideas to creativity.
The sketching of many different ideas is a relevant activity in design as fluency of ideas is linked to creative thinking (Torrance, 1969). The designers' focus on producing many creative ideas is in line with Cross' work. He argues that the focus on the generation of many creative and novel ideas is a form of fixation, caused by educational training in design (Cross, 2001b). The fixation on producing as many novel ideas as possible may have been rewarded during the design education. Therefore, the PDs might have positive emotion towards sketching OR a high motivation to sketch a lot.

Compared to the PDs who stressed relevance of sketching for generating ideas, the ODs have emotionally emphasised the value of sketching in their work for several reasons. The ODs mentioned especially to sketch for reflection, communication, and cooperation.

Furthermore, in contrast to the PDs, the ODs emphasised the value of good sketching skills as an expression of expertise and as relevant for cooperating with the client. Therefore, we assume and consider the ODs experienced and good sketchers. Goldschmidt argues that experienced sketchers can execute sketches with rather 'no cognitive costs' (Goldschmidt, 2014, p. 433). Thus, the ODs might need less time to sketch because as it is low cognitive load for them. In addition, the ODs expressed that they appreciate sketching although they do not need much time for it. The ODs may need little time to externalise their internal representation. We assume this is due among other reasons (e.g., knowledge experiences from prior projects) to good sketching skills.
The PDs' overemphasis on sketching could be explained by the fact that the PDs are inexperienced or poor sketchers. A poor sketcher has to sketch more and more extensively and overflowing until his external representation (sketch) matches the internal representation. Therefore, the phenomenon of PDs' sketching overflow may be an indication of poor sketching skills. Another relevant aspect of sketching is that it is seen as a valuable thinking aid (Goldschmidt, 2014; Tversky, 2002). It might also be possible that the PDs could sketch more because they think more - even if they didn't say so in the survey.
In contrast to the ODs who stressed the use of sketching to reflect. Reflection is advantageous activity in the context of complex problem solving, among other activities, when developing an idea into a concept. Based on the data, we assume that the PDs tend not to conceptualise their ideas carefully. This assumption can relate to research literature. Chen and You (2004) investigated sketching in conceptual design and found out that novice designers not fully conceptualise their ideas compared to experts. Furthermore, Cross' research indicates that ODs apply strategic knowledge such as framing based on personal experiences (Cross, 2001b).
In the survey data, the PDs did not stress to sketch using a methodological approach to reflection nor did expressed relevance for reflection. Therefore, there is indication based on the research results for the phenomena of ODs' sketching with purpose and the PDs' sketching overflow.

Model

The main difference between the models is PDs' unstructured approach to reflection on sketches, whereas ODs employ a structured approach to reduce the complexity in the design process. These different approaches to reduce complexity and reflection impact on the designer at an emotional, motivational, and cognitive level.

The amount of many diverse sketched ideas comes with divergence and complexity. We assume PDs even use this divergent and overstressed sketching approach when facing complexity. The unstructured reflection approach leads to a not fully reduced complexity. Moreover, we assume, that this not fully reduced complexity leads to uncertain conditions on an emotional level (stress), resulting in more sketching activities. We call this behaviour the PDs' sketching overflow.

In contrast to the PDs, the ODs' use of sketching is goal focused, purposeful, and aims at gaining certainty. Based on their answers, we found indication that the ODs use a structured approach to reflection to fully reduce the complexity of the design process. This results in a gain of certainty on an emotional, motivational level that impacts also on a cognitive level and facilitates the decision making. Over time, this self-reinforcing process leads to self-efficacy in solving design problems. The sketching behaviour described is called the ODs' sketching with purpose.

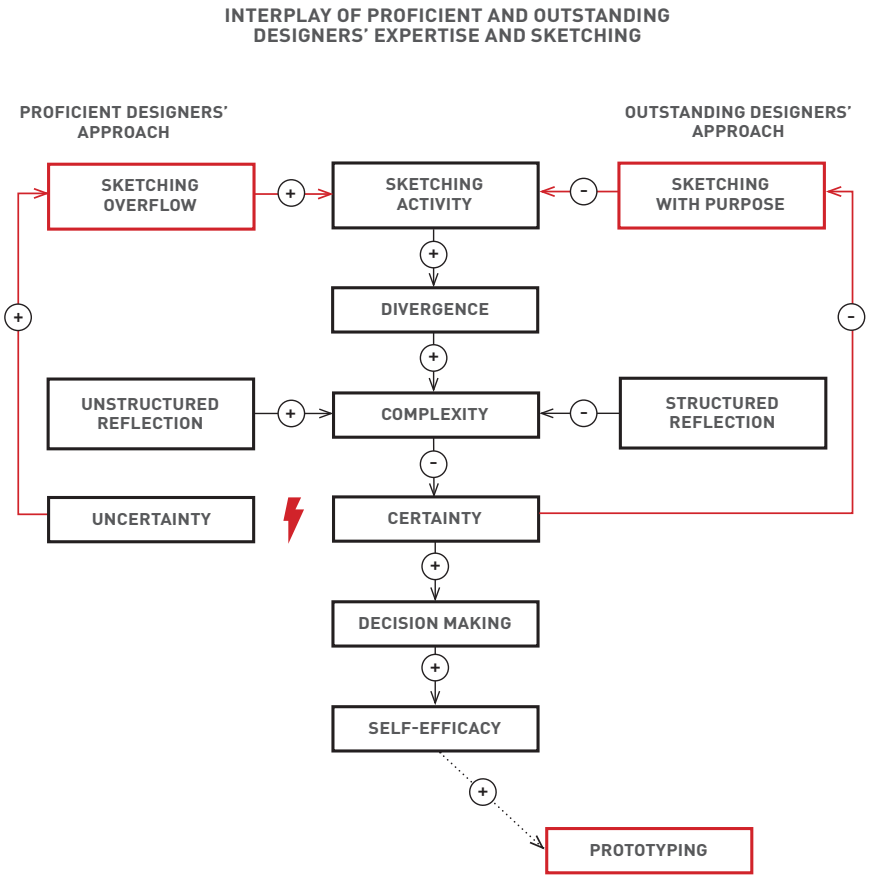


Figure 13. Interplay of design expertise and sketching.

5.4.4 PROTOTYPING: BONDING GAP VERSUS BONDING

In this section, the main findings from the comparison regarding the interplay of design expertise and prototyping are discussed. Based on the findings, the PDs expressed an emotional attachment to sketching in contrast to only a little for prototyping. There was an obvious difference on the emotional level regarding prototyping. This finding contrasts with the insights from the ODs' answers, that they are emotionally attached to both, sketching, and prototyping but expressed an even higher positive emotion towards the latter. The strong ODs' attachment to prototyping leads to a high motivation to use prototyping activities during the entire design process. We designate this aspect as a positive form of fixation on a cognitive level and refer to it as bonding. We call this interplay ODs bonding with prototyping in contrast to the PDs having a bonding gap with prototyping.

In the following, we collate the main findings regarding prototyping to explain the reasons to use prototyping as a basis for a way of regulating emotions especially by reducing complexity based on reflection in order to gain certainty. To visualise this relevant difference, we deduced a model that juxtaposes the prototyping activities of PDs and ODs. With PDs the main difference compared to the ODs behaviour is the use of a structured reflection approach. The gained certainty by using prototyping fortifies the bond with prototyping.
The model of the interplay of prototyping with design expertise of the two expertise levels illustrates the consequences of the cognitive activity of reflection on an emotional-motivational level. Based on the insights from two studies, we interpret the interplay of prototyping and two different levels of design expertise (in Figure 14).

We describe the model from the top down, from the left to the right side.
In general, the prototyping activities applied early in the process and executed roughly in low resolution prototypes, generate many different and divergent ideas (Dow et al., 2011; Yang, 2005). The more the designers use prototyping, the greater the divergence. High divergence leads to increased complexity, and complexity leads to uncertainty. The greater the complexity, the less the feeling of certainty (Dörner, 1996). In a moment of high complexity, the PDs and ODs differed in their activities to cope with the complexity. In this situation, we assume that PDs use an unstructured approach to reflection to cope with the complexity.

We further assume this approach insufficiently reduces the complexity, meaning uncertainty remains. According to Dörner (1996), uncertainty generates fear of failure. People want to protect themselves from this fear, and their brain tends to block out all that is complicated, inscrutable, and unpredictable (Dörner, 1996). Ignoring complexity can also display a confirmation bias. The confirmation bias describes the tendency of selecting information that supports one's own views. Thereby, the individual ignores contrary information, or interprets ambiguous evidence as supporting existing attitudes (Wason, 1960). This bias can be managed, for example, by applying reflection.

These findings from the research literature support our assumption that the PDs might ignore or cannot 'see' the complexity and therefore they continue to apply this sketching approach. The greater the complexity, the less the certainty. There is a link between certainty and a higher quality of outcome (Dörner et al., 1994). Therefore, the PDs' unstructured approach to reducing complexity not only results in uncertainty, but also in inferior quality of the outcome. We argue that in a situation of uncertainty, some PDs rely on their sketching routines. They prefer sketching because of good experiences they may have had with it, or they use it simply because they are 'better' at sketching than prototyping, meaning they feel supported and certain. The PDs who continue with prototyping, who perceive that with their approach the complexity is not reduced, and the quality of the outcome has not sufficiently increased, do not feel supported by prototyping activities in complex problem-solving. The PDs are motivated externally by clients to prototype, and the PDs seem not to be motivated by their own aim to gain certainty. The lower the quality of the design outcome, the less the designer is self-efficacious in further using prototyping for complex problem-solving. The lower the self-efficacy, the less positive emotion, less attachment, and less motivation there is to use prototyping again. We assume this situation is a vicious circle. This identified PD prototyping approach contrasts with the practised approach of ODs. The ODs cope with complexity by using a structured approach to reflection. A structured approach to reflection means to analyse, to structure in order to select based on e.g., previously developed criteria and relate and base the reflection activities on sketches and sketching. We expect that the more increased use of a structured approach to reflection, the more the complexity is reduced. Therefore, the more complexity is reduced, the more the certainty is increased. The more increased the certainty, the more increased the quality of the outcome.

The quality of the outcome results from mastery experiences in complex problem-solving based on prototyping. Based on Banduras' (1997) concept of self-efficacy, we postulate that these experiences, over time, lead to increased self-efficacy (Bandura, 1997). The more increase the self-efficacy, the more positive the emotion regarding prototyping. The more the designers use prototyping, the more positive the emotion and the more they become attached to prototyping. The ODs expressed high positive emotion towards prototyping. Therefore, we link this connection to the concept of bonding in the design context and designate it as denoting the relationship of an OD with her/his prototypes. We postulate that this prototyping approach is a positive and self-reinforcing loop.
Based on the results from the two studies, the models are substantiated but require further evaluation in the future. Through the models, we deduce actionable advice for the development of tools for supporting design education, to be explore further in Chapter 6.

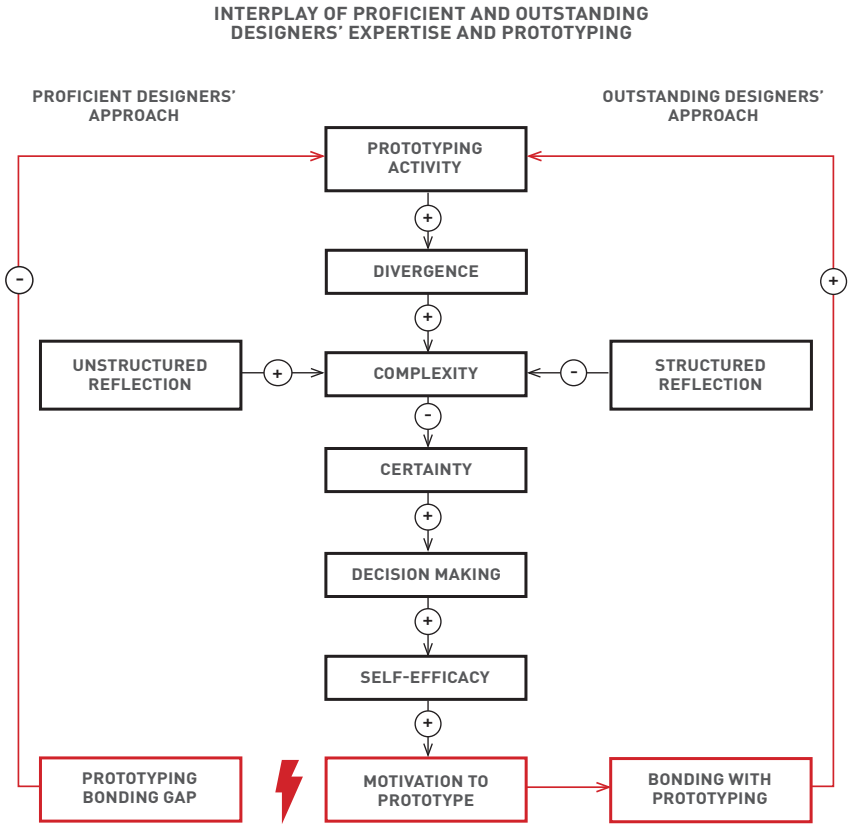


Figure 14. Interplay of design expertise and prototyping.

5.5 CONCLUSIONS

The results from studies with Proficient and Outstanding designers – outlined in Chapter 3 and 4 – were compared to answer the third research question:

> *What are the similarities and differences in the use of sketching and prototyping by Proficient and Outstanding designers? (RQ3)*

Based on the comparison similarities and differences were identified in order to deduce learning opportunities. Moreover, through the comparison valuable insights were gained regarding the relevance of professional experience and are highlighting the sketching and prototyping skills necessary to become an OD. We attribute the main reasons for the different behaviors to the different approaches PDs and ODs have toward reflection based on sketches and prototypes. The findings suggest ODs follow a more structured and reflective approach than PDs, being fully aware of the relevance of their sketching and prototyping activities.

Furthermore, the gained insights contribute to a better understanding of the interplay of expertise, sketching and prototyping. The results suggest that design expertise matters and impacts sketching and prototyping activities resulting in different use.

The PDs' sketching overflow relates to an overstressed and imbalanced use of sketching for generating ideas. Sketching is largely used to foremost generate many and novel ideas. The tendency of PDs to use a relatively divergent approach and to enjoy generating ideas requires a convergent approach to benefit the most from the ideas. The PDs tend to neglect sketching despite the supportive potential sketching offers for reflection and gaining certainty.
Interestingly the displayed (based on responses) problematic sketching approach did not affect PDs positive emotion towards sketching and their excessive use.

the ODs know the benefits of using sketching for a more ample approach, they emphasised openness to ambiguity (e.g., in their prototypes) and rigid diligence (e.g., in their sketches). The ODs' answers suggest an awareness for reflection and reflection activities. Additionally, they expressed relevance for realistic and good sketching skills to support reflection and certainty as well as for attaining

a shared mental model in order to cooperate with the client. Overall, the ODs use sketching with a focus on the goal. Building on their experiences they generate ideas related to a real solution instead of focusing on generating many novel ideas for their own sake. The ODs expressed a strong perseverance to follow own standards and to strive for success. Concluding, we call this behaviour 'ODs' sketching with purpose'.

Based on the results of our studies, we identified in the PDs' answers a lack of awareness of prototyping benefits – especially regarding reflection activities based on prototypes. Despite existing research that has emphasised the benefits of prototyping in the early phases of the design process – using in parallel various quick and simple prototypes –few of the PDs expressed relevance for using early prototyping. PDs neither emphasised relevance for reflection nor reported a strong emotional attachment towards prototyping (as they did with sketching). The identified behaviour is the 'PDs' bonding gap with prototyping'.

Whereas the ODs emphasis the use of prototyping especially in the early phase as well as generally during the design process. In the quotes the ODs emphasised routines to implement prototyping and expressed high emotional attachment to prototyping for their work, especially for reflecting, developing ideas further, and to gain certainty.
The ODs implemented best prototyping practices to accelerate the design process. Furthermore, prototyping is used to follow a high standard, to strive for success and to cooperate with the client. We designate this highly motivated use of prototyping as 'bonding with prototyping'.

In the responses some of the PDs expressed the relevance of using prototyping for interaction with the team, clients, and users. Furthermore, this interaction might lead to a reflective conversation about their prototypes, which might result in a reduced complexity. The involvement of users and testing of prototypes are relevant topics in design.
Surprisingly, none of the ODs mentioned any interaction with users. This finding contrasts with the influential concept of user-centeredness, which aims to frame problems, capture hidden needs, and incorporate the voice of the user into products, systems, and processes. Research in the field of software design stresses the relevance of involving users to gather users' implicit needs and requirements (Gerber, 2009; Kujala, 2003).

Future research shall investigate why ODs ignore user involvement in their design process.

The quality of the sketches produced was not the subject of this research and we cannot conclude that the PDs or ODs are good or bad sketchers; this needs to be investigated in the future. The mastery in sketching has several advantages: a positive effect on the designers' cognitive load during sketching (Goldschmidt, 2014) and also well sketched design ideas are assessed as being more creative (Kudrowitz et al., 2012).
The main findings from the comparison are two models visualising the interplay between Proficient and Outstanding designers' expertise with sketching (Figure 13) and prototyping (Figure 14). The models not only visualise the interplay but provide an explanation based on theoretical concepts for the identified behaviours. We postulate that the main issues with PDs' sketching and prototyping activities can mainly be attributed to the topic of reflection, especially the omission of reducing complexity through a structured approach to reflection.

The overall aim of this thesis, beside exploring the interplay, is to learn from ODs. To make the research results more accessible to education, recommendations were derived for facilitating the development of tools for guiding reflection. The requirements for the development of a guiding reflection toolkit are outlined in the end of the chapter.

Next Steps

The findings from the comparison indicates that reflection awareness and application of a structured reflection approach based on sketching and prototyping are increased by experience. The insights also suggest that the PDs are not aware of the advantages of using sketching and prototyping and have not yet fully explored it. Especially relevant is their lack of awareness of reflection and the omission of a structured reflection approach. We argue that designers with little positive experience in applying reflection activities would especially tend to avoid these. Therefore, designers must not only have declarative knowledge regarding reflection benefits, but they have to experience its impact to be motivated to apply reflection. Therefore, we propose two core elements of the support for designers.

First, providing knowledge about reflection benefits to create awareness of reflection. Second, providing guidance for experiencing a structured approach to reflection. Both aids have to be provided to students already as early as possible in design education to start the formation of a new habit for behavioural change.

The next research aims are making the insights of this thesis research applicable to education. We argue that tools can effectively facilitate the complicated process of reflection and support the transfer of knowledge and know-how. A tool can provide step-by-step guidance (e.g., integrated in a template of a canvas) for applying the complicated process of reflection. Furthermore, a tool (such as Cards) facilitates repetition. All in all, tools can facilitate learning by providing guidance and repetition to reduce the lengthy process of habit formation.

Requirements

The findings from two studies were synthesised and culminated into two explanatory models to facilitate the deduction of recommendations. This knowledge, underlined with theoretical concepts, is transferred into actionable advice informing the development of tools.

The following requirements shall be imbued in the tools:

- Knowledge regarding the impact of a structured reflection approach based on sketching and prototyping for the design process.
- Knowledge and guidance to apply reflection activities analysing, structuring, and selecting – in a structured way.
- Support for creating awareness for reflection. Especially, the transfer of knowledge about reflection for raising expectation and motivation to identify cues of uncertainty.
- Creating awareness for reflection as precondition for initiating moments of reflection.
- Knowledge regarding the benefit of a dialogue-based question asking to facilitate a rational-analytical thinking style.
- Facilitating a question based (inner) dialogue asking to support the students' rational-analytical thinking style.
- Guidance for applying a switch between verbalisation and visualisation.
- Facilitation for a positive physical arousal to support certainty and self-efficacy.
- Facilitation for a positive physical arousal to support awareness for cues of uncertainty to initiate a moment of reflection.

These requirements are imbued in a toolkit for providing guidance for reflection activities and for creating awareness for reflection in design students.

Parts of this chapter have been published in:
Jobst, B., Thoring, K., & Badke-Schaub, P. (2020). Introducing a Tool to Support Reflection through Sketching and Prototyping during the Design Process. *Proceedings of the Design Society: Design Conference, 1*, 207–214.

6 A TOOLKIT TO GUIDE REFLECTION

In the first part of this thesis, we have applied an explorative research approach to gain insights from ODs and PDs into how they use sketching and prototyping (Study 1 and Study 2). Based on a comparison of the results, we identified similarities and differences in PDs' and ODs' use of sketching and prototyping. From all the differences identified, valuable learning opportunities can be derived for the design students, including very good sketching and prototyping skills. Despite other relevant themes that have emerged in our research, we have chosen to develop interventions with a focus on reflection, as we see unstructured reflection as a cause of weaknesses in designers' sketching and prototyping behaviour. Our assumption is that a high level of expertise is relevant for reflection using sketches and prototypes. Much research has been done in cognitive psychology on how to improve problem solving and increase the quality of results (Dörner, 2011). It has been shown that one of the most successful methodological approaches is reflection. In addition, (self-) verbalisation has an important supportive effect on reflection (Wetzstein & Hacker, 2004).

In this second part of the thesis, we therefore build on the findings from two studies and translate them into tools. One main insight drawn from the comparison is that designers with few experiences in practice tend to neglect the benefits of using reflection based on sketching and prototyping. Therefore, our first design question is as follows:

> *DQ 1: How can we create awareness for reflection among design students in the design process?*

Our goal is to develop and design a set of tools that consolidate the insights and knowledge we acquired throughout the PhD research. Thus, the second design question is as follows:

> *DQ 2: How can we support design students' reflection activities in the early stages of the design process through appropriate tools?*

The toolkit should provide support for less experienced designers and offer step by step guidance to try out and apply the knowledge from literature and ODs best practice insights. The toolkit offers this knowledge to be applied and experienced by the designers in their sketching and prototyping practices.

Based on these research insights we aim to lay the basis for reflection as early as possible in design education. Therefore, we provide findings and knowledge

in the tangible and accessible form of tools for design students used to guide their reflection. Our approach contains the planning and the design of various facilitation tools, followed by two design workshops for testing, using a Research-through-Design (RtD) approach (Frayling, 1993). The developed tools were introduced und used in a real design education context with design students in two workshops. The tools and their impact were observed and subsequently evaluated through employing an action design research (Sein et al., 2011) approach. Based on these results, aims and steps for future work are deduced.

6.1 MOTIVATION FOR THE CREATION OF TOOLS

In order to make our research findings and insights accessible to less experienced designers we provide a toolkit. Based on our findings, we argue that the 'reflection conversation with materials' of a design situation (Schön, 1992) is not necessarily a common practice of designers. Reflection is not always practised in a structured way by PDs, and we expect the same approach with design students. Our findings suggest that reflection does not come naturally. Reflection, and we assume especially a structured approach to reflection, is relatively time-consuming and requires effort. The literature stresses that people must be motivated to reflect (Fleck & Fitzpatrick, 2010; Moon, 2013).

Based on this insight, reflection awareness should be created in design students, and motivation must be enhanced to apply reflection activities related to sketching and prototyping in a structured way – even when time-consuming. In Chapter 5, we reported that the PDs displayed little awareness of reflection and did not mention a structured approach to reflection, compared with the ODs. We assume this lack of awareness results in fewer self-initiated reflection activities. A reason for this lack could lie in the current design of education curricula, which might not explicitly teach students about the benefits (and methods) of structured reflection. To change a routine requires effort and time. To solve this gap in the education curricula, we aimed to develop tools to create awareness of reflection, targeting at design students in the early phases of their design education. Thus, the first design question (how can we create awareness for reflection among design students in the design process?) led our subsequent steps. We postulate that to be aware of when is an appropriate

moment to reflect is as important as knowing how to apply reflection activities in a beneficial way. A further research insight is that ODs tend to use a more systematic and structured approach to reflection than the PDs do. Thus, the second design question addresses the support of reflection activities (how can we support design students' reflection activities in the early stages of the design process through appropriate tools?). The development of the tools is based on the assumption that the switch between visualisation and verbalisation creates a thinking pattern that helps coping with complex design problems (Wetzstein & Hacker, 2004). Based on this assumption, we further explore and strengthen the interrelations of sketching and prototyping on the one hand, and reflection on the other.

With the two design questions in mind, we underpin our assumptions with theoretical concepts from research literature. The theoretical concepts form the basis for the development of tools to create awareness for reflection and to guide reflection activities. Consequently, we developed a set of tools that consolidate all the insights and knowledge acquired throughout the PhD research. These findings and knowledge were imbued into tangible and accessible tools for design students.

6.2 THEORETICAL CONCEPTS OF REFLECTION

The development of the toolkit is based on research results and theoretical concepts to answer the two design questions. The theoretical concepts necessary for tool development will be introduced below.

Reflection

Reflection can generally be characterised as individual contemplation about the past, the present, and the future. In the 1980s, reflection became an ample discussed topic in education (Biggs & Tang, 2011; Bloom, 1956; Dewey, 1933; Kolb, 1983; Krathwohl, 2002; Moon, 2004; Schön, 1992).

Researchers have approached the topic through different angles and investigated when reflection happens, how reflection can be inspired, and how reflection can be facilitated. Dewey, emphasised that settings of practice cause

feelings and emotions that mostly result in opportunities to reflect (Dewey, 1933). Hereby the 'doing extends thinking in the tests, moves, and probes of experimental action, and reflection feeds on doing and its results' (Schön, 1983, p. 280). The – reflection on action – approach refers to reflection after the activity and about the activity. Therefore, the individual takes a conscious look at emotions, experiences, actions and uses this information to integrate these to the existing knowledge base in order to attain a higher level of understanding. Based on this reflection on action approach the individual can deduce future steps.

An essential aspect of reflection was contributed by Mann and colleagues who point out that 'most models of reflection practice depict reflection as activated by the awareness of a need or disruption in usual practice' (Mann et al., 2009, p. 597).

A further approach to reflection in nursery education stresses the relevance of and explicitly links reflection with experience to enable learning. This approach is mirrored in the term 'reflective learning' (Moon, 2004, p. 80). Reflection also plays a role in organisational practice for teams. Based on research on teams (within organisations), it is plausible that complex decision-making depends on learning, and that reflection enables learning (West, 2000). These descriptions are based on concepts contributing valuable and different foci on reflection in students' and practitioners' education.

In design, reflection has been investigated and divided into different branches. One characteristic topic is the connection of reflection with visualisations and its impact for the design process. Several researchers have highlighted the supportive role of visualisation for reflection. In particular, one part of the reflection process – the analysis of the problem – can be supported by using representations via sketches (Sachse et al., 2004) or via sketches and prototypes (Römer et al., 2000). A good problem understanding is crucial for the development of a solution and the solution quality (Sachse et al., 2004). Goldschmidt (2002) emphasises sketching and prototyping for reflection because designers 'use the representational act to reason on the fly' (Goldschmidt, 2002, p. 72). Moreover, she argues that especially manual sketching fortifies reasoning (Goldschmidt, 2017).

In the design context, Schön (1992) highlights the relevance of materials for causing and supporting reflection.
According to Schön (1992), designers can converse with the materials of a design situation (e.g., sketches and prototypes support their reasoning process). Designers can see the outcome of their work evolving because 'designers work in a medium' (Schön & Wiggins, 1992, p. 154). Designers not only develop a thorough understanding of the task, but also create knowledge and experience when dealing with this task. The preliminary output of the design activity guides and stimulates the ongoing design process. Furthermore, the impact of reflection based on visualisation can be enhanced by the inclusion of verbalisation, as it promotes an analytical-rational thinking style and supports reflection (Wetzstein & Hacker, 2004).

Part of the discussion about reflection, concerns how to inspire reflection among students or/and practitioners. Teaching and transferring knowledge to students about reflection and its relevance for learning is one approach (Osland et al., 2001; Sims & Lindholm, 1993). In design education, researchers aim to deduce concrete recommendations to improve designers' reflection approach. Reymen and Hammer (2002) investigated design reflection and introduced a structured approach to reflection, which is performed on a regular basis and in a systematic way. To apply this approach can help designers to improve their design process, its results, and the designer's proficiency to apply reflection.

The described approaches for exploring reflection remain relatively general. We aim to develop tools for design education, and therefore we define reflection for this purpose. We build on previous descriptions, namely Reymen and Hammer (2002) and Schön (1983) and their definitions of reflection (in action and on action). We define reflection as thinking in a structured way about your ongoing design (work) in alignment with your set goals with the aid of sketching and prototyping to gain certainty. Moreover, to develop tools, we defined the term reflection regarding reflection activities and reflection awareness. The characteristics of reflection and what is needed on an individual level to become aware of reflection were defined before we started the tool development.

Reflection in Education

The need for reflection in the design context at university level (Reymen, 2001) and on the workplace (Fleck & Fitzpatrick, 2010), for practitioners (Badke-Schaub & Frankenberger, 1999) has been supported by various researchers developing means for reflection. Reyman (2001) argued for a need to enhance reflection competency and offers support through a digital tool (software). Support for practitioners in the engineering context was developed in the form of training accompanied by a tool (checklist) to facilitate reflection (Badke-Schaub et al., 1999; Geis & Birkhofer, 2009; Weixelbaum et al., 2013). In the context of self-regulated learning to support reflection in action researchers promoted the use of reflection amplifiers (Salmon et al., 2007; Verpoorten, 2012). The goal of a reflection amplifier is to provide support to the students at examining aspects of their learning experience in the moment of learning. A typical characteristic of the amplifiers is inducing regularly structured and repeated reflection affordances. These affordances are interspersed in the learning material providing stop-and-reflect episodes during learning.

Reflection Awareness

Awareness of reflection is a background control system that works continuously to ensure the current situation does not deviate from the expected situation. Only when a cue indicates newness, surprise, or danger is the activity of reflection initiated. If a situation differs from the mental model, the routine answer cannot be applied, perhaps because something new or different occurs or because a completely new situation that cannot be solved by applying well-known patterns to the solution. A further characteristic of awareness of reflection is motivation as a prerequisite of any activity. Without motivation, the designer does not act or exercise. There is a specific relevance of motivation for practising reflection as it is time consuming. Usually individuals need a reasons or need to be encouraged in order to engage in a time consuming approach (Fleck & Fitzpatrick, 2010; Moon, 2013). Consequently, we emphasis the relevance of knowledge and motivation to engage design students to experience new approaches to reflection.

Knowledge, motivation, and expectation

Knowledge is crucial for awareness because it influences expectation. Expectation is a precondition of perceiving minor 'discriminations'. Due '*to a vast*

repertoire of situational discrimination he (the expert) sees how to achieve his goal. Thus, the ability to make more subtle and refined discriminations is what distinguishes the expert from the proficient performer' (Dreyfus, 2002, p. 371). The ability to make more refined and subtle distinctions is an expression of a higher level of expertise. Thus, it is one relevant goal to create awareness for (to make) discriminations respectively – as designated in this research – cues of uncertainty.

Reflection awareness is based on knowledge, motivation, and expectation, and we address these three characteristics to raise awareness in design students. In terms of awareness, a person must be aware of a critical situation and act according to their knowledge to find or apply a solution to the current problem. Thus, the designer has to employ knowledge and skills and develop a mental model of the design problem and the solution. We argue it makes sense to develop a frame and deduce criteria for creating a mental model of the design problem. The designers' mental model impacts the expectations of how the design must be and enhances the awareness of cues of uncertainty.

We argue designers should learn methods to create a structured conversation with sketches and prototypes to gain insight and certainty. In addition to learning a good approach to reflection, Gonçalves (2016) raises the question of when the most opportune moment is to reflect. Based on our results with PDs, it is important to identify relevant moments for reflection, and there is a need to be aware of and be able to perceive cues of uncertainty (see Chapter 5). We argue the three characteristics of knowledge, motivation, and expectation raise awareness for initiating reflection when cues of uncertainty occur. Thus, we define cues of uncertainty as external stimuli that allow one to draw conclusions in alignment with the mental model of the design frame regarding (among other aspects) mistakes and discrepancies with criteria and/or requirements. The ability to perceive cues of uncertainty and to identify relevant moments for reflection during design activities seems to grow with experience, as identified in research with the ODs (see Chapter 4). In our second research study (described in Chapter 4), we identified the ODs' emphasis on using sketches and prototypes to gain certainty and to reflect on it in a structured way when cues of uncertainty are perceived. We argue that a designer who perceives minor cues of uncertainty interrupts the process and starts to reflect. This action can lead to changing the prototype and the outcome of the object.

Reflection Activities

Reflection activity is a pattern concerning analysing, structuring, and selecting. Analysis is crucial to understand the task and the inert problem. The problem analysis is known to be beneficial for the whole design process outcome (Leinert et al., 1999; Römer et al., 2000). We postulate being relevant to structure ideas and criteria in order to prioritise and to develop a hierarchy of the criteria and information relevant to elements in the design process. Further we consider being relevant to select ideas or solutions based on criteria, reflection, and visualisation. To select an idea involves reflecting for consequences in the futures and the development of the next steps We argue that applying this pattern of activity provides a better understanding of the situation. The pattern comprises the activities regarding how to react and how to learn from it, as well as how to structure, select, make decisions, and plan future steps. A structured approach to 'reflection can support designers in their design process and can also impact the design results' (Reymen, 2001, p. 13). However, the described process is difficult. Additionally, applying reflection activities requires openness from designers to recognise how a situation differs from expected, and it needs the cognitive capacity to act suitably.

We postulate that this process can be trained and is of special interest in the sketching or prototyping situation, in which the designer often thinks in an unstructured as opposed to a structured manner. Verbalisation is relevant for facilitating a beneficial thinking style. According to Wetzstein and Hacker (2004), verbalising thoughts and ideas are supportive of reasoning. We argue that the insights from our research and the literature substantiate our efforts to create a a toolkit to raise awareness for and to guide reflectionthat is tangible and accessible for design students.

Conceptual Definition of Reflection

To summarise our findings from the previous studies and the literature discussed above, we define reflection for this research and its characteristics as' a dynamic process of a unique pattern of activities steered by continuous awareness' (Jobst, 2020). This pattern of activity is executed in the moment when awareness signals a new, dangerous, or surprising cue. In Figure 15, reflection is visualised as a two-step process combining two thinking processes: reflection awareness and reflection activities.

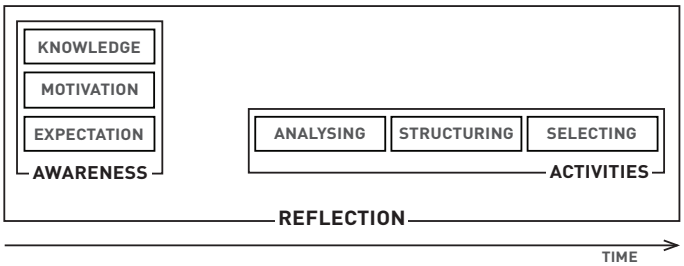


Figure 15. Reflection defined as a combination of awareness and verbalised activities.

$$\text{Reflection} = R_{awareness}\,(knowledge, expectation, motivation) + R_{activities}\,(analysing, structuring, selecting)$$

Both thinking processes involve characteristics that underpin and inform the development of the tools.

6.3 RESEARCH APPROACH

We developed and designed a toolkit containing three tools to answer both design questions. The toolkit was designed following a Research through Design (RtD) approach (Frayling, 1993) and Gestalt principles (Arnheim, 1965). The design of the toolkit was part of an action design research approach. We planned, developed, and conducted two design workshops for design students to intervene in a real context, here a design educational situation, with the developed toolkit. The tool-based interventions allowed us to reflect and evaluate the tools in order to be able to identify potential for improvement and to iterate the tools.

We designate reflection as a complex activity, and it takes time to form the habit of using reflection in a structured way and to form a reflection mindset. Therefore, we wanted to lay the foundation for this formation as early as possible in design education. We build on the results of our study with PDs, which led to our assumption that design students display relatively few reflection activities in a structured way. Therefore, we postulate that a reflection mindset must be developed already in design students. A change in habit formation requires time (Lally et al., 2010). A more intellectually challenging and complex behavioural change (i.e., using sketching and prototyping for a structured approach to reflection) requires at least the same time, and probably even more.

Therefore, we suggest introducing tools to steer reflection in design students and to start the formation of a reflection mindset as early as possible in design education, leading to our sample. In alignment with our design questions, our goal is to develop tools to guide reflection in design students and to apply and validate these tools in a workshop setting. We set up two action design research workshops.

Action Design Research

A toolkit was developed in order to answer the two design questions applying an action design research approach (ADR). For our research approach we built on Kemmis (Kemmis et al., 2013) and Sein & colleagues (Sein et al., 2011). The aim of our action design research was twofold: first to plan and design tools, using a RtD approach and following the rules and principles of Gestalt theory (Arnheim, 1965) and second its evaluation. Hence, the aim was to plan and conduct two workshops to intervene in an existing real design education context with design students. We followed Kemmis' four-step-action-research cycle (Kemmis et al., 2013) covering the following activities:

Step 1: Plan. We conceptualised, developed, designed, and prototyped three tools. The conceptualisation of the tools was informed by theoretical concepts from social sciences, psychology, pedagogy, such as vicarious experiences (Bandura, 1997), as well as by the insights from the ODs. The design of the tools was informed by design methods, such as the two-by-two matrix, and Gestalt Principles (Arnheim, 1965).

(1) Tool 1 is the Awareness Card Set aiming at creating awareness for reflection in providing findings from research literature and ODs best practice insights (Info Cards) as well as trigger questions (Reflection Cards) the latter is used with a logbook to write down the answers.

(2) Tool 2 is the Breathing Exercise consisting of two elements, the 'Three Micro Breath Practice' and a Slow-Paced Breathing Exercise.

(3) Tool 3 is the Reflection Canvas – a wall-mounted Canvas, which provides step-by-step guidance for reflection activities. The Canvas is accompanied by Post-its with prompts to trigger answers and scales to tick.

Also, we created a common environment for the design students. For this, two workshops with a specific design task were developed.

The task of the first workshop had to be solved in one day (six hours), and the task for the second workshop had to be solved within three days (six hours each day).

Step 2: Act. The two design workshops were conducted to intervene with the tools in a real design educational context and to introduce the tools to students.

Step 3: Observe. The participants were observed during the design workshop as to how they interacted with the tools. The observation was captured by photos and notes.
Additionally, the students had to answer questions related to the design question and research aims in a feedback session in the end of the workshop (notes were taken).

Step 4: Reflect. At the end of each workshop, the answers from the feedback session and the data from the observations were analysed. We related the findings to the research literature evaluating the tools. The results informed the iteration of the tools, and we suggested further research steps.

The two cycles are illustrated in Figure 16. The first cycle was intended to answer the second design question whereas the second cycle aimed at answering the first design question for organisational reasons.

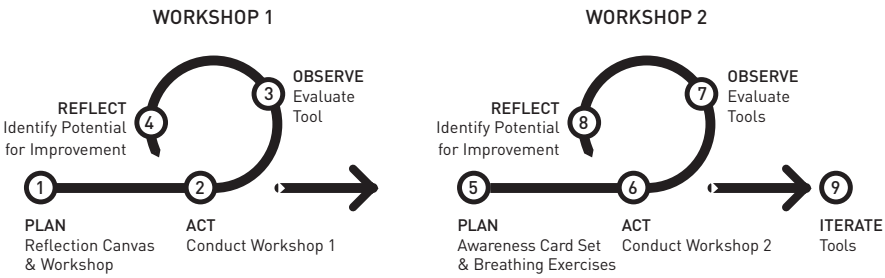


Figure 16. Overview of research approach on two action research cycles.

6.4 THE TOOLKIT

The insights from our research from interviews with ODs inform the development of our reflection toolkit in order to make learnings from the ODs accessible for design students. A tool can be described as a working aid to support the application of a design method (Birkhofer et al., 2002). Moreover

> *'tools might be based on particular methods, guidelines, processes or approaches or can be generic environments that can be used in conjunction with many methods'* (Gericke et al., 2020, p. 3).

Building on the previous descriptions of tools, we define a tool as a primarily tangible artefact that is based on methods, guidelines, processes, and approaches that facilitates a particular task or activity.

The tools are provided to support design students regarding creating awareness of a structured reflection approach on their sketches and prototypes. The tools address two aspects of reflection: awareness of reflection and reflection activities related to sketching and prototyping.

In the first design workshop (W1), the 'Reflection Canvas' was presented to guide reflection in the early phase. The second design workshop (W2) aimed at introducing tools to create awareness of reflection in design students. The conceptualisation and design of the tools followed theoretical concepts, as previously described, research literature, and insights from ODs' best practice. The tools can offer guidance to support design students in learning to apply reflection activities and create awareness of reflection.
In the following section, we used our research findings and additional theoretical concepts to develop a toolkit to guide reflection activities tailored to design students.
There is evidence that a training for novices must consider that novices and experts have different needs regarding the use of, for example, a process. According to Laubheimer (2020) a new user, before having developed a mental model of how a system works, needs guidance and obvious options. Expert users would feel slowed down by too narrow guidance. Experts use shortcuts and a quicker (and less guided) approach than Novices. We build on these findings and integrate step-by-step guidance especially for the Reflection Canvas and the Breathing Exercise.

6.4.1 TOOLKIT REQUIREMENTS

The tools to be developed to create awareness of reflection and to guide reflection among design students. The addressed activities and related theoretical concepts are listed in the following.

We designed reflection tools for design students. The tool development was led by the following general requirements:

- easy to use.
- enable standalone use (without instructors)
- accessible for an educational context (price-conscious)

More specifically, the goal was to guide reflection activities and provide step-by-step guidance for an explicit and written design frame. The noted frame with derived criteria supports the designer aligning the criteria with sketches and prototypes. Therefore, the tool addressing guiding reflection activities facilitate:

- analysis of the problem
- deduction of a framing, criteria, and constraints.
- structuring information and insights, prioritising criteria, etc.
- selecting ideas and solutions proposals in alignment with set goals, criteria of the design frame, mental model, etc. and to deduce next steps and future aims.
- a switch between visualisation and verbalisation because this enables a rational-analytical thinking style (Wetzstein & Hacker, 2004)

Secondly, to create reflection awareness, the tools shall facilitate:

- the transfer of accumulated knowledge from our research, specifically the insights from ODs' best practice.
- the transfer of knowledge to give reasons for applying reflection and thus enhance motivation and engagement.
- the transfer of knowledge to continuously build expectations.
- calming down to attain a mental and physiological state of certainty by breathing exercises. According to Bandura (1997), a positive physiological arousal is beneficial for enhancing self-efficacy.
- to gain focus.

- to notice cues of uncertainty by breathing exercises and to initiate reflection.
- to trigger reflection by question asking

These described requirements informed the development of three tools: a card deck, a canvas, and breathing exercises.

6.4.2 TOOLKIT OVERVIEW

Three tools are developed in order to make the research insights accessible for design students. Based on the described requirements, we selected three types of tools: a set of cards, a breathing exercise, and a poster template (canvas). The tools aim to create awareness and to guide reflection in design students. We provide a short description of the tools (see Table 15) before we present their development and use in more detail in the following sections.

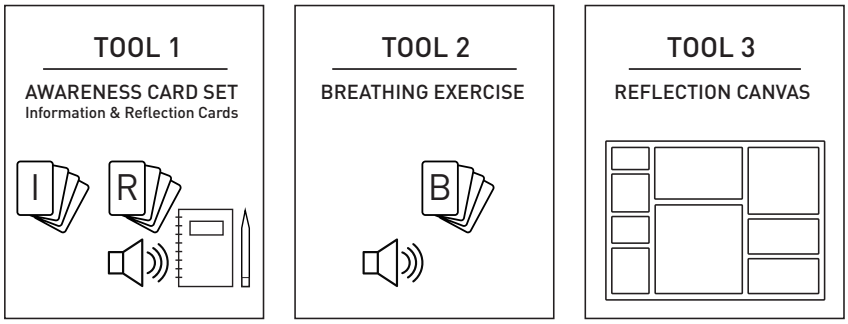


Figure 17. Overview of tools.

Table 15. Overview of Tools.

Design Question 1: *How can we create awareness of reflection among design students in the design process?*	
Tool 1 / Awareness Card Set	The Awareness Card set is a card deck consisting of two sets of cards, 14 Reflection Cards and 14 Information Cards formatted in A6. The cards are used with a Reflection Logbook to facilitate verbalisation.
	- The **Information Cards** provide knowledge regarding the benefits of using sketching and prototyping in the design process. The knowledge is derived from -among other sources – research with ODs. We argue that ODs' 'hints' can relate to the theoretical concept of vicarious experience, which is one of four sources of self-efficacy (Bandura, 1982). We postulate that the ODs are considered as being 'role models' by design students. - The Cards transfer knowledge aiming at enhancing motivation to use sketching and prototyping (for reflection) in the design process.
	- The **Reflection Cards** are related to the methods facilitating a structured approach to reflection activities. The cards provide trigger questions in order to induce stop-and-reflect moments. The provision of questions in learning material can be considered as reflection amplifiers (Verpoorten, 2012). The students are prompted to write the answers to the questions down in the **Reflection Logbook**, a blank notebook for verbatim and visual thoughts. Acting as an add on for the Reflection Cards is a digital sound as impulse to stop and reflect. We posit that the designer has to learn to identify moments for reflection. Therefore, we support the designer with an external impulse to create stop-and-reflect moments. The impulse is linked to the prompt to draw a card and to start reflection, initiated by a random sound impulse steered by an app (www.mindfulnessbell.org).
Tool 2 / Breathing Exercise	- A tool represented on two cards, formatted in DinA6. The tool consists of two elements each written down on a card describing the exercises. - Aim is to induce a positive physical arousal, calming effect, to facilitate awareness, focus and certainty. Positive physical arousal is related to an enhancement of self-efficacy (Bandura et al., 1999)and we postulate a gain of certainty. - The tool was developed based on two existing exercises. Both exercises aim to create awareness to identify cues of uncertainty. The designer is supported by a **sound impulse** (as with the Reflection Cards) from an app and can be seen as a reminder performing the exercise.
	The **exercise '4-7-11'** bases on the **Slow-Paced Breathing** approach (Loew & Pfeifer, 2019).
	The **'Three Breath Micro Practice'** is derived from an online video where the exercise was introduced (Race, 2021).
Second Design question: *How can we support design students' reflection activities in the early stages of the design process through appropriate tools?*	
Tool 3 / Reflection Canvas	- Canvas in A1 format and is intended to be wall mounted. The Canvas is supplemented with several Post-its providing prompts for reflection and answers as well as scales to tick and lists to fill in. - Aim is to provide step by step guidance through the early process phase for design students to come up with ideas related to the initial design task. The prompts on the canvas provide instructions facilitating reflection in a structured way by using sketches and prototypes. The prompts support the switch between visualisation and verbalisation. - The layout of the tool bases on Principles of Gestalt Theory (Arnheim, 1965). The content of the Canvas refers to several Design Methods used to facilitate a structured approach to reflection activities.

6.4.3 AWARENESS CARD SET & BREATHING EXERCISE

Two of the three developed tools – the Awareness Card Set and the Breathing Exercise – aim to create awareness of reflection in design students in order to answer the first design question (how can we create awareness of reflection in design students in the design process?)
The two tools conceptualised and underpinned by our research findings and a selection of concepts among others from social psychology, education, and research in the context of health care. In the following section, we explain these concepts and how we used them to create both tools, the Awareness Cards (Tool 1) and the Breathing Exercise (Tool 2). The goal of the first tool, the Awareness Cards, is to transfer knowledge and know how to create reflection awareness. By transferring knowledge, the tool aims to enhance motivation of the design student to apply reflection related sketching and prototyping. We posit the transferred knowledge and insights feed expectation and create awareness. The second tool is the Breathing Exercise and aims at preparing and calming the design student on a physical level to support focus, awareness and to favor a mental state of clarity and certainty. Thereby, both tools aim creating awareness – and address cognitive and emotional-motivational levels – in design students.

6.4.4 AWARENESS CARD SET

In alignment with the first design question we developed the Awareness Card Set (Tool 1) to address reflection awareness and its three characteristics (Jobst et al., 2020b): knowledge, expectation, and motivation, described in section 6.2. The three characteristics were not addressed one at a time by one tool but there is an overlap, and all three characteristics are addressed by one tool. For example, the Info Cards address knowledge transfer, which aim to enhance motivation to act and reflect. The Reflection Cards not only introduce trigger questions but at the same time provide example questions for to learn which type of question support a deeper level of thinking and reflection.

We postulate that gaining knowledge regarding e.g., the benefits of reflection based on sketching and prototyping for the design outcome increases the motivation for a behaviour change and favour the new habit formation.

Moreover, we assume the insights from ODs' best practice are perceived as convincing reasons to strengthen the motivation for applying reflection based on sketching and prototyping. Additionally, the ODs can be perceived as role models by less successful designers and thus, the motivation to apply reflection activities might be enhanced.

Card-based tool: The general advantages of card-based tools are their tangibility and visualised contents (Yoon et al., 2016, p. 6). Knowledge is inscribed on the cards (Beck et al., 2008). In the design field, a variety of card sets is available, covering a wide range of purposes, such as supporting the creation of creative spaces (Thoring, 2019). The decision to develop a card set was mainly made based on the following considerations:

- tangible and easily accessible (low-cost) solution that enables designers to quickly browse.
- intuitively applicable and accessible (compared with a digital tool) and independent from a technical environment.
- flexible in terms of transport (easy to carry)
- easy to use frequently to memorise information and questions familiar to designers (e.g., the IDEO Method Cards (IDEO, 2003)
- standalone and no need of a further person, team, or instructor
- Cards can be considered being learning material and thus as a reflection amplifier here used with a random impulse (sound by an app) and supported by a Reflection Logbook.

Based on the requirements for the tools and the advantages of Cards, we developed two sets of cards (measuring 105 x 74 mm) with different content and foci.

Awareness Card Set (Information and Reflection Cards)

The Awareness Card Set consists of two parts: The Reflection Cards and the Info Cards. First, the Reflection Cards provide questions triggering reflection. Second, the Info Cards reporting findings from ODs, results from research literature and best practice hints regarding sketching, prototyping, reflection to transfer knowledge and to feed expectation. As described earlier we posit knowledge, expectation enhances the motivation of the design student to apply a structured approach to reflection using sketching and prototyping. We introduce the different aims and content of the card decks more in detail below.

Reflection Cards

The aim of the Reflection Cards (see Figure 18) is to support reflection activities and to facilitate reflection. Further aim of the card set is to give the designer randomly questions to trigger reflection in order to reflect on their sketches and prototypes.

The questions e.g., support the designer to verbally align criteria with sketches and prototypes and in a structured manner. Further goal of the questions is to facilitate establishing a habit of questioning oneself in a structured way. To support the beneficial switch between sketch and prototype to verbalise and vice versa, the answers have to be written down. To write the answers down stresses the verbalisation, which facilitates a rational-analytical style of thinking (Wetzstein & Hacker, 2004;), which is also used in the Reflection Canvas.

The user is invited to work on the prompts and to write the answers down in the 'Reflection Logbook'. We chose the blank Reflection Logbook to offer the user (we address design students) as much freedom as possible when answering. (An exemplary trigger prompt is 'Please describe your design idea in two sentences'). For the tool we incorporated the concept of 'asking questions' in the tool development.

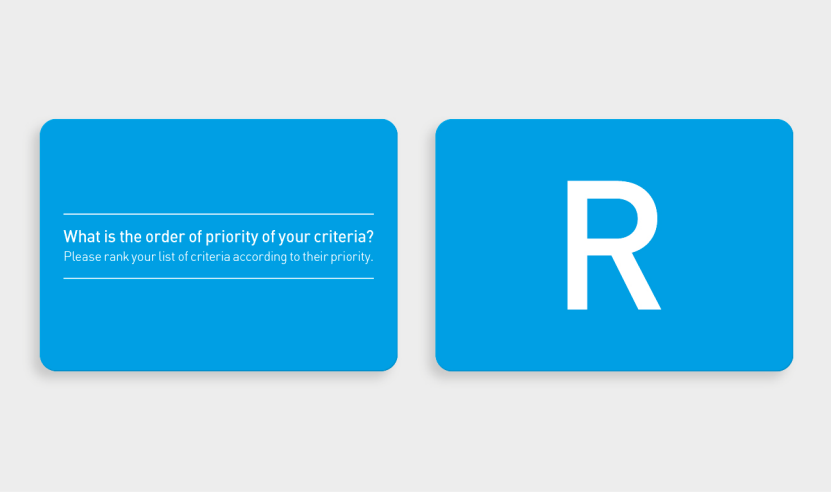


Figure 18. Reflection Cards.

Question-asking: The Reflection Cards build on the benefits of asking question, is also subject to disciplines such as philosophy, cognitive psychology, and linguistics (Graesser & Black, 1985).

In design, the relevance of question-asking for thinking and learning processes has been investigated in design crits (Cardoso et al., 2016; Eris et al., 2007; Graesser & Black, 1985). In design education, design crits involve a feedback situation between students and teacher, for example, regarding an ongoing design process or project. Asking questions is an established design crits technique, especially for supporting breakthrough routines, typical ways of thinking about problems, and facilitating out-of-the-box thinking. Question-asking supports avoiding fixation and confirmation bias. The formulation and type of question can facilitate rational-analytical thinking and can impact the quality of the answer. The questions of the Reflection Card deck were formulated to facilitate a certain style of thinking. The students are prompted to 'enter in a dialog with themselves and to answer the question in writing down the answer to support their reflection process. We postulate that students enter by using question to trigger a form of inner dialogue when writing down the verbatim answer in the Reflection Logbook. We posit this can be considered as a form of verbalisation and can result in a beneficial rational-analytical thinking style (Wetzstein & Hacker, 2004). We assume this process fortifies the effect of switching between visualisation and verbalisation because this supports a rational-analytical thinking style, that is emphasised as being beneficial for problem solving (Wetzstein & Hacker, 2004). Therefore, all the questions are open-ended and can involve prompts to prioritise, fill lists and scales (1–5) to support the reflection activities: analysing, structuring, and selecting.

Journaling and Reflection Logbook. For reinforcing the impact of verbalisation we link the Reflection Cards with a Reflection Logbook building on journaling. Journaling is the frequent routine of writing about experiences and thoughts. We linked one of our tools to journaling because journaling implies asking questions to oneself, here supported by questions of the Reflection Cards.

Journaling is considered a method for enhancing reflection and has received much attention in nursing education (Blake, 2005). According to Pinkstaff (1985), writing thoughts and ideas helps students to be actively involved in their learning process. Here to practice journaling enables the students to deepen the connections of their thoughts with experiences and/or information because they are declared explicitly by the learning person.

Journaling supports making connections between experiences and the classroom and improves critical thinking and problem-solving skills (Blake, 2005).
A further positive effect on journaling is when the students know the journals will not be read or judged by a teacher. Blake (2005) argues the quality of the answers is generally better, more personal, and self-critical if pupils are not forced to share them. However, it seems beneficial to us to offer the students the possibility to share their experience voluntarily as part of the workshop to evaluate the tools.
Here, in this context we used for journaling a Reflection Logbook. To answer the questions from the Reflection Cards the student writes the answers in the Reflection Logbook. With the idea of using a Reflection Logbook we hook on a typical designers' habit: using a Reflection Logbook. Most designers rely on Reflection Logbooks to keep information and knowledge (McAlpine et al., 2006). With the Reflection Card we hook on this habit using Reflection Logbooks and moreover, aim to facilitate with questions to apply a structured approach to reflection and the switch between verbalisation and visualisation. The other part of the Awareness Card set is the Information Card set.

Information Cards

The overall aim of the research is to learn from ODs. The Information Cards (see Figure 19) build on insights from our interviews with ODS (Chapter 4), as well as on research findings and best practice hints regarding sketching, prototyping, and reflection. We postulate that learning from ODs best practice insights increases the motivation for the students to apply those insights. We created a tool to transfer insights and knowledge about reflection, sketching, and prototyping, and how they impact the design process. To mediate the best practice hints and knowledge to increase the motivation to apply it, we refer to theoretical concepts to transfer and communicate the information to our target group: design students.
The purpose of the Information Cards is to inform and motivate design students regarding a higher frequency of using prototyping and sketching to apply reflection in a structured way. There is evidence that knowing why it is beneficial to reflect can enhance the motivation to reflect in order to take on the developing the habit of a structured approach to reflection.

The Information Cards builds on the theoretical concept of vicarious experiences: Seeing similar others perform successfully can raise efficacy expectations in observers who then judge that they too possess the capabilities to master comparable activities (Bandura, 1982, pp. 126–127). Witnessing other people – in this case role models, respectively ODs – successfully complete a task is an important source of self-efficacy. Each of the cards comprehend the information 'Learn from ODs' to reinforce the effect of vicarious experiences being a source of self-efficacy which enhances not only the self-efficacy of the design students but also their motivation. Example: The Cards state relevant insights from the research on prototyping and sketching. For example: 'Use prototyping early and often because it avoids sunk costs (appearing later in the process)'.

To achieve the aim of creating awareness for reflection in less experienced designers we provided cards containing insights about how ODs use sketching, prototyping, and reflection. The insights are supplemented und theoretically underpinned with insights from research literature. The Awareness Cards aim to (a) transfer knowledge, feed expectation to enhance motivation to reflect and (b) provide an environment for verbatim reflection to strengthen the beneficial switch between verbalisation and visualisation.

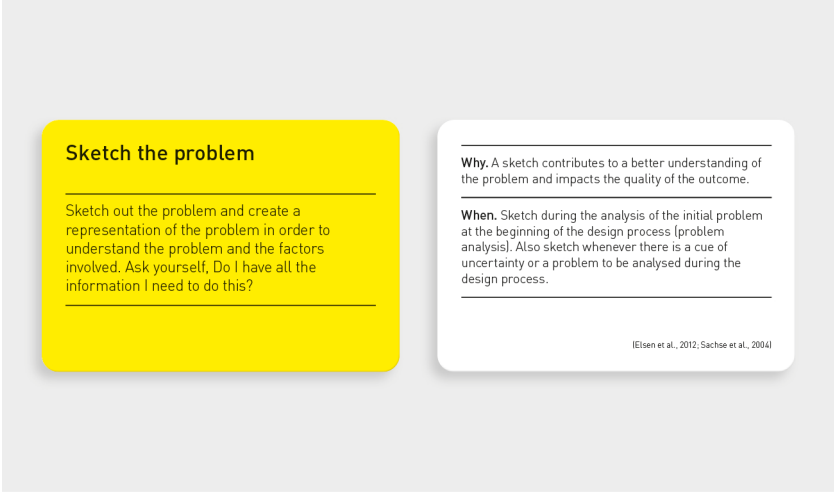


Figure 19. Information Cards.

6.4.5 BREATHING EXERCISE

The second tool of the toolkit provides support for design students on an emotional-motivational level to facilitate cognition and support reflection. The tool is designed to calm breathing and to attain a certain state of mind: awareness. The literature contains little quantitative evidence about mindful breathing exercises as psychological interventions for creating awareness. Nevertheless, there is a long tradition in the history of humans of using such exercises (Loew et al., 2019). There is also evidence for the effect of mindful breathing being part of a combination of treatments, for example, in dialectical behavioural therapy (Linehan, 1993), which is growing.
The Breathing Exercise tool builds on the insight that our breathing is the only function of the autonomic nervous system we can consciously influence. Breathing is the gateway to regulating psychosomatic symptoms consciously, such as fear of failure, uncertainty, or stress. These symptoms can occur in the design process and influence the design outcome (Dörner, 2008). Furthermore, needs such as searching for certainty are relevant for the design process: because of 'Problem-solving is a motivated process and determined by human motivations and needs' (Guess et al., 2015, p. 6). We assume an individual who breathes deeply is neither anxious nor uncertain and is rather aware of cues of uncertainty in their own sketches and prototypes.

The development of the tool is based on two existing exercises. The instructions how to apply the exercises are described on two Cards (74x105 mm), one per exercise. The first exercise builds on the slow-paced breathing approach with the exercise 4-7-11 (Loew & Pfeifer, 2019). The second exercise is based on the Three Breath Micro Practice that combines breathing and question-asking and originates from an online workshop (Race, 2021); both exercises are described below. In addition, we insert a stop moment to remind the designer to reflect and therefore, we provide an auditive and random impulse in order to relate it to both breathing exercises.

Slow-Paced Breathing

The '4-7-11' exercise was introduced to the students as daily practice. One central impact of practicing the exercise is to deepen the breathing that comes with the amount of systematic repetition. To take advantage of the slow-paced breathing method, regular practice is crucial to achieve the desired effect of

slow-paced breathing, such as being supportive against chronic stress and acute anxiety (Loew & Pfeifer, 2019). The original exercise prescribes inhaling for four seconds, exhaling for seven seconds, and repeating it for at least 11 minutes at a time. We adapted the exercise and shortened the exercise down to four minutes for the workshop context. We add an auditive stimulus randomly initiates conscious breathing. To support the development of a habit to practice the breathing exercises we support the designers with a stimulus as reminder.

Arrange the criteria on the matrix in such a way that the criteria that are furthest apart in terms of content are also arranged in this orderWe use as an auditive stimulus the sound of a sound bowl, inserted by an app to remind the participants to practice the breathing exercise in order to support the design student to calm down and concentrate.

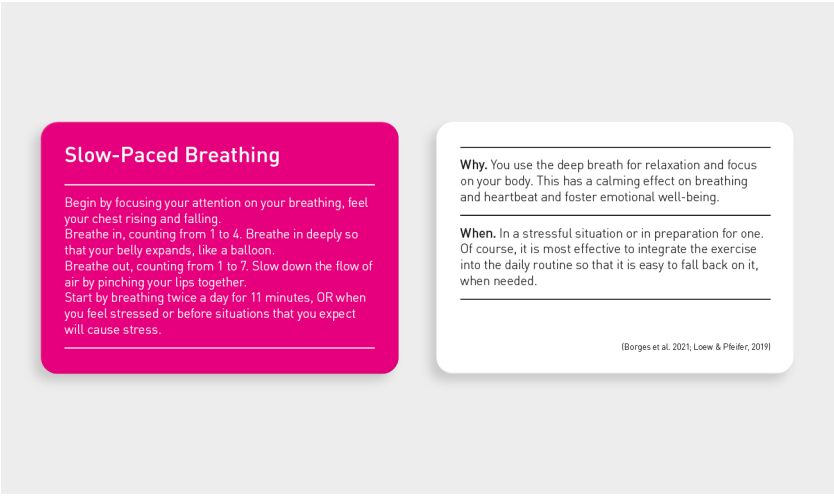


Figure 20. The Breathing Exercises on cards.

Three Micro Breath Practice

The second exercise – the Three Micro Breath Practice – also aims at calming (Race, 2021) and relates to question asking. The exercise was selected and adapted in order to support the designer in choosing how to proceed in the ongoing design process. The designer is asked to breathe deeply three times.

Then to inhale and when exhaling to ask themself one of three prescribed questions one after another on the Card. To question oneself while breathing and in order to be able to answer the designer has to notice one's own body, feelings, and thoughts. We built on the exercise from Race by adapting and modifying the number of breaths and the three questions for our tool. An example question is: 'What do you feel when you look at your prototypes?' *(E.g., which thoughts are popping up when you touch your prototype?* The entire set of questions was printed on the cards (74 x105 mm). The aim of the Breathing Exercise tool is creating awareness for reflection and to lay the foundation for reflection habits.

The first design question – how can we create awareness of reflection in the design process among design students? – was answered by developing two tools to create awareness of reflection. In the next section, the second design question is addressed. To support the design students to become aware of cues of uncertainty the Breathing Exercise aim to:

a) calm down and b) facilitate physical arousal to support certainty and to increase self-efficacy.

6.4.6 THE REFLECTION CANVAS

Building on our research insights that reflection based on sketching and prototyping is not applied in a structured way, we posit a need to support design students early in their education.

Our second design question – how can we support design students' reflection activities in the early stages of the design process through appropriate tool? – contains two sub questions: First, how can we support designers' reflection on the design process through sketching and prototyping? And second, how can we develop a tool that facilitates switching between verbalisation and visualisation to support reflection during the design process. The first sub question addresses relevant activities for reflection, such as analysing, structuring, and selecting. We extracted relevant methods and interventions regarding the three activities for reflection (analysing, structuring, selecting). For the development of the tool, we decided on a certain sequence of steps and methods to be included in the tool. The second sub question, addressing a need to facilitate switching between verbalisation and visualisation is to support reflection during the design process. Consequently, a tool was designed so that designers are supposed to reflect on their visualisation through verbalisation and create visualisations through verbalisations. Humans use both representations (verbatim and visual ones) but the switch is not necessarily integrated but occurs because of individual preferences or by chance. As mentioned before this dialogue-specific style of questioning supports a rational thinking style beneficial for the design outcome. We describe a 'reflection mindset' as containing a dialogue-specific style of questioning and awareness of cues of uncertainty that facilitates problem-solving. We assume these powerful advantages of reflection outweigh possible disadvantages (as e.g., ignoring experienced-based intuition). The benefit of reflecting is not only relevant for the design context but goes beyond the design context (Desautel, 2009; Mann et al., 2009; Whipp, 2003). Consequently, for offering step-by-step guidance for applying reflection activities based on sketches and prototypes we chose as tool a template to fill in, known as the 'Canvas'. A canvas is a wall-mounted poster template and a well-known tool in design, such as the Business Model Canvas (Osterwalder & Pigneur, 2010).

The advantages of a canvas are as follows:

- it structures a complex task into smaller components (Thoring et al., 2019).
- it can facilitate participants to work (alone or together) on a task and guide them through the instructions on the canvas.
- it can support and structured thinking processes (Thoring et al., 2019)
- it makes it possible to write comments directly on the canvas, which supports verbalisation and visualisation of ideas.
- it can support the documentation of a project.

To develop the Reflection Canvas, we followed three consecutive steps. First, we built on insights from our research and design methodology to compose the content of the Reflection Canvas. The aim of the Reflection Canvas is to give the design students guidance for a structured reflection process. Thus, the Canvas provides prompts, instructions, and methods to facilitate – among other goals– a verbatim and written framing of the design problem. The framing supports the derivation of solution criteria and its prioritisation. In line with traditional design process models, such as the Pahl and Beitz's approach (Pahl et al., 2007a), we refer to the idea of subsequent steps in the design process. The main task for designers in the early design process is to understand the problem and to define and frame that problem. From there, the next step – the generation of ideas – is linked to creativity and innovation (Goldschmidt, 1997; Sachse et al., 2004). The ideation phase can be methodologically supported by creativity techniques, for example, brainwriting and brainstorming (Kumar, 2012).
The requirements and objectives for the intended solution were revised into the developed Reflection Canvas to support reflection through sketching and prototyping. The Reflection Canvas supports students as they progress through the reflection process by outlining to follow certain steps and methods. Second, we conceptualised the Reflection Canvas by building on the theoretical assumptions (see Table 16). Third, the selected methods and interventions were structured and organised based on the guidelines from Gestalt theory (Arnheim, 2013). Nine building blocks with short instructions make the Reflection Canvas self-explanatory. Each building block has a headline for quick understanding of the overall aim and, on a second level in smaller font sizes, some instructions for the participants to follow. We linked the addressed activities to the instructions on the Reflection Canvas (see Figure 21).

Table 16. Composition of nine activities during the design process.

	Aim	Three reflection activities:		
		Analysing	Structuring	Selecting
1	Defining: The aim is to define and document the project and the project owners and responsibilities.	-	-	-
2	Developing insights. The aim is to verbalise and write down relevant information, starting with user information, expert knowledge, and switch to question relevant inspiration and stimuli.	x	x	x
3	Framing. The aim is to decide on being aware of the direction for the design process	x		x
4	Building criteria. The aim is to verbalise criteria and prioritise the criteria.	x	x	
5	Collecting ideas. The aim is to verbalise the underlying design idea of one's own sketches/prototypes. Visual and verbal representation may require different levels of maturity and resolution.		x	
6	Structuring information. The aim of structuring into the two-axis matrix is to facilitate the visualisation of dependencies and relations between two criteria.		x	
7	Analysing interrelations and interdependencies of ideas as well as strengths, weaknesses, and potentials for a further concept.	x	x	
8	Voting and deciding. The aim is to decide based on relevant criteria that most fit the problem description and describe the arguments for the decision.			x
9	Forecasting. The aim is to formulate future steps based on reflection.	x	x	

The Reflection Canvas comes with additional Post-its with imprinted prompts and scales on them to facilitate to flexibly work on the Canvas. The use of the Post-its allow a flexible arrangement and structure and can easily added, rearranged and removed. Each Post-it is used representing one idea, derived from a sketch or prototype, etc. The imprinted Post-its can provide e.g., prompts to prioritise ideas on scales (1–5) to support the reflection activities: analysing, structuring, and selecting. In addition, there are Post-its that offer specific methods guided by prompts and questions. We expect several benefits when following and using the Reflection Canvas. Using the Reflection Canvas should (a) increase processual and methodological knowledge on how to apply reflection activities based in sketching and prototyping, (b) lead to positive experiences, and (c) enhance the motivation to apply a structured approach to reflection (d) enhances reflection self-efficacy (e) knowledge analysing, structuring, selecting.

This chapter presented the conceptualisation and design of a toolkit. The toolkit was developed to lay the foundation to form reflection habits already in design education.

REFLECTION-CANVAS

USING SKETCHES & PROTOTYPES TO REDUCE UNCERTAINTY

This is a tool intended for facilitating team-based discussion while analysing, structuring and selecting ideas
2022 by Birgit Jobst

PROJECT NAME

INSIGHTS

What do you know about the problem or task? Are there information from a user or facts from an expert? Are there stimuli or an inspirational moment, material, shape, surface, color you can name?

FRAMING

How would you frame the problem or task?

CRITERIA

List your criteria & prioritise them.

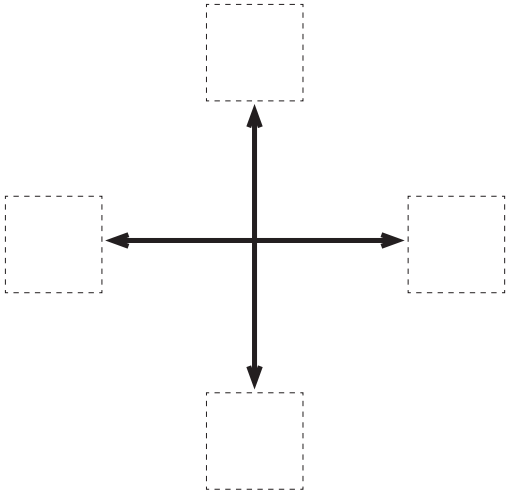
- ○
- ○
- ○
- ○
- ○
- ○
- ○
- ○

COLLECT IDEAS FROM SKETCHES & PROTOTYPES

Using Post-It notes, describe in only a few words what the idea of your sketch/prototype. Please be aware that the sketch and prototype should show the same level of maturity and resolution.

STUCTURE & COMPARE IT

Write each of your four criteria on Post-Its notes and place them in the fields below. Arrange the criteria on the matrix in such a way that the criteria that are furthest apart in terms of content are also arranged in this order Arrange your ideas by similarity and relationship to each other on the XY axis below.



ANALYSE IT

Use the Post-It notes to analyse your idea regarding their strengths, weaknesses, and potential for a concept.

VOTE FOR IT

Use the insights from your reflection and select your three favorite ideas.

1	2	3

Why did you select this one?

FUTURE STEPS

Based on your reflection, formulate future steps.

Figure 21. Reflection Canvas.

6.5 TOOLKIT EVALUATION

For evaluating the intervention of the toolkit, two design workshops in an educational environment were developed. The first workshop was used to intervene and evaluate the Reflection Canvas. The second workshop consisted of Awareness Card Set and Breathing Exercises, which were supposed to create awareness of reflection. Furthermore, we observed the interaction of the students with the tools. The students' interaction with the toolkit was observed to evaluate the usability of the tools and their acceptance by the students. The Reflection Canvas was used as intervention in workshop 1. In workshop 2 the Awareness Cards and the Breathing Exercise are used as an intervention.
The students' interaction with the toolkit was observed to assess the usability of the tools and their acceptance by the students.

6.5.1 WORKSHOP PROCEDURES

The workshops were conceptualised for the tool evaluation and an overview of the workshop procedure is given in Table 17. In the two workshops the design students had to work on a solution for a design task and to present a prototype (explained in detail below).
In the beginning of the workshops, a questionnaire was given to the students to ask for their personal data. The tool(s) were introduced to the students in detail and Breathing Exercises were also practiced together.

Table 17. Overview of Workshop procedure.

	Workshop 1	Workshop 2
Intervention	Reflection Canvas	Awareness Cards Breathing Exercise
Duration	One day of 6 hours	Three days of 6 hours
Participants	Nine design students	Four design students
Design Task	Design of 'instant sitting' stool And presentation of paper prototype	Design of 'protest stool' and presentation of paper prototype
Data Collection	Observation, notes + photos taken. Final feedback session.	Morning feedback sessions Observation, notes + photos taken. Regular feedback sessions in the beginning and the end of each workshop day.

During the workshop the design students received inputs about tools and related topics. For solving the task, the students used the tools and were coached during the design process. The interaction of the design students with tools were observed and documented (notes, photos) by one researcher/workshop leader.

The participants had access to paper prototyping material, such as cupboard, tape, Post-its, cutter, scissors, cutting mat, etc. to work on the tasks and build prototypes. At the end of the workshop the students had to present a prototype and its development process to the audience. In the beginning and in the end of the workshop a feedback session was conducted. For organisation reasons and a short workshop slot, we evaluated the Reflection Canvas in the first workshop.

Sample

For both workshop the samples belonged to the same level of expertise.
According to Dorst and Reymen (2004) the levels of design expertise of the sample for the workshops can be designated as novice designers. The novice designers are described as being at the beginning of their design education.
The sample of the workshop (2) comprised nine design students, the group participating in workshop (1) consisted of four design students. The age of the participants ranged between 20 and 26.
They were all students in the first half of their bachelor's degree. They were studying Integrated Design at Anhalt University of Applied Sciences, Germany. Since we did not explicitly ask the students, we do not know whether they have already had experience with a similar design workshop.

Table 18. Overview of Sample.

	Workshop 1		**Workshop 2**	
Integrated Design Students (BA)	Male	Female	Male	Female
	4	5	2	2
Age	20-24 years		20-25 years	
Years of study	In average studying in the fourth semester.			

Procedure of data collection

The data was collected from different sources to evaluate the toolkit with design students. The observations from the interaction of the design students with the tools were noted on paper as well as photographs were taken to capture the interaction. A questionnaire was handed out to the students in the beginning of the workshop. The questionnaire contained questions about the demographics of the design students and took approximately five minutes to complete.

Feedback and statements. In the end of the workshop a feedback session was held. In contrast to Workshop 1 in Workshop 2 an additional feedback session was held. As the Workshop 2 was held over a longer period than the first workshop we therefore, decided on obtaining additional feedback from the students. For capturing changes in the students' attitudes during the workshop and towards tools used in the workshop.

6.5.2 WORKSHOP 1: INTERVENTION WITH THE REFLECTION CANVAS

The first workshop was conceptualised and conducted to evaluate the Reflection Canvas (T3). At the start of the workshop, the Reflection Canvas was briefly introduced, and its use was described.

Table 19. Overview of activities in workshop 1

Day 1	Questionnaire / Personal data Intro: Knowledge and insights from our research. Sketching, Prototyping. Expertise, Reflection, etc. Intro: design task and persona Intro: Reflection Canvas and how to guide reflection activities (divided into various parts) Presentation of prototypes Feedback session

The design students were placed into teams and two student teams (n= 9 students) received the task to design a stool. The stool had to be designed for short-term sitting and so that you could transport it easily. In addition, the stool had to be developed based on a persona. Therefore, the teams drew lots and were assigned a brief with task and a description of a persona.

The task was to build a paper prototype in the realistic size (1:1 dimension) allowing the testing of the functions, such as sitting and portability.
The two teams started to work on the task using the wall mounted Reflection Canvas. At the end of the workshop, the two teams presented their stool prototypes. The process, the prototypes, the use of tools were discussed, and feedback was exchanged.

6.5.3 WORKSHOP 2: INTERVENTION WITH THE AWARENESS CARD SET AND THE BREATHING EXERCISES

The second workshop aimed at evaluating the Awareness Cards and the Breathing Exercise. The workshop took place over the course of three days, with six hours each day.

Table 20. Overview of activities in workshop 2.

Day 1	Questionnaire / Personal data Intro: Knowledge and insights from our research. Sketching, Prototyping. Expertise, Reflection, etc. Info Cards (DINA3) as reminder mounted on the wall. Intro: design task and persona Intro: Reflection Canvas and how to guide reflection activities (divided into various parts) Intro and practice of the Breathing Exercise Feedback session
Day 2	Morning feedback session Intro: Reflection Cards (+ Reflection Logbook) Feedback session (experience with Reflection Cards)
Day 3	Morning feedback session Presentation of prototypes, Feedback session

The task for the design students was to design and to build a paper prototype of a stool (1:1) to be used at a protest march. For additional constraints a brief with the task and a persona was drawn by lot by each of the two teams.
The Breathing Exercise was explained and practised at the same time. After the first workshop unit, the participants practised the Breathing Exercises, alternating (the first day nine times) around six times a day without external instructions; using only the auditive impulse by the digital bell.

The group of design students was asked to interrupt their activity when the bell rang. Then they had to practice the slow-paced beathing and then to draw a Reflection Card.
The interruption was triggered by a randomly controlled digital sound of a sound bowl that had been recorded and reproduced digitally (www.mindfulnessbell.com). The prompt to use the Reflection Cards and which of the Breathing Exercise shall be practised, was initiated externally from the workshop leader. The frequency of using the card deck regressed on the second and third day to three times a day. No specific moment was identified for this use but was randomly initiated by an auditive impulse of an app, provided by the workshop leader.
Additionally, the Reflection Canvas was introduced and used during the workshop but was not in the focus of the evaluation. The second and third day of the workshop started with a morning feedback session to capture e.g., questions, thoughts, and feedback. The process, the prototypes, the use of tools were discussed, and feedback was exchanged.

6.6 EVALUATION: RESULTS

The first and second workshop were conducted to intervene with the toolkit to learn from the interaction with the tools in terms of usability and acceptance by the participating design students. The insights were gained based on observations of the design students and how they interacted with the tools. The observations, the statements of the participants during the working process as well as from the feedback sessions were written down during the workshop. The insights deduced from the interventions are used to identify potential to iterate the toolkit.
In addition, insights outside the thesis' scope but considered as being relevant were also reported for deriving future steps. In order to be able to allocate the quotes to the participants, we have numbered each participant consecutively. We abbreviate participants with a 'P' and we consecutively numbered the participants from P1 to P9 in the first workshop and for the second workshop the participants are numbered from P10 to P14.

6.6.1 RESULTS OF WORKSHOP 1: REFLECTION CANVAS

The insights from the intervention are related to the usability of the tool and its acceptance by the design students. Based on the insights the potential for iterating the tool was identified.

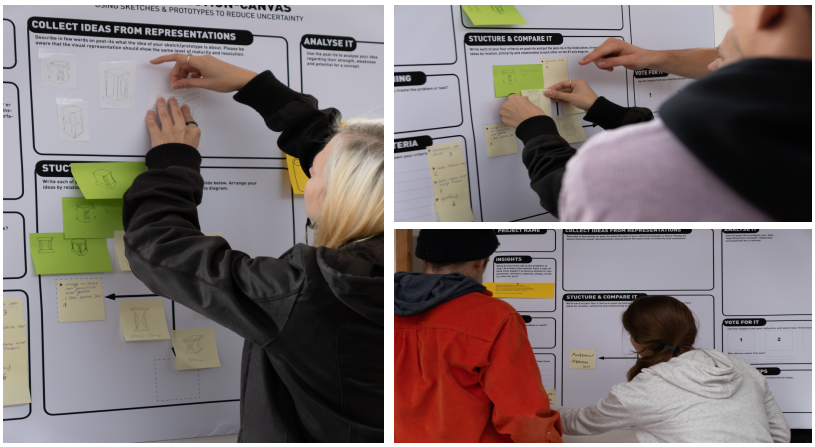


Figure 22. Design students are using the Reflection Canvas.

Insight: Need for methodological know how and practice

The first step when following the step-by-step guidance of the Template –after writing down the team and project name– is the analysis of the problem. The aim of analysing the problem is to generate an understanding of the design task. Here, especially the participants had to work on a task and to understand the need of the given persona for deriving relevant insights. Building on this point, the participants are prompted to follow the step-by-step guidance and then develop a frame to derive criteria before starting to generate ideas.

Despite the guidance, the requested steps were not followed by the participants in a consistent and continuous way. Thus, the design students started to generate ideas and skipped the steps before. The relevant steps for analysing the task and developing a frame were ignored by one team (team 1). The design students started to generate ideas before formulating the insights, the framing, and the criteria, as well as the verbalisation. The workshop leader intervened to remind the participants of team 1 to consider the structured approach and to follow the prompts of the Canvas step by step.

Based on the observations, we could note that both teams had difficulties in following these steps and both teams also struggled with developing a framing. The omission of the steps might have happened when the prompt was not clear to the student or seemed too difficult.

Further step on the Canvas, is to write down on Post-its the underlying/incorporated ideas behind the sketches and prototypes. These Post-its with ideas (abstracted from sketches/prototypes) are the basis for the next step to analyse these ideas. To verbalise the main ideas from sketches and prototypes in one to three sentences and to write these on (A) Post-it seemed to be difficult for the team members and resulted in discussion. The design students seem to have difficulties in narrowing down an idea and verbalising the idea succinctly.

For the step of analysing the ideas they had to verbally formulate the strengths and weaknesses of each idea. Also, the activity of analysing the incorporated idea in a sketch or in prototypes seemed quite difficult for the members of both teams. We observed that the participants of one team jumped between the task and initial ideas, which were sketched or realised as quick prototypes (in paper or collages) for a solution. In this analysis situation, team 2 experienced an information deficit without being conscious of it.

There is a need for (more) awareness of the lack of information in the design students. Nevertheless, one student commented in the feedback session the relevance of a careful analysis of the problem (which is supported by the Reflection Canvas).

> *(...) and 'if you do not analyse the problem carefully, many problems will arise later in the process'*

Insight: Difficulties in verbalisation and abstraction

The design students struggled with deriving verifiable criteria. The criteria were formulated vaguely, using terms such as 'modern', 'sustainable', and 'functional', which made the later design more arbitrary and difficult to verify or to question. The design students seemed to have difficulties in deriving and verbalising verifiable criteria.

Insight: Facilitation for the reflection process,

By making explicit the criteria the decisions of the students were more traceable and transparent. The decision made based on criteria allowed the questioning of these in a rather objective way. It seemed that the instruction on the Reflection Canvas for analysing the pros and cons of an idea resulted in a deeper reflection process of the design students. The design students expressed facilitation using criteria in the reflection process.

Insight: Canvas provides guidance

In addition, based on their statements, the students expressed appreciation for writing down the framing (4/9) and considered the Canvas as providing guidance for ideation.

> (The Canvas) *'supports in creating a frame in order to avoid getting lost in generating ideas'*

The student's acceptance of the Canvas became visible when they worked with the critieria to analyse the ideas. The deduced criteria gave the discussions a structure nevertheless, the discussion was time consuming. Obviously, supported by comments, the design students experienced to work with criteria as supportive for their process. The priorisation of criteria resulted in discussions, which were foremost intuitive and little task-solution focused. It was time intensive. Prioritising the criteria, seemed difficult for the design students.

Insight: Facilitation for a more structured and reflective approach

Thus, from the beginning to the end of the process, the participants displayed an open and few emotional attitudes regarding their favorite idea. Another participant stressed the support of the Canvas for the design process.

> *[the canvas] 'supports the guidance of framing: it 'gives you a directory for the project').*

Insights: Acceptance of Reflection Canvas (by statements)

Based on statements we gained additional insights about the Reflection Canvas. Participants were asked to identify their three most relevant aspects of the Reflection Canvas for reflection.

The Reflection Canvas was considered being supportive for:
Formulating criteria, bringing the criteria into a sequence, and noting them down on the Reflection Canvas. Moreover, all the participants (9/9) from Workshop 1 agreed that the Canvas is beneficial and that they used it for analysing, structuring, and selecting sketches and prototypes.
The participants stressed relevance for developing a framing and the use of criteria. Both being supportive for: limiting the scope of the topic, offering guidance, staying focused, and for working purposefully.

Insight: Support for visualisation and cognitive facilitation

'it's important to visualise, thus insights stay present and are not lost.'

Summing up, according to the insights, the participating design students considered the Reflection Canvas as understandable and (almost) self-explanatory. Initially, the Reflection Canvas seemed time-consuming and hindering for the teams. This attitude changed after using the Reflection Canvas and going through the template. Verbal reflection within the team was triggered in parallel to making further sketches and prototypes. Moreover, the switch from sketching/prototyping to verbalisation seemed to become increasingly accepted and considered as being supportive by the design students.

6.6.2 RESULTS OF WORKSHOP 2: AWARENESS CARDS AND BREATHING EXERCISE

The second workshop was conducted to evaluate the toolkit in terms of usability and acceptance by the workshop participants. The gained insights were used for informing the iterations of the tools and future steps.

6.6.3 RESULTS: AWARENESS CARDS

Reflection Cards and Logbook

Insight: Perceived support by verbalising (internally) and writing into the logbook

After the auditory stimulus has sounded, students draw a Reflection Card. The design students wrote down their answers to the Cards' question in their Reflection Logbook. The workshops participants were concentrated and focused on the task. We assume the students were open to prompts and questions on the Reflection Card. This observation relates to the feedback of the students that this process of writing down and being obliged to verbalise was considered as being helpful for the process. One of the students commented:

'the cards help to formulate ideas and goals'

The participating design students used the Reflection Cards' question to answer that specific question. One student said that the question helped him to narrow a complicated aspect of the design problem.

'the cards ask questions I would not come up with myself'

The Reflection Cards were experienced being beneficial for reflection:

'the cards help to reflect on own one's own actions'

Another student mentioned (in the feedback session) that one question on the Reflection Card 'appeared' too late within the design process and should appear earlier for a better match and did not address the current phase.

Iteration goal: Assigning questions on the Reflection Card with the current design phase the user is in. Changing the back of the cards for distinguishing for which design process phase the question is suitable. Possibility to differ the

design phase of the cards' backside. There was no clear tendency for the acceptance of the Reflection Cards and the Logbook. Two students were unsure if they will use the Cards in the Future and two students mentioned that they would use the Reflection Cards in their design practice. The Cards have to be evaluated after the iteration.

Information Cards

According to their self-assessment, the students were well informed about the research literature and resulting recommendation e.g., for prototyping, as well as, at least partly, about reflection. Thus, many of the insights presented to the students from the (non-iterated Info Poster) were commented as already known. The students commented on the input regarding reflection, sketching, and prototyping benefits as being mostly known.
Nevertheless, the students could not apply their knowledge and act accordingly. In addition, the students did not ask probing questions or state relate the cards to their current practice.

Iteration goal: For increasing the acceptance and usability of the tool the transfer of declarative knowledge into procedural knowledge has to be facilitated. Therefore, not only the declarative knowledge should be addressed but also the procedural knowledge.

Insight: Teamtalk versus information (posters)

The information Posters were wall mounted to provide knowledge about reflection and sketching and prototyping best practice and were visible during the workshops. In short, quiet moments during the workshop the students preferred to talk to each other instead of looking at the posters hanging on the wall. The information on the posters, related to the impact of reflection, using sketching, prototyping for reflection. There are several explications for this behavior. We assume a lack of motivation or two competing options, talk within the team or reading information on the poster.

Iteration goal: Access to information at a time of individual choosing.
The information should be accessible in individually selectable moments. Thus, the students have access to the information and can use these at a time of their choosing, e.g., on the way or during the process when they are stuck.

Students' feedback related to the acceptance of the Info Cards. The Info Cards provide knowledge and based on statements the insights suggest that the students considered the learnings about reflection and sketching to be foremost motivating and about prototyping to be very motivating. The student's opinion differed regarding whether they already applied the recommendations on the Info Cards and whether they would like to use them in the future. Two students (out of 4) stated that they already applied a recommendation and the two other ones mentioned that they would be likely to use them in the future. The acceptance and usability of the tools (specifically the Awareness Cards) shall be enhanced by the iterations.

6.6.4 RESULTS: BREATHING EXERCISE

Each of the two exercises, were practised together and the students were observed to say that they felt rather annoyed that they had to take a break and to interrupt their design process for conducting a Breathing Exercise.

The students criticised the timing of the sound bell, which was around two to three times in one hour. The four students negatively considered the frequency of practicing the breathing exercise as they felt interrupted in their design process. At the end of each workshop day, there was a feedback session as occasion for questions and statements. Based on the feedback, the frequency of impulses was reduced to six times a day corresponding to once an hour.

The Exercise Slow-Paced Breathing 4-7-11

On the second workshop day and after the change of the frequency of practice they were more open to the Breathing Exercise and tried to pay more attention to the exercise. A meta communication of the workshop leader was led with the students about their own attitude to something new, such as a method or exercise.

Insight: The need to open more to new things

One aspect, the need for a better understanding of the impact of the exercise became apparent. In addition, another issue of how the students deal with new situations and how open they are to trying out new things became obvious.
(Once the issue of being open minded to new exercises was discussed, the students, they seemed motivated and more open to continue).

Iteration goal: Integrating 'Breathing' into larger concepts such as relaxation techniques. The tool will be iterated to give design students more information about the benefits of practicing slow-paced breathing. We expect that with more knowledge, students will be more motivated to practice the breathing exercise. In addition, to communicate with participants on a meta-level about the breathing exercise.

Insight: Difficulty establishing a breathing routine

The workshop was held over three days with the students being asked to practice the breathing exercise in their daily lives. Students reported that they had difficulty remembering to practice the Breathing Exercises in everyday life. In the feedback sessions the students discussed ideas about how the slow breathing exercise could be implemented to become part of their daily practice. They also shared experiences they already had with the Breathing exercises in the previous day(s) in the workshop.

Iteration goal: Gaining one's own access to the Breathing exercise. Aim is providing support for establishing an individual breathing routine. The design students shall be supported to develop individual strategies for incorporating daily breathing exercises to achieve behavioural change by building on old habits already in place.

Three Micro Breath Practice

As for the Slow-Paced Breathing exercise, the willingness of the design students to engage in the second breathing exercises was observed as being limited rather low.

Insight: Supporting idea flow

Two students said that they came up with a new idea just after having conducted the Three Micro Breath Practice and stated both were pleased with this experience of capturing a valid idea. A second student reported that after a breathing break an idea popped up. The participants considered the Three Micro Breath exercise as very helpful. The students mentioned the following aspects to be relevant for them about the Breathing Exercise:

'Taking a short break',

The statement might relate to relaxation.

'making subconscious processes visible'

A surprising insight seemed to appear.

'observing my work from a distance'

The term 'observing' could describe a moment before starting analysing, structuring, selecting.

The Three Micro Breath exercise was the most controversial and emotionally discussed tool. An initial defensive attitude was apparent. Luckily, the workshop a three-day time frame allowing a change in the students' attitude. Despite a challenging start with Breathing, those students who felt comfortable with the Breathing could draw benefit out of this exercise. Interestingly, none of the participants explicitly mentioned a positive physical arousal. The iteration hopefully contributes to a higher acceptance and usability of the tool.

Further relevant findings are reported that are outside the scope of the research project.

Based on notes from the feedback session, we gained relevant insights that shall be addressed in future research in design education. The answers to the question of what they would like to become better at regarding the design process were as follows:

Insight: More methodological support

'an extensive view of the correct problem definition'

Insight: Supporting confidence in design students' skills

'to become more confident in relation to my skills'

Insight: Need to enhance prototyping knowledge and skills

'spontaneous prototyping without the fear of misconstructions or an unaesthetic look'

Insight: Supporting motivation and perseverance

'I would like to have more stamina'.

The insights that are outside of research scope state the need of the students for more methodological know how. In addition, in the statements, the need for prototyping skills and knowledge about different types of (early) prototypes is expressed. One student might refer to the need for more feedback from teachers to be clear and conscious about what he has already learned.

6.7 TOOLKIT ITERATION

Based on the interventions with the toolkit potential for iteration was identified. Following the action design research approach, the toolkit was iterated based on insights from the interventions in two design workshops with students and theoretical concepts from the research literature.

Iteration of the Reflection Canvas. The Reflection Canvas was iterated regarding more detailed prompts. This step addressed students who need to gain a better understanding and require more information. Thus, supplementary cards with instructions, explication and links to the research literature were provided to the students in order to use the Reflection Canvas independently from instructors. This would make the Reflection Canvas also applicable for designers with little or no design experience. The knowledge about methods especially regarding methodological topics such as framing. Thus, based on additional information on the cards, the Reflection Canvas becomes more self-explanatory even for people with little or even no methodological know how. So, supplementary methodological input will be added on Cards to enlarge the Info Card deck.

Iteration of the Awareness Card Deck. The aim of the iteration addresses to allow more individually selectable use of the Info Cards. Therefore, we decided to change the format to be used on the fly.
Based on the evaluation and adapted requirements for the tools we changed the size of the Info Cards (former Poster) into the same size (measuring 105 x 74 mm) as the Reflection Cards. Both sets of cards were iterated and form a unity from now on; the Awareness Card Set. The Awareness Card Set can be used wherever the designer feels the need to be supported, to reflect on design work (Reflection Cards), or for to reading (again) insights from research (Information Cards) due to the compact size.

Iteration of Breathing Exercise. To promote breathing and to give the students (more) reasons why they should practice breathing, we provided additional information. Therefore, the Breathing Exercise was embedded into a larger theoretical context becoming relaxation techniques and breathing therapy. This information was added on Cards to enlarge the Info Card deck. In addition, to the knowledge about breathing, we conceptualised a supplementary exercise.

Figure 23. Three sets of cards in one format (A6).

For supporting the students to develop individual ways to establish a daily breathing routine, we referred to the concept of habit stacking (Scott & Green, 2017). The concept of habit stacking uses already existing connections such as daily habits. The students are requested to identify an everyday habit and building the new behaviour on it. It is more likely that the new behaviour – Slow-Paced Breathing or the Three Micro Breath Practice – will become established if the new habit is built into an existing routine.
In total five supplementary Cards were developed providing knowledge from the research literature regarding the impact of breathing, forming breathing habits and a related an exercise facilitating the identification of appropriate existing habits to build. The evaluation of the iterated tools must be conducted in a future workshop.

Furthermore, it is planned to expand the card set with relaxation exercises (that can address the five senses for this purpose). The research literature shows that physical exercise has an impact on a person's mental state (Croos-Müller, 2012; Li et al., 2020).

6.8 DISCUSSION

The insights –regarding the usability and acceptance – drawn from the interaction of the students with the tools are used for the iteration of tools, discussion, and the derivation of future steps.

Based on observation and students' feedback the Reflection Canvas in general was accepted and the provided step-by-step guidance was experienced as supportive by the students. The guiding prompts of the Canvas facilitated the application of reflection activities and the switch between verbalisation and visualisation. The provision of step-by-step guidance is recommended for beginners and would slow down an expert who would rather uses short cuts (Laubheimer, 2020).
For not hindering the design students' progress the Reflection Canvas should only be used for a limited amount of time until the steps are learned. Furthermore, the tool should ideally be used by designers with an appropriate level of expertise from Novice Designers to Advanced Designers. Adding to the Canvas more detailed and additional steps about applying the methods and would make the tool applicable even for non-designers.

The use of the Reflection Cards seemed beneficially, working as reflection amplifier. Reflection amplifiers aim to support students at examining aspects of their learning experience in the moment of learning. One characteristic of the amplifiers is inducing regularly mental tingling e.g., structured, and repeated reflection affordances, interspersed in the learning material and to offer stop-and-think episodes while learning for evaluating 'what is going on' (Salmon & al. 2007) and for nurturing internal feedback (Butler & Winne, 1995). The amplifiers invite learners to think about what they are doing while they are doing it (Verpoorten, 2012).

The aim of the Reflection Cards is to support students to become aware of cues of uncertainty and therefore, to start introducing moments of reflection. In the workshop the student was supported to insert stop-and-reflect moments by an extern impulse. In the future the students are requested to create their own responsibility a state of awareness facilitating the identification of cues of uncertainty.

Moreover, the questions from the Cards and writing the answers into the Reflection Logbook facilitated a rational-analytical thinking style in the design students and was experienced as being supportive.

We argue that this effect might be enhanced, because of students tended to struggle with using and finding the precise word for characteristics or properties of an idea or criterion.

In parallel to further explore the support of a switch between verbalisation and visualisation the students might be sensitised for developing their 'design vocabulary'. Verbalisation and verbatim expression are relevant for students and have to be developed further.
The advantage of learning asking questions facilitating a certain thinking style is beneficial and knowing how to develop these questions also. We assume students might learn or internalise the patterns behind the questions from the Cards and could gain a repertoire of questions. In parallel to the assumed benefit there is a possible disadvantage of the tool that might be hinder the students to fully develop a habit of developing their 'own' questions for reflecting on sketches and prototypes. The Info Cards are reporting – among other knowledge – insights from ODs' best practice. We expected that the ODs are considered as role models by the design students. Therefore, we considered that reported insights from ODs practice would relate to the concept of vicarious experiences and consequently would have an impact on the students' self-efficacy. The vicarious experiences are one source of self-efficacy and motivation. Within the short amount of workshop time using the Info Cards it was not possible to observe a major effect on the students' awareness for reflection. In addition, the student seemed unmotivated to better understand, discuss, or practice the best practice insights from the ODs. First assumption for the student's attitude is that the attitude is due to a deficient association pattern that makes vicarious experiences 'ineffective'. Moreover, the reported ODs' best practice hints might represent limited vicarious experiences and could be different when students would have the opportunity directly observing the ODs.

A second assumption to explain the students' behaviour is that design students generally, do not consider ODs as role models. At the beginning of both workshops, the workshop leader gave an input on ODs best practices in sketching and prototyping to increase motivation to apply them later in the workshop.

We expected the ODs to be role models for the students, but the students did not show much interest and asked few questions about the ODs' best practices, which might indicate that they do not see the ODs as role models. Both assumptions need to be explored in the future, as role models can be relevant source not only of self-efficacy but also of inspiration and motivation (Bandura, 1965).

The students exercised the breathing exercises which is intended to support positive physical arousal. Two students reported sudden ideas to a current problem they were working on after practicing Slow-Paced Breathing. This is an unexpected insight that ideas can flow better after a 'breathing break'. The emergence of ideas just after Slow-Paced Breathing can be explained by the concept of the default mode network (Raichle et al., 2001; Sormaz et al., 2018). According to the concept, while the brain is not engaged in processing cognitive stimuli and while the individual is engaged in internal processes, certain regions of the brain continue to work that can explain the emergence of 'unconsciously developed' ideas.

Therefore, the benefits of introducing breathing into design education already seem promising in the short and also longer term, as there is evidence in health care that breathing influences physical arousal, certainty and relaxation (Loew & Leinberger, 2019; Middendorf, 1985).

Another aspect that was observed is that some of the students showed a defensive attitude towards the Breathing Exercises.
The students' defensive attitude towards breathing was not surprising as the Breathing Exercises were new to them, and they may have found it difficult to practice the exercises in front of the others (even though the group was rather small). It is assumed that this defensive attitude relates to difficulties in getting an individual access to conscious breathing or to a lack of sufficient confidence-building information. More information about the goal of tools could help to dissolve the defensive attitude of the students. This information can be expanded by managing participants' expectations of the learning objectives. A new tool might be perceived as unnecessary if it targets another aspect of being a designer that has not been addressed before. They should be informed that mastering such methods is part of being a designer.

Furthermore, it might be that these students lack certainty to leave their comfort zone out for something new. The conditions and context for 'taking the risk of being open to new things' should then be more considered.
Another possible interpretation is that the students need more knowledge about breathing. Such as providing knowledge of an overarching concept such as relaxation techniques. The impact of breathing for a positive physical arousal that can support a gain of certainty on a physical level, and that can also influence certainty on an emotional-motivational level, leads to engagement and to becoming more open and trustful.
We postulate relevance for the students to find their own individual access for establishing a breathing habit. Therefore, an exercise was added to the tool Card. The exercise relates to the concept of habit stacking. The habit stacking is about using existing connections such as habits. One identifies an everyday habit and builds the new behaviour on it. If the new habit is built into an existing routine, it is more likely that the new behaviour will become established (Scott & Green, 2017).
The support of the tools facilitating awareness for reflection was limited due to a limited workshop time frame. In addition, the use of tools has to be applied with willingness, effort and motivation to acquire successively supplementary knowledge building mental models about e.g., methods, systems, and processes. Overall, creating awareness of reflection requires the experience drawn from many projects, domain-specific knowledge, among other aspects, about technology and material.

The tools were iterated based on the insights from the evaluation by the author, but not by the students themselves. Tools and methods are meant to support the designer; therefore, the methods (application) need to be adapted to the contextual needs of the students by themselves. Therefore, students should also be trained to adapt and refine methods to their needs (Gericke et al., 2020). In the future, design students should be encouraged and trained to iterate tools themselves.

Summing up, based on the insights from the workshops and the research literature, the use of the tools is a promising step towards improving one's own design expertise. Moreover, the development of what is needed for attaining the next higher level of design expertise bases on strong personal commitment.

6.9 CONCLUSIONS AND NEXT STEPS

We acknowledge that the sample size of the participants (nine and four students) was small, and that further research must be conducted with more participants to be able to generalise the findings. Nevertheless, the small number of participants allowed for careful observation by the researcher and to better understand the motivations for interacting with the different tools.

In this chapter we built on findings from two studies with proficient and Outstanding Designers. The main insights from comparing their sketching and prototyping behaviour are that awareness for reflection and a structured approach to reflection support the designers in their process. There is indication that awareness for reflection and a structured reflective sketching and prototyping behaviour increases the design expertise. As the formation of a habit takes time, we postulate a need to provide support in form of tools already early in design education. Therefore, we proposed to create reflection awareness already among design students and posited the first design question:

> *DQ1: How can we create awareness for reflection among design students in the design process?*

In order to answer to this question, we developed the first tool, the Awareness Cards (T1), consisting of Info and Reflection Cards. The Info Cards provide insights from Outstanding designers' best practice (Study 2) as well as recommendations from the research literature. The providing of best practice hints and knowledge aim at enhancing knowledge and expectation of the designers in order to create awareness for reflection. In addition, to the first tool, a second tool, the Breathing Exercise (T2), was developed to support the designer in 'taking a deep breath'. Two exercises were provided to consciously train breathing because it supports a positive physiological arousal that facilitates certainty and enhances self-efficacy.
For consolidating the insight from the PDs, that a structured approach to reflection is not thoroughly applied based on sketches and prototypes we derived the second design question:

> *DQ2: How can we support design students' reflection activities in the early stages of the design process through appropriate tools?*

Consequently, we developed a third tool – the Reflection Canvas (T3). The Reflection Canvas is a wall mounted Poster template that provides step-by-step

guidance through the early process phase and supports a structured approach to reflection. In total an extensive toolkit was developed to make the main insights from two studies accessible for design education.

The tools were used as interventions to be evaluated regarding usability and acceptance with design students during two design workshops.

Based on observation and students' feedback the Reflection Canvas guided the design students through a design process based on a structured reflection approach. Methodological issues of the design students related to –among other methods– the analysis of the task and the framing, were identified and this has to be addressed in future research. Furthermore, the students were observed to have difficulties to abstract their ideas and to concisely verbalise these. There is potential to develop the verbal repertoire of the design students to enhance precision and clarity. This can facilitate careful reflection and impact a higher quality of the outcome.
Through the insights from the interventions with the Breathing Exercise, we can state an emotional and controversial feedback. On the one hand there were students who emphasised that ideas are popping up after the breathing exercise, on the other hand, we can state a defensive attitude towards slowed breathing. We assume this defensive attitude relates to difficulties in getting an individual access to conscious breathing or to a lack of sufficient confidence-building information.
Hence, the benefit of implementing breathing into the design education schedule seem to be promising already on a short and –also– on a longer term. Overall, one aspect that is out of our control lies in the responsibility of the participating design students to care for their own motivation and of a supportive attitude in order to 'be open' to a learning opportunity. This relates to a strong personal commitment that is – regarding Cross and Lawson (2005) – one characteristic of ODs' expertise.

The developed tools to create awareness build on an auditive impulse as stimuli and reminder to stop the current activity for taking a breath and to reflect. Practising awareness for reflection and a structured reflection approach itself, like every habit –especially for a more complex one as reflection– has to be implemented over period up to six months (Lally et al., 2010).

The Awareness Cards (T1) provide actionable advice and insights from ODs practice. Within the short amount of workshop time the Info Cards did not seem to have a major effect on the students' awareness of reflection, based on the observation and students' feedback.

Research on expertise has stressed the relevance of deliberate practice. Ericsson and Lehmann describe deliberate practice as specially designed training by a teacher 'to improve specific aspects of an individual's performance through repetition and successive refinement' (1996, pp. 278–279). The developed toolkit does not build on the trainer but on the students themselves, as we cannot say that design educators all over the world follows a deliberate practice approach in their education program. In many design educational settings, there are units of individual feedback and instruction in so-called 'crits' (Goldschmidt et al., 2010). However, we did not focus on teachers' training but on the design students' personal responsibility. We built on Ericsson and Lehmann (1996), emphasising that individuals have to monitor (and being aware to apply) their training with full concentration, which is effortful and limits the duration of daily training' (Ericsson & Lehmann, 1996, p. 279). The toolkit requires the development of students' openness to reflection and the motivation for improving one's own expertise.

In the 'reflective conversation' Schön (1992) relates reflection with the 'material of a design situation', such as visualisations (Schön, 1992, p. 133). By this Schön ignores to link reflection based on visualisations with verbalisation that we consider being relevant. The switch between visualisation and verbalisation is addressed by the Reflection Canvas and the Reflection Cards.

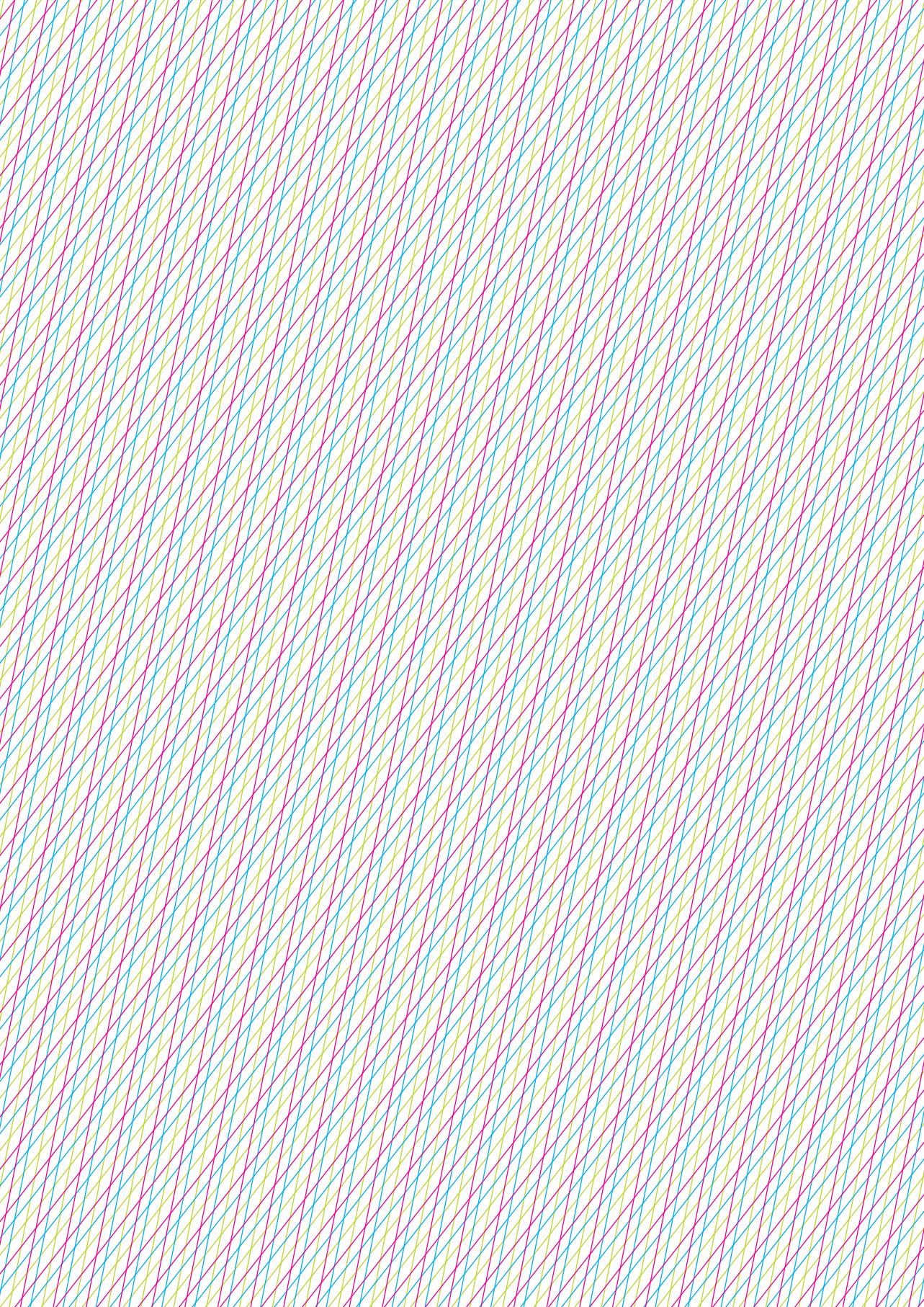
Despite the insights gained in two workshops, we can only argue that the differences in using sketching and prototyping by ODs are the consequence of many years of experience in the design profession. If it is the case, is this different use trainable? Therefore, we must evaluate whether the developed toolkit contributes to train design students in awareness for reflection and in the application of a structured approach to reflection using sketching and prototyping.

For evaluating the iterated tools about its usability and acceptance by the user more research has to be done. Additional research has also to evaluate the two main aims of the toolkit: first, towards creating of awareness for reflection in design students and second, regarding the application of a structured reflection approach. Moreover, we suggest implementing the toolkit, for example,

during a three-month lasting semester at university, to evaluate the iterated tools. More research is needed to find additional approaches or tools to create awareness for reflection in designers and considering therefore, different styles of learning personalities. One of the next research steps can be to contact the sample of the workshops again in the next 12 months. Thus, it can be assessed whether, based on the workshop, an awareness for reflection was created and whether already a fruitful routine to form a new habit has been established.

In addition, two or three five-day long workshops to refresh and deepen the experiences of reflection on a meta-level that can support forming a reflection habit and be a valuable further first step, as well as carefully practising the framing of the task and using verbalisation based on visualisation.
The need for the development of the toolkit is based on the results from two studies. The main insight was that the strength of using sketching and prototyping for reflection was not fully explored and applied by the Proficient Designers. Therefore, the toolkit was developed for creating awareness for reflection and for guiding reflection in a structured way.

As a first step the toolkit was evaluated regarding the understanding and acceptance by the design students. However, the effect of the toolkit regarding creating awareness for reflection and to guide reflection activities was not in the scope of the evaluation in this chapter.
In future research the tools will be evaluated based on different variables aiming to measure if the Awareness Cards and Breathing Exercises will create (or increase) awareness for reflection in design students.
Furthermore, future research will evaluate if and how far the toolkit can support the design students forming the new habit: a structured reflection approach based on sketching and prototyping.
A study will be set up with design students using the toolkit being surveyed in several measurement points during their design education. The aim is to measure if there is a new habit formed and if so, how long such habit formation for a complex activity – as reflection – will take. These insights inform the iteration of the toolkit and the design education curriculum.



7 CONCLUSIONS

The aim of this thesis was to explore the interplay of design expertise and the design activities, sketching, and prototyping. The thesis is structured into two parts: an explorative part and a design part. In the explorative part we conducted two studies and compared the results to present them in chapter 5. Following the three research questions. First, we conducted a survey study to answer the first research question (Chapter 3).

> *RQ 1: How do Proficient Designers (PDs) - who have just finished their bachelor's or master's degree but have already started to collect work experience - use sketching and prototyping in the design process?*

The second research question was to learn about the impact of differences in expertise on sketching and prototyping. Thus, we led an interview study aiming to learn from Outstanding Designers (ODs)' use of sketching and prototyping activities (Chapter 4).

> *RQ 2: How do Outstanding Designers (ODs) use sketching and prototyping in the design process?*

Based on the gained status quo of PDs' and ODs' sketching and prototyping activities we consequently used these results for a comparison. The results from both studies were used compare both groups to identify strengthens and weakness herein. Accordingly, the comparison was guided by the third research question.

> *RQ 3: What are the similarities and differences in the use of sketching and prototyping by Proficient Designers and Outstanding Designers?*

The second part – the design part – was used to design tools to transfer research results into education. According to the main results of the first part of the thesis, we identified different needs of awareness for reflection in the process of sketching and prototyping.
Therefore, we developed two design questions. The first design question addressed the creation of awareness:

> *DQ 1: How can we create awareness for reflection in the design process?*

The second design question aimed at investigating the support by standardised procedures.

> *DQ 2: How can we support reflection activities of design students through appropriate tools?*

The connection between the two parts of the thesis is as follows: the main findings of the comparison between PDs and ODs were visualised in four explanatory models. These models were used in the second part to develop a toolkit that creates awareness for reflection and guides reflection activities.

7.1 SUMMARY OF RESULTS

Although experience seems to be a highly relevant characteristic of the designer; it is still unclear what kind of processes are different compared to less experienced designers. This research aimed to explore about the differences influenced by design expertise regarding sketching and prototyping activities. Research literature shows that there are gaps regarding the impact of design expertise on design behaviour. It is not yet clear, how design expertise evolves over time, and which share design expertise has on cognitive, emotional, and motivational processes.
Thus, questions arise such as: In which way are design activities as sketching and prototyping influenced by design expertise? And are Outstanding Designers always high performers? Can ODs be role models for students to learn from? If we want to better understand the interplay of design expertise, sketching and prototyping activities we must take a closer look at the complex environment of the designer while designing.

Building on Lewin's (1936) behavioural equation, the designer (person) deals with design problems (environment) manifesting design activities (behaviour).

$$b = f(person, environment)$$

Thus, we used different research approaches such as survey, interview, and observation in order to catch the context of the designers.

Explorative Part I

Study 1

The questionnaire of Study 1 entailed closed questions, half open questions, and open questions. A coding system was developed to analyse the answers of the 54 PDs. Based on the results, we argue that PDs are overly reliant on sketching when they generate ideas for the problem at hand. We refer to this behaviour as the PDs' sketching overflow. This cognitive overflow leads to an increase of information but also to an increase of complexity instead of a reduction. Therefore, ideas are not elaborated to avoid a further increase of complexity. Based on the insights an explanatory model was deduced to visualise the relation between PDs' expertise with sketching (see Figure 6). Moreover, the findings suggested that the PDs avoid the step of manifesting their ideas into tangible prototypes. We refer to this behaviour as the PDs' bonding gap with prototyping (Jobst et al., 2020b). These insights led to the deduction of a second explanatory model representing the relation between PDs' expertise with prototyping (see Figure 7).

Study 2

The responses of seven ODs based on interviews were analysed using the same coding system as for the PDs' answers. Regarding sketching the main finding of the analysis is the behaviour of ODs' sketching with purpose. The ODs have a large solution space, with many ideas stored in their head based on many previous situations. In their long-term memory they have access to several solution ideas for one problem. Therefore, the solution process seems to be shorter and especially more goal oriented than the solution process of the PDs. The relation between ODs' expertise with sketching is visualised in a model (see Figure 9). The ODs' prototyping approach is guided by gaining certainty and this leads to a strong emotional attachment. This approach results in implementing best practice prototyping routines. We call this prototyping behaviour the ODs' bonding with prototyping, visualised in a model (see Figure 10).

Comparison

Based on a comparison of the two studies, learning opportunities for (young) designers about sketching and prototyping were identified. As reasons for the different behaviour we identified PDs' and ODs' approaches towards reflection, especially to neglect the need to reduce complexity.

The findings suggest that the ODs are more aware for reflection and follow a more structured reflective approach than the PDs. The ODs are, moreover, fully aware of the relevance of their sketching and prototyping activities. The ODs' activities result in a behaviour that on the one hand we describe as 'purposeful sketching' and as 'bonding with prototyping', on the other. In contrast, a neglected reflective approach using sketching and prototyping tend to result in a behaviour that we call the 'sketching overflow' and the 'bonding gap with prototyping'. Building upon the findings, two models visualise the relation between PDs' and ODs' expertise with sketching (see Figure 13) and the relation of PDs' and ODs' expertise with prototyping (see Figure 14). In Table 21 the differences of sketching and prototyping are listed. The research findings provide the foundation for the development of tools to support reflection. The models facilitate the deduction of
actionable advice and recommendations for design education.

Table 21. Overview of the main results for part 1 of the thesis.

Proficient Designers' sketching	**Outstanding Designers' sketching**
Sketching overflow - sketching during the whole process - Tendency to use sketching for ideation - Positive emotion - Feeling of being creative	Sketching with purpose - sketching as designers' language - awareness for using sketching for reflection - realistic and goal focused - used for reflection Good realistic sketching skills for: - Gain of certainty - Attaining a mental model - Displaying expertise to clients for cooperation
Proficient Designers' prototyping	**Outstanding Designers' prototyping**
Bonding gap with prototyping - External motivation to use prototyping - Used for the team, user, and the client	Bonding with prototyping - Gain of certainty - Positive emotion and bonding - Implementation of prototyping routines - Accelerating the decision making and the design process - Strive for success - For cooperation with the client

Design part II

Development and application of toolkit

Building upon our research insights we proposed the need for reflection awareness and a structured approach to reflection. Reflection awareness is an activity integrating three characteristics: knowledge, expectation, and motivation. The evidence for the development of a toolkit built upon research insights, explanatory models, and related theoretical concepts. The aim of the toolkit is to create awareness of reflection and guide reflection activities to support the development of future designers' habits.

The toolkit comprises three elements: first, an Awareness Card deck to supply best practice examples and to provide questions to trigger reflection.
Second, breathing exercises, to provide calmness and concentration. Finally, the Reflection Canvas provides a step-by-step guidance for applying reflection activities, which are analysing, structuring, and selecting.
We used an iterative action design research approach to develop, evaluate, and iterate the toolkit. The toolkit was designed and introduced in two design workshops to students. Based on the gained insights we iterated the tools towards a better understanding and acceptance. Until now sketching and prototyping education in design does not integrate the specific knowledge of Outstanding Designers.
More research is needed to develop design activities to a higher expertise level in a shorter time. Since it takes time to develop new habits, a structured approach to reflection based on using sketching and prototyping should be implemented as early as possible in the design education process. Therefore, it is necessary to replace long existing habits by the new ones (Lally et al., 2010).

7.2 RELEVANCE AND IMPLICATIONS FOR THEORY, PRACTICE, AND EDUCATION

Good theories are necessary to enable good conclusions. In order to make progress these should be put into practice. These can in turn be observed in education regarding their validity.

7.2.1 THEORETICAL RELEVANCE

Research with designers of very high expertise level is scarce. According to Cross (1990) - one of the researchers using single case studies to investigate ODs – argued that research on ODs are relevant for a better understanding of the nature of designing. This research contributes to the accumulation of knowledge about the interrelations between design expertise, sketching and prototyping. The overall aim of this thesis is to gain knowledge on how to shorten the time span of a decade (Simon & Chase, 1973) of deliberated practice (Ericsson et al., 1993) to become outstanding faster.

The overarching finding of our research was that the ODs behaviour was structured by a reflective approach that can be characterised as a combination of awareness for reflection and reflection activity. This reflective approach encompasses two kinds of behaviour relevant to understand ODs' expertise: Purposeful sketching and bonding with prototyping. The ODs' sketching approach is goal focused and motivated by gaining certainty. Also, their prototyping approach seems directed gathering further information for gaining certainty to master their design process and the outcome. These assumptions are transferred into models which visualise the interplay between design expertise, sketching, and prototyping, and thus can be the basis for further theoretical development. In addition, these results can be a mediator for further development of methodological approaches. And thus, influence educational progress.

7.2.2 PRACTICAL RELEVANCE

This thesis provides different contributions to practice, such as research results regarding sketching and prototyping activities and insights accessible for recommendations. The results of this research allow to derive recommendations which can support the designer in different ways. We developed a toolkit that facilitates the development of individual reflection routines based on sketching and prototyping. The toolkit supports training on the job for designers at the beginning of their career. Despite to learn from PDs was not in the scope of our research, there is practical relevance to build on the insight that ODs neglect the involvement of users. We did not expect to find weaknesses in the ODs' approach to design and knowing that they neglect user involvement requires support. Suggesting improvement for designers with already high expertise and success might not be obvious. Nevertheless, the development of a training format for the ODs would be consequent to enrich the solution space of the ODs and integrate the user's perspective. Therefore, it is plausible to conceptualise a training also for ODs in the future.

7.2.3 EDUCATIONAL RELEVANCE

Cross (1990) claims educational relevance for educators - before they can 'nurture' design students – they need an understanding of the nature of design. Based on a comparison of studies of PDs and ODs we gained insights into the strengths and weaknesses of using sketching and prototyping. Learning from ODs' expertise offer the basis to nurture and inform education.
We built on the gathered knowledge about the nature of ODs' use of sketching and prototyping and focused on the identified use for reflection. Intriguing insights were underpinned with theoretical concepts to consequently develop explanatory models visualising our theoretical assumptions. These models were used as foundation for developing a toolkit for design students.

The toolkit aims at nurturing awareness for reflection using sketching and prototyping. Moreover, the toolkit facilitates to feed and accelerate reflective sketching and prototyping habits. There are three tools developed to support reflection activities. First, the Awareness Cards, consisting of information and reflection cards used to create awareness for reflection.

The Reflection Cards facilitate reflection activities in a structured way and introduce moments of stop-and-reflect. Second, the Breathing Exercises, support concentration and positive physical arousal. The third tool – the Reflection Canvas –guides design students' reflection activities, such as analysing, structuring, and selecting in to mediate a structured reflection approach. The developed and tested toolkit provides support to students to change their sketching and prototyping routines so far. The aim is the formation of new habits, with special attention to reflection based on sketching and prototyping, to become outstanding faster.

The interviews provided several insights into the sketching and prototyping activities and thinking processes of the ODs that go beyond the core topic of reflection. These insights can contribute to a greater curricular focus on mastery of sketching, not on avoiding sketching for embellishment and its own sake, but on sketching purposefully to gain certainty and to successfully share mental models. Furthermore, the research findings can ideally be used to nurture the endeavor to build (early) prototypes among design students. The insights may encourage a didactic focus on systematically teaching a range of prototyping skills to stimulate the creation of a repertoire of prototypes from which students can draw to enhance certainty and the quality of their design outcome.

7.3 LIMITATIONS

For a topic like this, with ODs, is not always easy to gain rigorous and valid data in short time. It was not possible to convince the ODs to participate in a survey study and to answer on quantitative questions. Hence, instead of participating in a survey study the ODs were willing to agree to participate in an interview. This attitude of ODs was also observed by Cross and Lawson (Cross & Lawson, 2005; Lawson & Dorst, 2013) that it is not easy to involve ODs in data collection formats other than in interviews. Therefore, the ODs had to be investigated using a different research approach as the PDs. This problem was addressed by the selection of same issues and topics for the ODs as in the survey study with PDs. Nevertheless, the information obtained from the PDs is based on responses collected through a questionnaire. The answers and related findings might be different if interviews had been conducted instead of questionnaires.

Further research should include digital tools, which were not employed in this research (even being a relevant topic). Since the ODs did not emphasise digital tools, we did not consider them. Furthermore, the developed tools were not evaluated in terms of impact on the designer's reflection, sketching, and prototyping habits.

7.4 FUTURE WORK

This PhD research can be described as a holistic research approach. This includes the collection and analysis of the world as it is (in part I) and the subsequent action design approach based on this (in part II).
In this PhD, we focused on the exploration of the interplay of PDs and ODs expertise, sketching and prototyping. The research results and the theoretical assumptions are based on two samples with a high number of PDs and low number of ODs. Future research has to be done to collect data, to evaluate these for to redefine new research. The data collection shall be supported by observational data and be collected over a longer period to gain access to the complexity of design processes. Especially, we need to better understand ODs' behaviour of bonding with prototyping. Is to bond with prototyping expression of a fixation on prototyping activities? This can lead to an emotional judgement of choosing methods and might prevent the selection of more appropriate approaches.
Additional research has to be conducted to understand why the ODs neglect user involvement during their design processes. Do the ODs neglect user centeredness in general or 'just' the user testing? And does this mean that user testing is only of major interest for less experienced designers?

The research results show a tendency that ODs have good sketching and prototyping skills and that they can draw benefits from both. Research on sketching with less experienced designers suggests that the mechanical quality of sketches impacts outcome; such as ideas are assessed as being more creative (Das & Yang, 2022; B. Kudrowitz et al., 2012). Therefore, future research should investigate if 'good' sketching and prototyping skills are accelerating the designers' development towards a higher expertise level.

We explored the differences between PDs and ODs to foresee the consequences of these differences. This knowledge can be enlarged in further research and the toolkit should be adapted accordingly. Once the differences are known it becomes possible to make forecasting statements about the resulting behaviour. Therefore, to make the insights accessible we synthesised the research findings into four explanatory models which facilitated the derivation of recommendations for education and practice. These models are preliminary and have to be evaluated in the future.

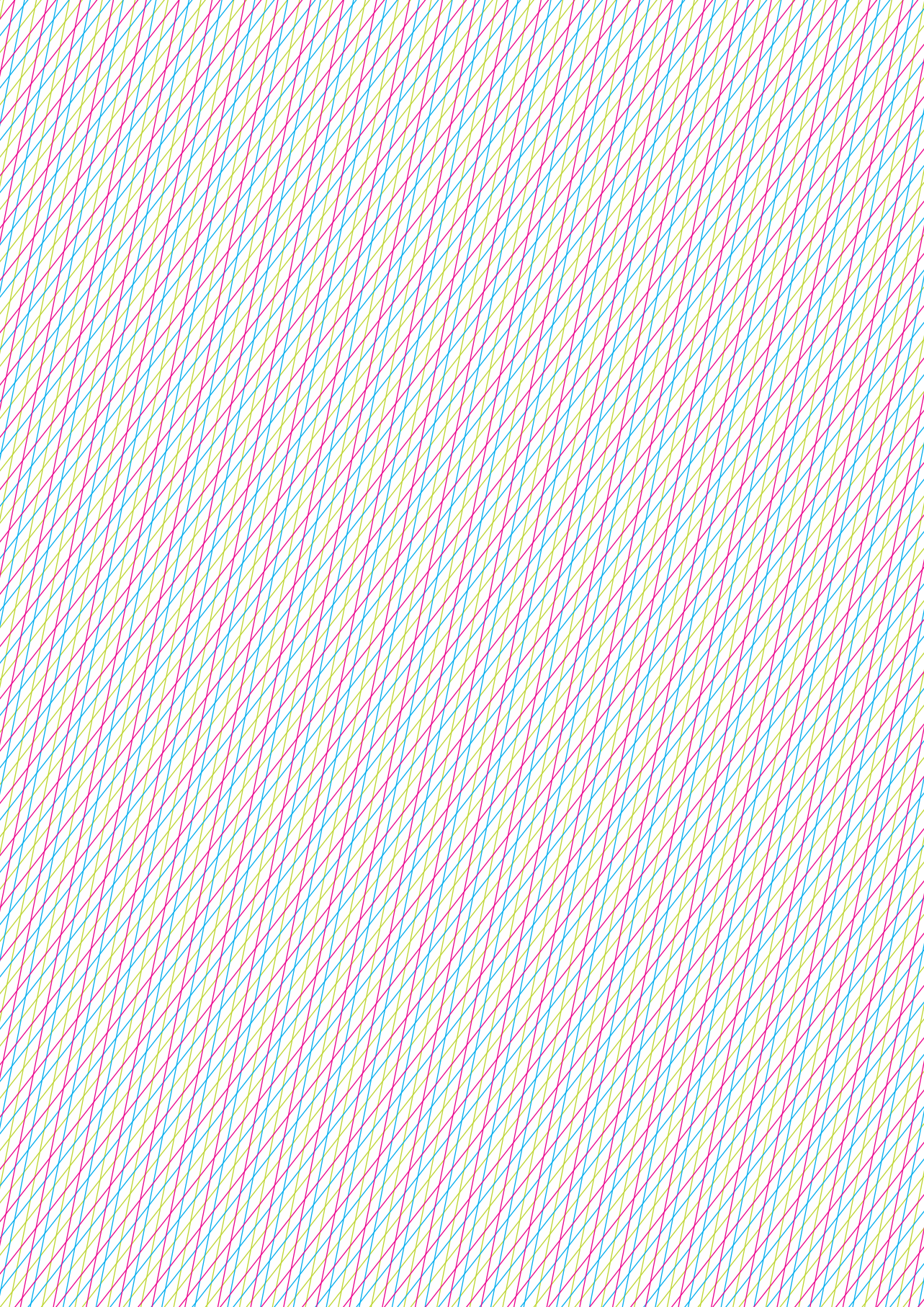
Based on the models the toolkit was developed. The toolkit was evaluated in terms of usability and acceptance and not in terms of actual impact. Further evaluation of the tools has to be conducted to ensure the toolkit impacts design students' reflection awareness and reflection habits. Whether the use of the toolkit can accelerate the step to the next higher level of expertise needs to be further researched - with the help of a longitudinal observational study.
The workshop intervention with the toolkit addressed students in a co-located, studio-like situation. Remote education became increasingly implemented in post-pandemic times. Future work will explore the toolkit for a remote online education. In remote contexts it is relevant that peers can provide feedback to each other (Lotz et al., 2015). Consequently, a further iteration of the toolkit for virtual use has to consider the dimension of social engagement of the students for a successful learning outcome.

In the research results a characteristic behaviour of the ODs was identified: the awareness for reflection leading to initiate structured reflection activities before, during and after sketching and prototyping. We see parallels of awareness for reflection with monitoring as described by Ericsson and Lehmann (1996). They found out that, monitoring oneself - the process of systematically observing - is part of improving own performance and is applied by exceptional performers during their activities (Ericsson & Lehmann, 1996). With this idea in mind that monitoring – and we postulate awareness for reflection - is key driver for improvement towards exceptional performance. The toolkits' Breathing Exercises should be further researched, because of indication to nurture awareness or reflection. We postulate that breathing facilitates the creation of awareness for reflection. Thus, the practice of breathing offers interesting potential for design students.

Further research should investigate whether breathing promotes awareness for reflection – the monitoring-like – approach in young designers to support progress and make them more independent from external feedback. Therefore, to form the habit of awareness addresses not only the key to individual improvement but moreover lays the expertise development into the hands of designers.

7.5 CONCLUDING THOUGHTS

We follow the arguments of distinguished researchers in the field of expertise who have identified characteristics in their work with experts. They conclude these characteristics cannot claim to be a universal characterisation of expert performance and that, 'An expert is someone who is capable of doing the right thing at the right time' (Ericsson et al. 1991, p. 309). We add that in the design context, an OD can use the right sketching and prototyping activities at the right time and in the right way to achieve the intended goal. This approach impacts outcomes, and we assume this also develops a strong emotional attachment to sketching and prototyping.



BIBLIOGRAPHY

Agnew, K. (1993). The spitfire: Legend or history? An argument for a new research culture in design. *Journal of Design History*, *6*(2), 121–130.

Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11. https://doi.org/10.1007/s00163-002-0023-z

Albers, A., & Burkardt, N. (1999). Proficient Designers-A Challenge to Academical Education. *International Conference on Engineering Design, ICED*, *99*, 24–26.

Alias, M., Gray, D. E., & Black, T. R. (2002). Attitudes Towards sketching and drawing and the relationship with spatial visualisation ability in engineering students. *International Education Journal*, *3*(3), 165–175.

Altshuller, G. (1999). *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*. Technical Innovation Center, Inc.

Anderson, J. R., & Jeffries, R. (1985). Novice LISP errors: Undetected losses of information from working memory. *Human–Computer Interaction*, *1*(2), 107–131.

Arnheim, R. (1965). *Art and Visual Perception: A Psychology of the Creative Eye*. University of California Press.

Arnheim, R. (2013). *Kunst und Sehen: Eine Psychologie des schöpferischen Auges*. Walter de Gruyter.

Badke-Schaub, P., & Frankenberger, E. (1999). Analysis of design projects. *Design Studies*, *20*(5), 465–480.

Badke-Schaub, P., Neumann, A., Lauche, K., & Mohammed, S. (2007). Mental models in design teams: A valid approach to performance in design collaboration? *CoDesign*, *3*(1), 5–20. https://doi.org/10.1080/15710880601170768

Badke-Schaub, P., Wallmeier, S., & Dörner, D. (1999). Training for designers: A way to reflect design processes and cope with critical situations in order to increase efficiency. *International Conference on Engineering Design, August*, 24–26.

Bandura, A. (1965). Vicarious processes: A case of no-trial learning. In *Advances in experimental social psychology* (Vol. 2, pp. 1–55). Elsevier.

Bandura, A. (1982). Self-Efficacy Mechanism in Human Agency. *American Psychologist*, *37*(2), 122–147.

Bandura, A. (1989). Regulation of cognitive processes through perceived self-efficacy. *Developmental Psychology*, *25*(5), 729.

Bandura, A. (1993). Perceived self-efficacy in cognitive development and functioning. *Educational Psychologist*, *28*(2), 117–148.

Bandura, A. (1997). *Self-Efficacy: The Exercise of Control* (pp. ix, 604). W H Freeman/Times Books/ Henry Holt & Co.

Bandura, A., Freeman, W. H., & Lightsey, R. (1999). *Self-efficacy: The exercise of control*. Springer.

Bao, Q., Faas, D., & Yang, M. (2018). Interplay of sketching & prototyping in early stage product design. *International Journal of Design Creativity*

and Innovation, *6*(3–4), 146–168.
Bartl, C., & Dörner, D. (1998). PSI: A theory of the integration of cognition, emotion and motivation. *Proceedings of the 2nd European Conference on Cognitive Modelling*, 66–73.
Beck, E., Obrist, M., Bernhaupt, R., & Tscheligi, M. (2008). Instant card technique: How and why to apply in user-centered design. *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008*, 162–165.
Best, K. (2006). *Design Management: Managing Design Strategy, Process and Implementation*. AVA Publishing.
Biggs, J. B., & Tang, C. (2011). *Teaching for Quality Learning at University: What the Student Does* (4th edition). McGraw-Hill Education (UK).
Bilda, Z., & Gero, J. S. (2005). Does sketching off-load visuo-spatial working memory. *Studying Designers*, *5*(2005), 145–160.
Bilda, Z., & Gero, J. S. (2006). Reasoning with internal and external representations: A case study with expert architects. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *28*(28).
Bilda, Z., & Gero, J. S. (2007). The impact of working memory limitations on the design process during conceptualization. *Design Studies*, *28*(4), 343–367. https://doi.org/10.1016/j.destud.2007.02.005
Bilda, Z., Gero, J. S., & Purcell, T. (2006). To sketch or not to sketch? That is the question. *Design Studies*, *27*(5), 587–613.
Birkhofer, H., Kloberdanz, H., Berger, B., & Sauer, T. (2002). Cleaning up design methods-describing methods completely and standardised. *DS 30: Proceedings of DESIGN 2002, the 7th International Design Conference, Dubrovnik*.
Björklund, T. A. (2013). Initial Mental Representations of Design Problems: Differences between Experts and Novices. *Design Studies*, *34*(2), 135–160. https://doi.org/10.1016/j.destud.2012.08.005
Blake, T. K. (2005). Journaling; An Active Learning Technique. *International Journal of Nursing Education Scholarship*, *2*(1). https://doi.org/10.2202/1548-923X.1116
Blessing, L., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer-Verlag.
Bloom, B. S. (1956). Taxonomy of educational objectives. Vol. 1: Cognitive domain. *New York: McKay*, 20–24.
Bobbe, T., Krzywinski, J., & Woelfel, C. (2010). Comparison of CAD and manual sketching tools for teaching architectural design. *Automation in Construction*, *19*(8), 978–987. https://doi.org/10.1016/j.autcon.2010.09.003
Book, W. F. (1925). *Learning to typewrite: With a discussion of the psychology and pedagogy of skill*. Gregg Publishing Company.
Brown, T. (2009). *Change by Design. How Design Thinking Transforms Organizations and Inspires Innovation*. Haper Collins.
Brown, T., & Wyatt, J. (2010). Design thinking for social innovation. *Development Outreach*, *12*(1), 29–43.
Buchenau, M., & Suri, J. F. (2000). Experience prototyping. *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices,*

Methods, and Techniques, 424–433. http://dl.acm.org/citation.cfm?id=347802
Calpin, N., & Menold, J. (2023). The Cognitive Costs of Design Tasks: Examining Cognitive Load Through Verbal and Physical Indicators. *Journal of Mechanical Design*, 1–48. https://doi.org/10.1115/1.4062976
Candy, L., & Edmonds, E. (1996). Creative Design of the Lotus Bicycle: Implications for Knowledge Support Systems Research. *Design Studies*, *17*(1), 71–90. https://doi.org/10.1016/0142-694X(95)00026-N
Cardoso, C., Badke-Schaub, P., & Eris, O. (2016). Inflection moments in design discourse: How questions drive problem framing during idea generation. *Design Studies*, *46*, 59–78. https://doi.org/10.1016/j.destud.2016.07.002
Casakin, H. (2004). Visual Analogy as a Cognitive Strategy in the Design Process. Expert Versus Novice Performance. *Journal of Design Research*, *4*(2), 197–217. https://doi.org/10.1504/JDR.2004.009846
Chen, H.-H., & You, M. (2004). The Comparison Between Novice and Expert Designers' Sketching in Conceptual Design. In J. in Redmond, D. Durling, & A. de Bono (Eds.), *Futureground*.
Chevalier, A., & Chevalier, N. (2009). Influence of proficiency level and constraints on viewpoint switching: A study in web design. *Applied Cognitive Psychology*, *23*(1), 126–137. https://doi.org/10.1002/acp.1448
Crakett, R. (2004). 'He's different, he's got "Star Trek" vision': Supporting the expertise of conceptual design engineers. *Design Studies*, *25*(5), 459–475. https://doi.org/10.1016/j.destud.2004.05.002
Croos-Müller, C. (2012). *Nur Mut! Das kleine Überlebensbuch: Soforthilfe bei Herzklopfen, Angst, Panik & Co.* (14th ed.). Kösel-Verlag.
Cross, N. (1990). The Nature and Nurture of Design Ability. *Design Studies*, *11*(3), 127–140.
Cross, N. (1994). *Engineering Design Methods: Strategies for Product Design*. John Wiley & Sons.
Cross, N. (1998). The Expertise of Exceptional Designers. *Research in Engineering Design*, *10*(Springer-Verlag London Limited), 141–149.
Cross, N. (2001a). Design Cognition: Results from Protocol and other Empirical Studies of Design Activity. In C. M. Eastman, W. M. McCracken, & W. C. Newstetter (Eds.), *Design Knowing and Learning: Cognition in Design Education* (pp. 79–103). Elsevier Science. https://doi.org/10.1016/B978-008043868-9/50005-X
Cross, N. (2001b). Strategic knowledge exercised by outstanding designers. *Strategic Knowledge and Concept Formation*, *III*, 17–30.
Cross, N. (2002a). Creative Cognition in Design: Processes of Exceptional Designers. *Proceedings of the 4th Conference on Creativity & Cognition*, 14–19. https://doi.org/10.1145/581710.581714
Cross, N. (2002b). Creative Cognition in Design: Processes of exceptional ss, N. (2007). Forty years of design research. *Design Studies*, *28*(1), 1–4. https://doi.org/10.1016/j.destud.2006.11.004
Cross, N., & Clayburn Cross, A. (1996). Winning by Design: The Methods of Gordon Murray, Racing Car Designer. *Design Studies*, *17*(1), 91–107. https://doi.org/10.1016/0142-694X(95)00027-O

Cross, N., & Clayburn Cross, A. (1998). Expertise in Engineering Design. *Research in Engineering Design*, *10*(3), 141–149. https://doi.org/10.1007/BF01607156

Cross, N., & Cross Clayburn, A. (1998). Expert designers. *Designers-The Key to Successful Product Development*, 71-84 https://doi.org/10.1007/978-1-4471-1268-6_7

Cross, N., & Dorst, K. (1998). Co-evolution of Problem and Solution Spaces in Creative Design: Observations from an empirical study. *Computational Models of Creative Design IV, JS Gero and ML Maher, Eds., University of Sydney, New South Whales*.

Cross, N., & Lawson, B. (2005). Studying Outstanding Designers. *Gero, J., Bonnardel (Eds.) Studying Designers*, 283–287.

Das, M., & Yang, M. C. (2022). Assessing Early Stage Design Sketches and Reflections on Prototyping. *Journal of Mechanical Design*, *144*(4), 041403. https://doi.org/10.1115/1.4053463

De Groot, A. D. (1946). *Thought and Choice in Chess* (1st ed.). Mouton Publishers.

Deci, E. L., & Ryan, R. M. (1987). The support of autonomy and the control of behavior. *Journal of Personality and Social Psychology*, *53*(6), 1024.

Deininger, M. (2018). *Informing Intentional Use of Prototyping in Engineering Design: Context-Specific Novice Approaches and Stakeholder Feedback* [PhD Thesis].

Deininger, M., Daly, S. R., Lee, J. C., Seifert, C. M., & Sienko, K. H. (2019). Prototyping for context: Exploring stakeholder feedback based on prototype type, stakeholder group and question type. *Research in Engineering Design*, *30*(4), 453–471.

Deininger, M., Daly, S. R., Sienko, K. H., & Lee, J. C. (2017). Novice designers' use of prototypes in engineering design. *Design Studies*, *51*, 25–65. https://doi.org/10.1016/j.destud.2017.04.002

Desautel, D. (2009). Becoming a thinking thinker: Metacognition, self-reflection, and classroom practice. *Teachers College Record*, *111*(8), 1997–2020.

Dewey, J. (1933). How we think (revised edition). *DC Heath, Boston*.

Diamond, A. (2016). Why Improving and Assessing Executive Functions Early in Life is Critical. In *Executive function in preschool-age children: Integrating measurement, neurodevelopment, and translational research* (pp. 11–43). American Psychological Association. https://doi.org/10.1037/14797-002

Do, E. Y.-L. (2005). Design sketches and sketch design tools. *Knowledge-Based Systems*, *18*(8), 383–405.

Dörner, D. (1976). *Problemlösen als Informationsverarbeitung: Vol. Kohlhammer-Standards Psychologie: Teilgebiet Denkpsychologie*. Kohlhammer. https://fis.uni-bamberg.de/handle/uniba/32344

Dörner, D. (1996). *The Logic of failure: Why Things Go Wrong and What We Can Do To Make Them Right*. Metropolitan Books, Henry Holt and Co.

Dörner, D. (2002). *Die Mechanik des Seelenwagens: Eine neuronale Theorie der Handlungsregulation*. Huber. https://fis.uni-bamberg.de/handle/uniba/11279

Dörner, D. (2008). *Bauplan für eine Seele*. Rowohlt-Taschenbuch-Verl. https://fis.uni-bamberg.de/handle/uniba/16827
Dörner, D. (2011). *Die Logik des Misslingens: Strategisches Denken in komplexen Situationen*. Rowohlt Verlag GmbH.
Dörner, D., Bick, T., Brüderl, L., Lüttner, A., Klee, U., & Reh, H. (1994). *Lohausen: Vom Umgang mit Unbestimmtheit und Komplexität* (2., unveränd. Nachdr.). Hogrefe AG.
Dörner, D., & Funke, J. (2017). Complex problem solving: What it is and what it is not. *Frontiers in Psychology*, *8*, 1153.
Dorst, K. (2019). Design beyond Design. *She Ji: The Journal of Design, Economics, and Innovation*, *5*(2), 117–127. https://doi.org/10.1016/j.sheji.2019.05.001
Dorst, K., Christianns, H., & Cross, N. (1996). *Analyzing design activity*. Wiley West Sussex.
Dorst, K., & Reymen, I. (2004). Levels of Expertise in Design Education. *Proceedings of the 2nd International Engineering and Product Design Education Conference, 2-3 September 2004, Delft*, 159–166. https://research.utwente.nl/en/publications/levels-of-expertise-in-design-education
Dow, S. P., Glassco, A., Kass, J., Schwarz, M., & Klemmer, S. R. (2009). The effect of parallel prototyping on design performance, learning, and self-efficacy. *Stanford Technical Report*, *10*.
Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., & Klemmer, S. R. (2011). Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. *ACM Transactions on Computer-Human Interaction*, *17*(4), 18:1-18:24. https://doi.org/10.1145/1879831.1879836
Dreyfus, H. L. (2002). Intelligence without Representation – Merleau-Ponty's Critique of Mental Representation The Relevance of Phenomenology to Scientific Explanation. *Phenomenology and the Cognitive Sciences*, *1*(4), 367–383. https://doi.org/10.1023/A:1021351606209
Dreyfus, S. E. (2004). The Five-Stage Model of Adult Skill Acquisition. *Bulletin of Science, Technology & Society*, *24*(3), 177–181. https://doi.org/10.1177/0270467604264992
Dreyfus, S. E., & Dreyfus, H. L. (1980). *A five-stage model of the mental activities involved in directed skill acquisition*. California Univ Berkeley Operations Research Center.
Ehrlenspiel, K. (1995). *Integrierte Produktentwicklung: Methoden für Prozessorganisation, Produktentwicklung und Konstruktion*. Hanser.
Ehrlenspiel, K., & Dylla, N. (1993). Experimental investigation of designers' thinking methods and design procedures. *Journal of Engineering Design*, *4*(3), 201–212.
Ehrlenspiel, K., Kiewert, A., Lindemann, U., & Mörtl, M. (1998). Kostengünstig entwickeln und konstruieren. *Kostenmanagement Bei Der Integrierten Produktentwicklung*, *3*.
Ehrlenspiel, K., & Produktentwicklung, I. (2007). Denkabläufe, Methodeneinsatz. *Zusammenarbeit, Hanser Fachbuchverlag*, *4*.
Ericsson, K. A. (2008). Deliberate practice and acquisition of expert

performance: A general overview. *Academic Emergency Medicine*, *15*(11), 988–994.
Ericsson, K. A. (2004). Deliberate Practice and the Acquisition and Maintenance of Expert Performance in Medicine and Related Domains. *Academic Medicine*, *79*(10), S70–S81.
Ericsson, K. A. (2014). *The road to excellence: The acquisition of expert performance in the arts and sciences, sports, and games*. Psychology Press.
Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychological Review*, *100*(3), 363–406.
Ericsson, K. A., & Lehmann, A. C. (1996). Expert and Exceptional Performance: Evidence of Maximal Adaptation to Task Constraints. *Annual Review of Psychology*, *47*(1), 273–305. https://doi.org/10.1146/annurev.psych.47.1.273
Ericsson, K. A., & Lehmann, A. C. (2003, November 28). *Expert and exceptional Performance: Evidence of Maximal Adaptation to Task Constraints* [Review-article]. Http://Dx.Doi.Org/10.1146/Annurev.Psych.47.1.273. https://doi.org/10.1146/annurev.psych.47.1.273
Ericsson, K. A., & Smith, J. (1991). *Toward a General Theory of Expertise: Prospects and Limits*. Cambridge University Press.
Ericsson, K. A., & Williams, A. M. (2007). Capturing Naturally Occurring Superior Performance in the Laboratory: Translational Research on Expert Performance. *Journal of Experimental Psychology: Applied*, *13*(3), 115.
Eris, Ö., Sheppard, S., & Kwan, A. (2007). Learning to Question: A Longitudional Analysis of Question Asking Behaviour and Engagement in Project-Based Learning. *DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28.-31.07. 2007*, 303–304.
Evans, M. A. (1992). *Model or prototype which, when and why?*
Ferguson, E. S. (1994). *Engineering and the Mind's Eye*. MIT press.
Fleck, R., & Fitzpatrick, G. (2010). Reflecting on reflection: Framing a design landscape. *Proceedings of the 22nd Conference of the Computer-Human Interaction - OZCHI '10*, 216. https://doi.org/10.1145/1952222.1952269
Frayling, C. (1993). Research in Art and Design. *Royal College of Art Research Papers*, *1*(1), 1–9.
Funke, J. (2010). Complex problem solving: A case for complex cognition? *Cognitive Processing*, *11*(2), 133–142. https://doi.org/10.1007/s10339-009-0345-0
Geis, C., & Birkhofer, H. (2009). Checklists as Tools for Reflective Practice for Designers. *DS 58-9: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 9, Human Behavior in Design, Palo Alto, CA, USA, 24.-27.08.2009*, 159–168.
Gerber, E. (2009). Prototyping: Facing uncertainty through small wins. *DS 58-9: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 9, Human Behavior in Design, Palo Alto, CA, USA, 24.-27.08. 2009*, 333–342.

Gerber, E., & Carroll, M. (2012). The Psychological Experience of Prototyping. *Design Studies*, *33*(1), 64–84. https://doi.org/10.1016/j.destud.2011.06.005
Gericke, K., Eckert, C., Campean, F., Clarkson, P. J., Flening, E., Isaksson, O., Kipouros, T., Kokkolaras, M., Köhler, C., & Panarotto, M. (2020). Supporting designers: Moving from method menagerie to method ecosystem. *Design Science*, *6*, e21.
Goel, V. (1995). *Sketches of thought*. MIt Press.
Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal*, *4*(2), 123–143.
Goldschmidt, G. (1992). Serial sketching: Visual problem solving in designing. *Cybernetics and System*, *23*(2), 191–219.
Goldschmidt, G. (1997). Capturing indeterminism: Representation in the design problem space. *Design Studies*, *18*(4), 441–455.
Goldschmidt, G. (2002). The backtalk of self-generated sketches. *Design Issues*, *19*(1), 72–88.
Goldschmidt, G. (2014). Modeling the Role of Sketching in Design Idea Generation. In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations* (pp. 433–450). Springer. https://doi.org/10.1007/978-1-4471-6338-1_21
Goldschmidt, G. (2017). Manual Sketching: Why Is It Still Relevant? In S. Ammon & R. Capdevila-Werning (Eds.), *The Active Image: Architecture and Engineering in the Age of Modeling* (pp. 77–97). Springer International Publishing.
Goldschmidt, G., Hochman, H., & Dafni, I. (2010). The Design Studio "Crit": Teacher–Student Communication. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *24*(3), 285–302. https://doi.org/10.1017/S089006041000020X
Gonçalves, M. G. (2016). *Decoding Designers' Inspiration Process*.
Görg, C., Pohl, M., Qeli, E., & Xu, K. (2007). Visual Representations. In A. Kerren, A. Ebert, & J. Meyer (Eds.), *Human-Centered Visualization Environments* (Vol. 4417, pp. 163–230). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-71949-6_4
Graesser, A. C., & Black, J. B. (1985). *The Psychology of Questions*. Lawrence Erlbaum Associates Inc.
Guess, C. D., Donovan, S. J., & Naslund, D. (2015). *Improving dynamic decision making through training and self-reflection*.
Häggman, A., Tsai, G., Elsen, C., Honda, T., & Yang, M. C. (2015). Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design. *Journal of Mechanical Design*, *137*(7). https://doi.org/10.1115/1.4030181
Hammond, T., Kumar, S. P. A., Runyon, M., Cherian, J., Williford, B., Keshavabhotla, S., Stephanie, V., Wayne, L., & Julie, L. (2018). It's Not Just About Accuracy: Metrics That Matter When Modeling Expert Sketching Ability. *ACM Transactions on Interactive Intelligent Systems (TiiS)*, *8*(3), 1–47.
Heckhausen, H. (1977). Achievement Motivation and its Constructs: A

Cognitive Model. *Motivation and Emotion*, *1*(4), 283–329. https://doi.org/10.1007/BF00992538

Heckhausen, J., & Heckhausen, H. (2010). Motivation und Handeln: Einführung und Überblick. In J. Heckhausen & H. Heckhausen (Eds.), *Motivation und Handeln* (pp. 1–9). Springer. https://doi.org/10.1007/978-3-642-12693-2_1

Hilton, E., Williford, B., Li, W., McTigue, E., Hammond, T., & Linsey, J. (2016). Consistently Evaluating Sketching Ability in Engineering Curriculum. *DS 86: Proceedings of The Fourth International Conference on Design Creativity, Georgia Institute of Technology, Atlanta, GA, USA*.

Holmquist, L. E. (2005). Prototyping: Generating ideas or cargo cult designs? *Interactions*, *12*(2), 48–54.

Houde, S., & Hill, C. (1997). What do Prototypes Prototype? In *Handbook of Human-Computer Interaction* (2., pp. 367–380). Elsevier.

IDEO. (2003). *IDEO Method Cards: 51 Ways to Inspire Design*. William Stout Architectural Books.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Jobst, B. (2020, August 6). *The Bonding Gap Between Proficient Designers and Their Prototypes* [Conference Presentation]. 23rd DMI: Academic Design Management Conference, Toronto, Canada.

Jobst, B., Thoring, K., & Badke-Schaub, P. (2020a). Introducing a Tool to Support Reflection through Sketching and Prototyping during the Design Process. *Proceedings of the Design Society: Design Conference*, *1*, 207–214.

Kahn, W. A., & Fellows, S. (2013). *Employee engagement and meaningful work.*

Kahneman, D., & Tversky, A. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology*, *3*(3), 430–454. https://doi.org/10.1016/0010-0285(72)90016-3

Kahneman, D., & Tversky, A. (2013). Prospect theory: An analysis of decision under risk. In *Handbook of the fundamentals of financial decision making: Part I* (pp. 99–127). World Scientific.

Kannengiesser, U., & Gero, J. S. (2017). Can Pahl and Beitz' systematic approach be a predictive model of designing? *Design Science*, *3*. https://doi.org/10.1017/dsj.2017.24

Kelley, T., & Littman, J. (2001). *The Art of Innovation: Lessons in Creativity from IDEO, America's leading design firm*. Crown Publishing.

Kemmis, S., McTaggart, R., & Nixon, R. (2013). *The action research planner: Doing critical participatory action research*. Springer Science & Business Media.

Klauer, K. C. (1993). *Belastung und Entlastung beim Problemlösen: Eine Theorie des deklarativen Vereinfachens*. Verlag für Psychologie, Hogrefe.

Kolb, D. A. (1983). *Experiential Learning: Experience as the Source of Learning and Development* (00002 ed.). Prentice Hall.

Krathwohl, D. R. (2002). A Revision of Bloom's Taxonomy: An Overview. *Theory Into Practice*, *41*(4), 212–218. JSTOR.

Kudrowitz, B. M., & Wallace, D. (2013). Assessing the quality of ideas from prolific, early-stage product ideation. *Journal of Engineering Design*, *24*(2), 120–139.
Kudrowitz, B., Te, P., & Wallace, D. (2012). The Influence of Sketch Quality on Perception of Product-Idea Creativity. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *26*(3), 267–279.
Kujala, S. (2003). User involvement: A review of the benefits and challenges. *Behaviour & Information Technology*, *22*(1), 1–16. https://doi.org/10.1080/01449290301782
Kumar, R. (2014). *Research Methodology* (4th Edition). Sage Publications Ltd.
Kumar, V. (2012). *101 Design Methods: A Structured Approach for Driving Innovation in Your Organization* (1.). Wiley.
Lally, P., van Jaarsveld, C. H. M., Potts, H. W. W., & Wardle, J. (2010). How are habits formed: Modelling habit formation in the real world. *European Journal of Social Psychology*, *40*(6), 998–1009. https://doi.org/10.1002/ejsp.674
Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, *11*(1), 65–100.
Laubheimer, P. (2020, November 22). *Flexibility and Efficiency of Use: The 7th Usability Heuristic Explained*. Nielsen Norman Group. https://www.nngroup.com/articles/flexibility-efficiency-heuristic/
Lawson, B. (1980). *How Designers Think: The Design Process Demystified*. Elsevier Architectural Press.
Lawson, B. (1994). *Design in Mind*. Architectural Press.
Lawson, B., & Dorst, K. (2005). Acquiring Design Expertise. *Computational and Cognitive Models of Creative Design VI. Key Centre of Design Computing and Cognition, University of Sydney, Sydney*, 213–229.
Lawson, B., & Dorst, K. (2013). *Design expertise*. Routledge.
Leinert, S., Römer, A., & Sachse, P. (1999). *Externe Unterstützung der Problemanalyse bei entwerfenden Tätigkeiten*.*18* (Zeitschrift für Sprache & Kognition), 30–38.
Lewin, K. (1936). *Principles Of Topological Psychology*. McGraw-Hill Book Company, Inc.
Lewin, K. (1946). Action Research and Minority Problems. *Journal of Social Issues*. Wiley Online Library.
Li, M., Yao, X., Aschenbrenner, D., van Eijk, D., & Vink, P. (2022). Ergonomics 4.0: Human-Centered Procedure for Ergonomic Design Using Virtual Reality Prototyping. *INCOSE International Symposium*, *32*, 195–211.
Li, Z., Liu, S., Wang, L., & Smith, L. (2020). Mind–body exercise for anxiety and depression in copd patients: A systematic review and meta-analysis. *International Journal of Environmental Research and Public Health*, *17*(1), 22.
Lim, C. S., & Mohamed, M. Z. (1999). Criteria of project success: An exploratory re-examination. *International Journal of Project Management*, *17*(4), 243–248.
Lim, Y.-K., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction*, *15*(2), 1–27.

https://doi.org/10.1145/1375761.1375762
Lipson, H., & Shpitalni, M. (2000). Conceptual design and analysis by sketching. *AI EDAM*, *14*(5), 391–401. https://doi.org/10.1017/S0890060400145044
Loew, T. H., Hamdy, A., & Pommer, P. (2019). Slow paced breathing (SPB) in asthma patients-A controlled randomized study using a tactile rhythm device. *Journal of Psychosomatic Research*, *121*, 141.
Loew, T. H., & Leinberger, B. (2019). Entschleunigtes Atmen – Zentrales psychosomatisches Angebot in der Ordnungstherapie. *Erfahrungsheilkunde*, *68*(02), 67–72.
Loew, T. H., & Pfeifer, M. (2019). *Langsamer atmen, besser leben: Eine Anleitung zur Stressbewältigung*. Psychosozial-Verlag.
Lotz, N., Jones, D., & Holden, G. (2015). Social engagement in online design pedagogies. *Proceedings of the 3rd International Conference for Design Education Researchers*, 1645–1668.
Lozoff, B., Brittenham, G. M., Trause, M. A., Kennell, J. H., & Klaus, M. H. (1977). The mother-newborn relationship: Limitsof adaptability. *The Journal of Pediatrics*, *91*(1), 1–12.
Mann, K., Gordon, J., & MacLeod, A. (2009). Reflection and reflective practice in health professions education: A systematic review. *Advances in Health Sciences Education*, *14*(4), 595–621. https://doi.org/10.1007/s10459-007-9090-2
Maslow, A. H. (1943). A Theory of Human Motivation. *Psychological Review*, *50*(4), 370.
McAlpine, H., Hicks, B. J., Huet, G., & Culley, S. J. (2006). An investigation into the use and content of the engineer's logbook. *Design Studies*, *27*(4), 481–504. https://doi.org/10.1016/j.destud.2005.12.001
Menezes, A., & Lawson, B. (2006). How designers perceive sketches. *Design Studies*, *27*(5), 571–585.
Middendorf, I. (1985). *Der erfahrbare Atem: Eine Atemlehre* (Vol. 2). Junfermann Verlag GmbH.
Moon, J. A. (2004). *A Handbook of Reflective and Experiential Learning: Theory and Practice* (Illustrated Edition). Routledge.
Moon, J. A. (2013). Reflection in learning and professional development: Theory and practice. *New Technology in the Human Services*, *13*(1 & 2).
Morgan, W. P., & Pollock, M. L. (1977). Psychologic Characterization of the Elite Distance Runner. *Annals of the New York Academy of Sciences*, *301*(1), 382–403. https://doi.org/10.1111/j.1749-6632.1977.tb38215.x
Nelson, J., & Menold, J. (2020). Opening the black box: Developing metrics to assess the cognitive processes of prototyping. *Design Studies*, *70*, 100964. https://doi.org/10.1016/j.destud.2020.100964
OECD. (2022, July 9). *OECD Future of Education and Skills 2030* [Oecd.org/education/2030-project]. OECD Future of Education and Skills 2030. https://www.oecd.org/education/2030-project/
Oosthuizen, M. J. (2002). Action research. In K. Williamson (Ed.), *Research methods for students, academics and professionals: Information management and systems* (2nd ed., pp. 75–159).
Osborn, A. F. (1953). *Applied Imagination: Principles and Procedures of*

Creative Problem-Solving. Charles Scribner's Sons.
Osland, J., Kolb, D. A., Rubin, I. M., & Turner, M. E. (2001). *Organizational Behavior: An Experiential Approach*. Prentice Hall Upper Saddle River, NJ.
Osterwalder, A., & Pigneur, Y. (2010). *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*. John Wiley & Sons.
Pahl, G., & Beitz, W. (2013). *Engineering Design: A Systematic Approach*. Springer-Verlag.
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007a). *Engineering Design: A Systematic Approach* (Third Edition). Springer London.
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007b). *Pahl/Beitz Konstruktionslehre: Grundlagen erfolgreicher Produktentwicklung. Methoden und Anwendung* (7. Edition). Springer.
Parfitt, M. K., & Sanvido, V. E. (1993). Checklist of critical success factors for building projects. *Journal of Management in Engineering*, *9*(3), 243–249.
Pei, E., Campbell, I., & Evans, M. (2011). A taxonomic classification of visual design representations used by industrial designers and engineering designers. *The Design Journal*, *14*(1), 64–91. https://doi.org/10.2752/175630610X12877385838803
Peng, C. (1994). Exploring communication in collaborative design: Co-operative architectural modelling. *Design Studies*, *15*(1), 19–44. https://doi.org/10.1016/0142-694X(94)90037-X
Petre, M. (2004). How expert engineering teams use disciplines of innovation. *Design Studies*, *25*(5), 477–493. https://doi.org/10.1016/j.destud.2004.05.003
Pipes, A. (2007). *Drawing for Designers*.
Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review*, *83*(2), 157.
Pugh, S. (1991). *Total Design: Integrated Methods for Successful Product Engineering*. Addison-Wesley.
Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*(4), 363–383. https://doi.org/10.1016/S0142-694X(96)00023-3
Purcell, A. T., & Gero, J. S. (1998a). Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, *19*(4), 389–430. https://doi.org/10.1016/S0142-694X(98)00015-5
Race, K. (Director). (2021). *Three Micro Breath Practice*. https://www.facebook.com/solvasa1/videos/dr-kristen-race-3-micro-breath-practice/3475714235776972/
Radcliffe, D. F. (1998). Event scales and social dimensions in design practice. In *Designers* (pp. 217–232). Springer.
Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(2), 676–682.
Reason, J. (1990). *Human Error*. Cambridge University Press.
Reymen, I. (2001). *Improving Design Processes Through Structured Reflection: A Domain-Independent Approach* [Technische Universiteit

Eindhoven]. https://doi.org/10.6100/ir538800
Reymen, I., & Hammer, D. K. (2002). Structured Reflection for Improving Design Processes. *DS 30: Proceedings of DESIGN 2002, the 7th International Design Conference*, 887–892.
Robertson, B. F., & Radcliffe, D. F. (2009). Impact of CAD tools on creative problem solving in engineering design. *Computer-Aided Design*, *41*(3), 136–146. https://doi.org/10.1016/j.cad.2008.06.007
Römer, A., Leinert, S., & Sachse, P. (2000). External Support of Problem Analysis in Design Problem Solving. *Research in Engineering Design*, *12*(3), 144–151. https://doi.org/10.1007/s001630050029
Roy, R. (1993). Case studies of creativity in innovative product development. *Design Studies*, *14*(4), 423–443. https://doi.org/10.1016/0142-694X(93)80016-6
Rubin, H., & Rubin, I. (2005). Structuring the Interview. In *Qualitative Interviewing: The Art of Hearing Data* (2nd ed., pp. 129–151). SAGE Publications, Inc. https://doi.org/10.4135/9781452226651
Rudd, J., Stern, K., & Isensee, S. (1996). Low vs. High-Fidelity Prototyping Debate. *Interactions*, *3*(1), 76–85.
Sachse, P. (1999). Unterstützung des entwerfenden Problemlösens im Konstruktionsprozess durch Prototyping. *Design Thinking*, 68–145.
Sachse, P. & Hacker, W. (1997). Unterstützung des Denkens und Handelns beim Konstruieren durch Prototyping. *Konstruktion (1981)*, *49*(4), 12–16.
Sachse, P. & Hacker, W. (2012). External procedures in design problem solving by experienced engineering designers – methods and purposes. *Theoretical Issues in Ergonomics Science*, *13*(5), 603–614. https://doi.org/10.1080/1464536X.2011.555788
Sachse, P., Hacker, W., & Leinert, S. (2004). External thought—Does sketching assist problem analysis? *Applied Cognitive Psychology*, *18*(4), 415–425. https://doi.org/10.1002/acp.992
Sachse, P., Martini, M., Pinggera, J., Weber, B., Reiter, K., & Furtner, M. (2014). Das Arbeitsgedächtnis als Nadelöhr des Denkens. *Psychologie Menschlichen Handelns: Wissen & Denken—Wollen & Tun. Pabst Science Publishers*.
Salmon, P. M., Stanton, N. A., Jenkins, D. P., Walker, G. H., Young, M. S., & Aujla, A. (2007). What Really Is Going on? Review, Critique and Extension of Situation Awareness Theory. *International Conference on Engineering Psychology and Cognitive Ergonomics*, 407–416.
Sauer, J., Seibel, K., & Rüttinger, B. (2010). The influence of user expertise and prototype fidelity in usability tests. *Applied Ergonomics*, *41*(1), 130–140. https://doi.org/10.1016/j.apergo.2009.06.003
Schenk, P. (1991). The role of drawing in the graphic design process. *Design Studies*, *12*(3), 168–181. https://doi.org/10.1016/0142-694X(91)90025-R
Schön, D. (1983). *The Reflective Practitioner: How Professionals Think In Action*. Basic Books.
Schön, D. (1992). Designing as reflective conversation with the materials of a design situation. *Research in Engineering Design Theory, Applications, and Concurrent Engineering*, *3*, 131–147. https://doi.org/doi.org/10.1007/BF01580516

Schön, D. (1983). *The Reflective Practitioner: How Professionals Think in Action* (Vol. 5126). Basic Books.
Schön, D. (1992). *The Reflective Practitioner: How Professionals Think in Action* (1. edition). Routledge.
Schön, D., & Wiggins, G. (1992). Kinds of seeing and their functions in designing. *Design Studies*, *13*(2), 135–156.
Schütze, M., Sachse, P., & Römer, A. (2003). Support value of sketching in the design process. *Research in Engineering Design*, *14*(2), 89–97. https://doi.org/10.1007/s00163-002-0028-7
Scott, S. J., & Green, J. (2017). *Habit Stacking: 127 Small Changes to Improve Your Health, Wealth, and Happiness* (2nd ed.). Oldtown Publishing LLC.
Scrivener, S., Ball, L., & Tseng, W. (2000). Uncertainty and sketching behaviour. *Design Studies*, *21*(5), 465–481. https://doi.org/10.1016/S0142-694X(00)00019-3
Sein, M. K., Henfridsson, O., Purao, S., Rossi, M., & Lindgren, R. (2011). Action Design Research. *MIS Quarterly*, *35*(1), 37–56. https://doi.org/10.2307/23043488
Seligman, M. E. (1990). *Learned Optimism: How to Change Your Mind and Your Life*. A.A.Knopf.
Simon, H. A. (1995). Problem Forming, Problem Finding, and Problem Solving in Design. In *Design and Systems, General Applications of Methodology* (Vol. 3, pp. 245–257). Transaction Publishers.
Simon, H. A. (1996). *The Sciences of the Artificial* (3rd ed.). The MIT Press.
Simon, H. A., & Chase, W. G. (1973). Skill in Chess. *American Scientist*, *61*(4), 394–403.
Simpson, E. J. (1972). *The classification of educational objectives in the psychomotor domain* (Vol. 3). Washington, DC: Gryphon House.
Sims, R. R., & Lindholm, J. (1993). Kolb's experiential learning model: A first step in learning how to learn from experience. *Journal of Management Education*, *17*(1), 95–98.
Snelders, D., & Vervloed, J. (2015). Service design as finished business. *Design Studies*, *36*, 122–124. https://doi.org/10.1016/j.destud.2014.09.002
Sormaz, M., Murphy, C., Wang, H., Hymers, M., Karapanagiotidis, T., Poerio, G., Margulies, D. S., Jefferies, E., & Smallwood, J. (2018). Default mode network can support the level of detail in experience during active task states. *Proceedings of the National Academy of Sciences*, *115*(37), 9318–9323.
Stappers, P. J. (2012). Doing Design as a Part of Doing Research. In *Design Research Now* (pp. 81–91). Birkhäuser. https://doi.org/10.1007/978-3-7643-8472-2_6
Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In M. Soegaard & R. Friis-Dam (Eds.), *The Encyclopedia of Human-Computer Interaction* (pp. 1–94). The Interaction Design Foundation. https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design
Stebbins, R. A. (2001). *Exploratory Research in the Social Sciences*. SAGE.
Sturdee, M., & Lindley, J. (2019). Sketching & Drawing as Future Inquiry in HCI. *Proceedings of the Halfway to the Future Symposium 2019*, 1–10.

https://doi.org/10.1145/3363384.3363402
Sun, G., & Yao, S. (2012). Investigating the relation between cognitive load and creativity in the conceptual design process. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *56*(1), 308–312.
Suwa, M., Gero, J. & Purcell, T. (1998a). Analysis of cognitive processes of a designer as the foundation for support tools. *Artificial Intelligence in Design'98*, 229–247.
Suwa, M., Gero, J. & Purcell, T. (1998b). The roles of sketches in early conceptual design processes. *Proceedings of Twentieth Annual Meeting of the Cognitive Science Society*, 1043–1048.
Suwa, M., Purcell, T. & Gero, J. (1998). Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies*, *19*(4), 455–483. https://doi.org/10.1016/S0142-694X(98)00016-7
Svanaes, D., & Seland, G. (2004). Putting the users center stage: Role playing and low-fi prototyping enable end users to design mobile systems. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 479–486.
Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, *4*(4), 295–312.
Thaler, R. (1980). Toward a positive theory of consumer choice. *Journal of Economic Behavior & Organization*, *1*(1), 39–60.
Thoring, K. (2019). *Designing Creative Space: A Systemic View on Workspace Design and its Impact on the Creative Process*. [Technische Universiteit Delft]. https://doi.org/10.4233/uuid:77070b57-9493-4aa6-a9a5-7fed52e45973
Thoring, K., Desmet, P., & Badke-Schaub, P. (2019). Creative Space: A Systematic Review of the Literature. *Proceedings of the Design Society: International Conference on Engineering Design*, *1* (1), 299–308.
Thoring, K., & Mueller, R. (2012). The Role of Role-Play: Intangible Systems Representations for Business Innovations. *Leading through Design*, 537.
Torrance, E. P. (1969). *Creativity. What Research Says to the Teacher, Series, No. 28.*
Tversky, B. (2002). What do sketches say about thinking. *2002 AAAI Spring Symposium, Sketch Understanding Workshop, Stanford University, AAAI Technical Report SS-02-08*, 148–151.
van der Lugt, R. (2005). How Sketching Can Affect the Idea Generation Process in Design Group Meetings. *Design Studies*, *26*(2), 101–122. https://doi.org/10.1016/j.destud.2004.08.003
Van Merrienboer, J. J., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, *17*, 147–177.
Verpoorten, D. (2012). *Reflection amplifiers in self-regulated learning*.
Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R., & Hennessey, J. M. (1998a). Sketching and creative discovery. *Design Studies*, *19*(4), 519–546.
Virzi, R. A., Sokolov, J. L., & Karis, D. (1996). Usability Problem Identification Using Both Low- and High-Fidelity Prototypes. *Proceedings of the*

SIGCHI Conference on Human Factors in Computing Systems, 236–243. https://doi.org/10.1145/238386.238516

Visser, W. (2006). *The Cognitive Artifacts of Designing*. Lawrence Erlbaum.

Viswanathan, V. K., & Linsey, J. S. (2012). Physical Models and Design Thinking: A Study of Functionality, Novelty and Variety of Ideas. *Journal of Mechanical Design*, *134*(9), 091004. https://doi.org/10.1115/1.4007148

Viswanathan, V. K., & Linsey, J. S. (2013). Role of Sunk Cost in Engineering Idea Generation: An Experimental Investigation. *Journal of Mechanical Design*, *135*(12), 1–12. seiten 121002.1-121002.12. https://doi.org/10.1115/1.4025290

Wang, J., Ranscombe, C., & Eisenbart, B. (2022). Prototyping in Smart Product Design: Investigating Prototyping Tools to Support Communication of Interactive and Environmental Qualities. *Proceedings of the Design Society*, *2*, 2243–2252.

Wason, P. C. (1960). On the failure to eliminate hypotheses in a conceptual task. *Quarterly Journal of Experimental Psychology*, *12*(3), 129–140.

Weixelbaum, I., Badke-Schaub, P., & Dörner, D. (2013). Training for reflective competency in design teams: An empirical study. *Proceedings of the International Conference on Engineering Design, ICED*, *7*, 49–58.

West, M. A. (2000). Reflexivity, Revolution and Innovation in Work Teams. In M. Beyerlein, D. Johnson, & S. Beyerlein (Eds.), *Product development teams* (pp. 1–29). JAI Press.

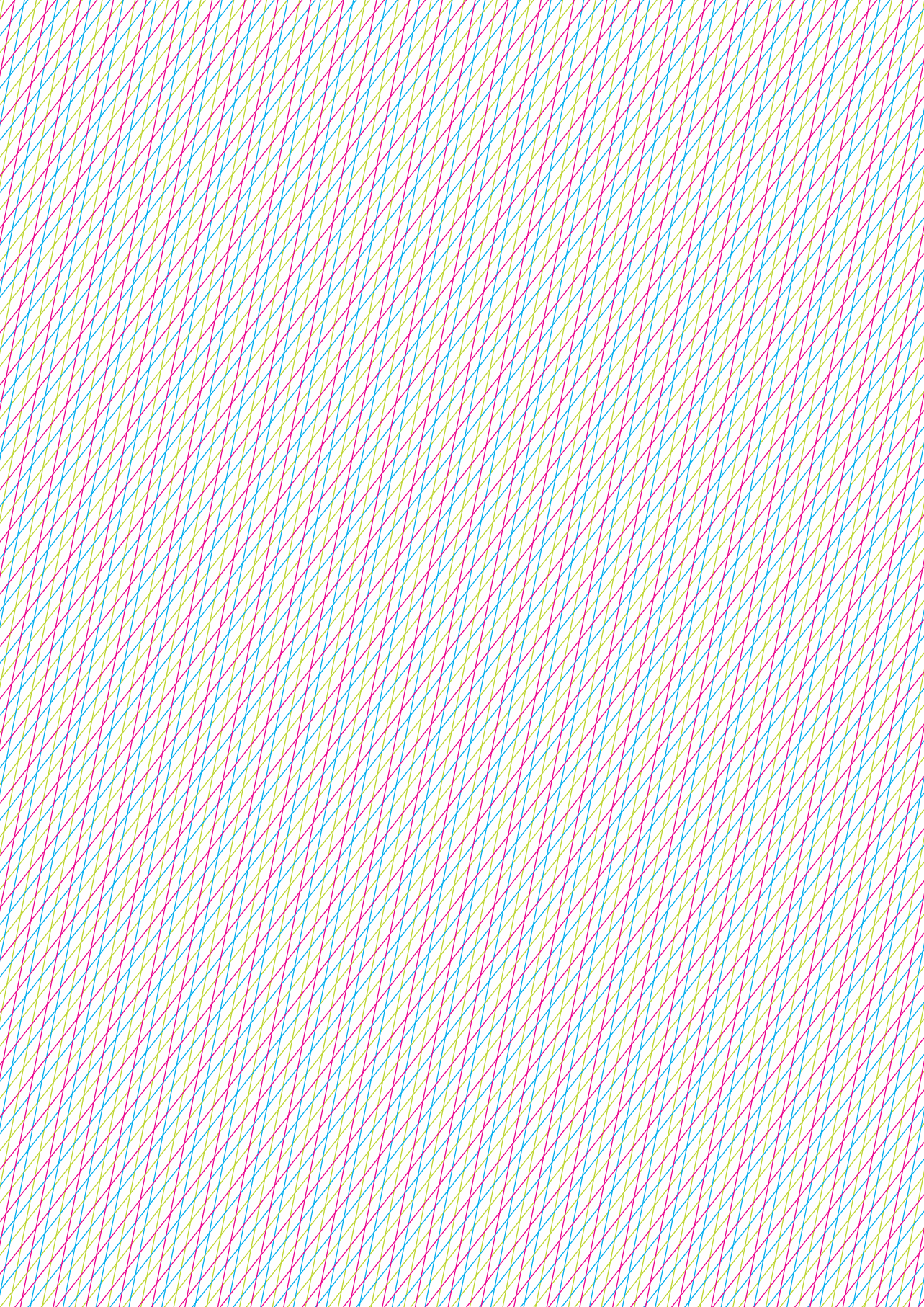
Wetzstein, A., & Hacker, W. (2004). Reflective Verbalization Improves Solutions—The Effects of Question-Based Reflection in Design Problem Solving. *Applied Cognitive Psychology*, *18*(2), 145–156. https://doi.org/10.1002/acp.949

Whipp, J. L. (2003). Scaffolding Critical Reflection in Online Discussions: Helping Prospective Teachers Think Deeply about Field Experiences in Urban Schools. *Journal of Teacher Education*, *54*(4), 321–333. https://doi.org/10.1177/0022487103255010

Yang, M. C. (2005). A study of prototypes, design activity, and design outcome. *Design Studies*, *26*(6), 649–669. https://doi.org/10.1016/j.destud.2005.04.005

Yang, M. C. (2009). Observations on Concept Generation and Sketching in Engineering Design. *Research in Engineering Design*, *20*(1), 1–11. https://doi.org/10.1007/s00163-008-0055-0

Yoon, J., Desmet, P. M., & Pohlmeyer, A. E. (2016). Developing usage guidelines for a card-based design tool: A case of the positive emotional granularity cards. *Archives of Design Research*, *29*(4), 5–18.



APPENDICES

APPENDIX A: SURVEY STUDY / QUESTIONNAIRE

I Personal Data

1. Gender
   - o female
   - o male
   - o other

2. Educational Background. In which field do you hold a degree?
   - o 2d (e.g., visual/communication design
   - o 3d (e.g., product design
   - o 4d (e.g., interaction design, multimedia design
   - o other. Which one? Please note.

   Comments.

3. How many years of design experience do you have as professional designer?
   - o up to one year
   - o 1 year
   - o 2 years
   - o 3 years
   - o 4 years
   - o up to five years
   - o more than five years

II Sketching and Prototyping as design activities

...regarding sketching as design activity

4. In your opinion, what is the most important function (or use) of a sketch in your design work/process?

5. Do you consider further important functions or uses of sketching?
   Which are they? Please note:

6. What do you think about sketches? A sketch should...

6a be realistic (e.g., in terms of proportion and details).

o	o	o	o	o
I don´t agree at all -	I rather not agree -	I neither agree nor disagree -	I rather agree -	I agree completely

6b have degrees of freedom to allow (re-) interpretation.

o	o	o	o	o
I don´t agree at all -	I rather not agree -	I neither agree nor disagree -	I rather agree -	I agree completely

6c support communicating the design idea including the design idea.

o	o	o	o	o
I don´t agree at all -	I rather not agree -	I neither agree nor disagree -	I rather agree -	I agree completely

7. Please note the most important kind of sketches that you use in your work:

7a Why do you use it in your work (as opposed to others)?

7b When do you use it?

...regarding prototyping as design activity

8. In your opinion, what is the most important function (or use) of a prototype in your design work/process?

9. Do you consider further important functions or uses of prototyping?
Which are they? Please note:

10. What do you think about prototypes? A prototype should...

10a be realistic (e.g., in terms of proportion and details)

o o o o o

I don´t agree at all - I rather not agree - I neither agree nor disagree - I rather agree - I agree completely

10b have degrees of freedom to allow (re-) interpretation.

o o o o o

I don´t agree at all - I rather not agree - I neither agree nor disagree - I rather agree - I agree completely

10c support communicating the design idea including the design idea.

o o o o o

I don´t agree at all - I rather not agree - I neither agree nor disagree - I rather agree - I agree completely

11. Please note the most important kind of sketches that you use in your work:

11a Why do you use it in your work (as opposed to others)?

11b When do you use it?

III Sketching and Prototyping in Practice

...regarding sketching in practice

12. How important is sketching for you in the following design phase?

12a Clarification of the task and problem analysis (i.e., defining the problem, get to know the problem space):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

12b Idea generation and conceptual design (i.e., building on the previously gathered information you generate ideas and develops a solution proposal and narrows it down to a concept):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

12c Embodiment design (i.e., the concrete idea and concept will be made visible and tangible):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

12d Detail design (i.e., what kind of surface, color, measures will the design have?):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

13. Is there a core moment where you cannot do without sketching?

o o o

Yes No I don't know

13a If yes, please describe this moment:

...regarding protoyping in practice

15. How important is prototyping for you in the following design phase?

15a Clarification of the task and problem analysis:

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

15b Idea generation and conceptual design (i.e., building on the previously gathered information you generate ideas and develops a solution proposal and narrows it down to a concept):

o o o o o

Not important at all - Slightly Important - Moderately Important important - very important

15c Embodiment design (i.e., the concrete idea and concept will be made visible and tangible):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

15d Detail design (i.e., what kind of surface, color, measures will the design have?):

o o o o o

Not important at all - Slightly Important - Moderately Important - important - very important

16. Is there a core moment where you cannot do without prototyping?

o o o

Yes No I don't know

APPENDIX B: INTERVIEW STUDY / GUIDELINE

I Personal Data

1. Gender
   - o female
   - o male
   - o other

2. Educational Background. In which field do you hold a degree?
   - o 2d (e.g., visual/communication design
   - o 3d (e.g., product design
   - o 4d (e.g., interaction design, multimedia design
   - o other. Which one? ...

   Comments...

3.. How many years of experience do you have as professional designer?
   - o up to eleven years
   - o more than eleven years

II Sketching and Prototyping as design activities

...regarding sketching as design activity

4. In your opinion, what is the most important function (or use) of a sketch in your design work?
5. Do you consider further important functions or uses of sketching?
   Which are they?
6. What do you think about sketches? What is characteristic for a sketch.
   Should a sketch rather...

   be realistic, have degrees of freedom to allow (re-) interpretation, support communicating the design idea?
7. Do you have a favorite sketch? If yes:

7a Why do you use it in your work (as opposed to others)?

7b When do you use it?

...regarding prototyping as design activity

8. In your opinion, what is the most important function (or use) of a prototype in your design work?
9. Do you consider further important functions or uses of prototyping?
   Which are they? Please note:

10. What do you think about prototypes? What is characteristic for a prototype?
Should a prototype rather...
be realistic, have degrees of freedom to allow (re-) interpretation, support communicating the design idea?

11. Do you have a favorite prototype? If yes:

11a. Why do you use it in your work (as opposed to others)?

11b. When do you use it?

III Sketching and Prototyping in Practice

...regarding sketching in practice

11. How important is sketching for you in the different phases of the design process?

12. Is there a core moment where you cannot do without sketching?

12a If yes, please describe this moment:

...regarding prototyping in practice

13. How important is prototyping for you in the different phases of the design process?

14. Is there a core moment where you cannot do without prototyping?

14a If yes, please describe this moment:

APPENDIX C: WORKSHOP / QUESTIONNAIRE

Workshop 1 / Guideline

I Personal Data

Gender

o female
o male
o other

2. How old are you?
3. In which semester are you studying Integrated design?

II Feedback session

4. What did you like about the Reflection Canvas?
5. What less?
6. What are the three most important advantages of the Reflection Canvas for you?
7. What would you wish for that would be better?
8. Would you like to use the tool in the future?

Workshop 2 / Guideline

I Personal Data

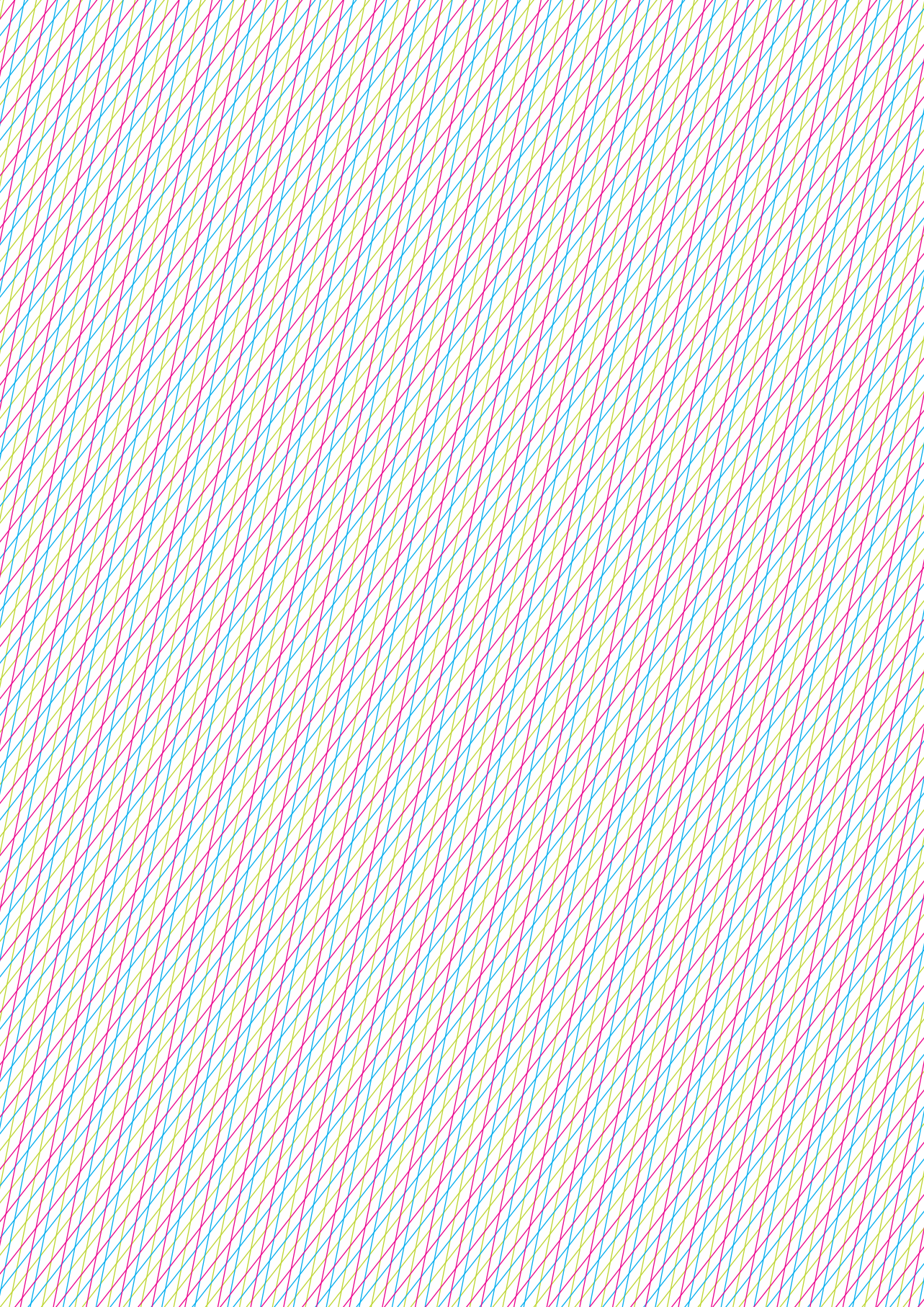
Gender

o female
o male
o other

2. How old are you?
3. In which semester are you studying Integrated design?

II Feedback session

4. What did you like about the Awareness Card Set respectively the Breathing Exercises?
5. What less?
6. What are the three most important advantages of the two tools for you?
7. What would you wish for that would be better? For the Awareness Cards?
   For the Breathing Exercises?
8. Would you like to use the tools in the future?



PUBLICATIONS

Publications related to this PhD thesis

Parts of this doctoral thesis have already been published; these are the following two publications.

Jobst, B. (2020, August 6). *The Bonding Gap Between Proficient Designers and Their Prototypes* [Conference Presentation]. 23rd DMI: Academic Design Management Conference, Toronto, Canada.

Jobst, B., Thoring, K., & Badke-Schaub, P. (2020). Introducing a Tool to Support Reflection through Sketching and Prototyping during the Design Process. *Proceedings of the Design Society: Design Conference*, *1*, 207–214.

During the process of researching and writing the PhD, two publications for design related conferences were published in conference proceedings respectively in a conference presentation. The first author made the main contributions to the paper and the presentation. The two co-authors are also the two promoters of this PhD thesis.

ABOUT THE AUTHOR

Birgit Jobst, born in Hannover in 1973, began her career with an apprenticeship as a goldsmith. During this time, her enthusiasm for the creative process and great design was awakened.

Following her curiosity and interest in in-depth knowledge, she went on to study industrial design at the Berlin University of the Arts (UdK). During her studies, she spent a semester abroad at Central St. Martins' College in London. She then completed her Master's degree in Industrial Design at the UdK Berlin in 2004.

After graduating, she founded her own design studio in Berlin, launching design products, some of which won awards (e.g., Design plus, Thrüringer Designpreis, Form).

She further enriched her design practice by linking it with theory and research through numerous research projects. For example, Birgit conducted a one-year design reserach project, which was awarded the Elsa Neumann Scholarship of the State of Berlin (NaFöG), on the topic of intercultural design in Angola.

Her interest in research led her to the Hasso-Plattner-Institute (HPI), Potsdam, Germany in 2010. There she participated in the HPI-Stanford Design Thinking Research Program for three years. Completely taken by the possibilities of releasing creativity and the joy of sharing knowledge, she immersed herself more and more in the Design Thinking approach. Soon Birgit was working as a coach and teaching Design Thinking to multidisciplinary project teams at the HPI School of Design Thinking in Potsdam, Germany.

Birgit took a position as a research assistant at Anhalt University of Applied Sciences in Dessau, Germany. Here she taught design theory, and design foundation courses to integrated design students. Parallel to her teaching, she started her PhD project at Delft University of Technology, The Netherlands.

Over the years Birgit focused her research interests on design thinking, design education and design expertise. She has presented her research findings at several conferences and was awarded the prize for the best paper at the E&PDE conference in London.

She has been a lecturer at Anhalt University of Applied Sciences since 2022, where she teaches design fundamental courses.

ACKNOWLEDGEMENTS

With these lines, a long and exciting journey comes to an end. Numerous companions have accompanied and supported me on this journey.

First and foremost, I would like to express my sincere gratitude to my two promoters, Petra and Katja.
Petra, I appreciate your humorous repartee in fencing out many methodological and scientific discussions! As a by-product of our discussions, many sketches were created on the napkin during dinner. With your impressively broad range of knowledge, your fundamental interest in everything and your farsightedness you have always supported me constructively and pushed me to do better day after day. During my PhD journey, you became what is called in Germany a ‚Doktormutter' - a reliable rock in the wild scientific surf.
Katja, thank you for always stepping into the ring with me, fighting for perfection in terms of scientific rigor, academic writing, Gestaltung, and even Word formatting ;) The many passionate scientific discussions you had with me during the day and deep into the night were always intense and the most fertile ground for new ideas, drive and courage. Your passion for science is contagious and your thinking deeply inspiring!
You are both truly wonderful and this journey with you has made me stretch and grow…and – amazingly – was a lot of fun at the same time.
Thank you both for your shared deep interest in the expertise of outstanding designers and for your certainty, that one day I will hold this book in my hands.

With so much passion for the subject, the nightlong discussions and many working hours flew by…but maybe not for everyone. Therefore, I would like to explicitly thank your wonderful and understanding husbands, Harald and Roland. You both had a significant share in the journey with a lot of patience and your dazzling humour.

And then there are my dear members of the opposition committee: Kilian, Daan, Boris, Frido, Dirk, and Nicole. I am so greatful to have you as members of my committee. Having you as my challengers makes me really proud!

Wilfred, my PhD mentor, thank you for your empowering support – I will never forget your magic words at the Go-meeting.

Many thanks to TU Delft and especially to the PIM and ID departments for your constant support. A special thanks to Ena, Hanneke, Leandra, and Milene for your kind support. You have always been my dearest and first point of contact in Delft and infinitely important for me, as an external candidate.

I would like to thank Anhalt University of Applied Sciences for supporting me on this project while I was working as a research associate. My special thanks go to the Department of Design in Dessau: To the deans, Nicolai and Severin, for your believe in me, your advice, moral, and financial support. And of course, to Claudia the good soul of the dean's office, who very charmingly makes the impossible possible. Also, to the printing workshop, Manfred Schwarz, Denis Geserick, and Anke Hanusch who supported me with professional and high-quality earlier versions of my book.

Thanks to the wonderful HPI- Stanford Design Thinking Research community, it was an intense and inspiring deep dive experience into the world of design thinking.

I would also like to express my gratefulness to my outstanding interview partners, who shall remain anonymous as well as to the participants in my survey study and workshops. Thank you all for generously sharing your valuable knowledge and fascinating insights. Without your help the research would not have been possible.

My Paranymph — I am grateful to you my friend Nicole, that you will support me mentally on stage. We met in Zurich, where you worked as an assistant to Alfredo Häberli and I worked for Christophe Marchand - my first encounters with outstanding designers. All our experiences and observations of that time had a lasting impact on me and my thinking.

Julia, my dear friend and colleague. Thank you very much for the valuable discussions and for the support with the data analysis in my studies.

It is well known that it takes a whole village to raise children, even more so, when you are working on a PhD at the same time. Infinite gratitude goes to my village, invaluable is your support and the warm hours spent with my children. So, I say THANK YOU to Stefanie, Dariusz, Rosa, Ute, Janet, Maria, Julius, Anne, Gudny, Maike, Naim, Nicole, Oona, and many others. Special thanks to the wonderful teachers Ilka, Kate, Thorsten, and Ortfried.

Relaxation is just as important as work. In my case, that means music. Kate, from the bottom of my heart, thank you for the many concerts of your violin students, for your infectious passion for music, and the numerous rehearsals for Amalia's trio that let to the unforgettable ‘Jugend musiziert‘ concerts.
And thank you Christian for the performances of the Kinderchor der Deutschen Oper (German Opera Berlin, Children's Choir), which fill Ana with so much joy. Attending the performances makes me indescribably happy.

A big thanks goes to my friends Lilo and Helmut, who set up a warm and welcoming place for me to write in their office. With plenty of coffee and humor - and when necessary, a sip of Calvados - they created exactly the atmosphere in which both hard work and deep friendship, both inspiring creativity and sorrowful hours had their place. I will always thank you for that.

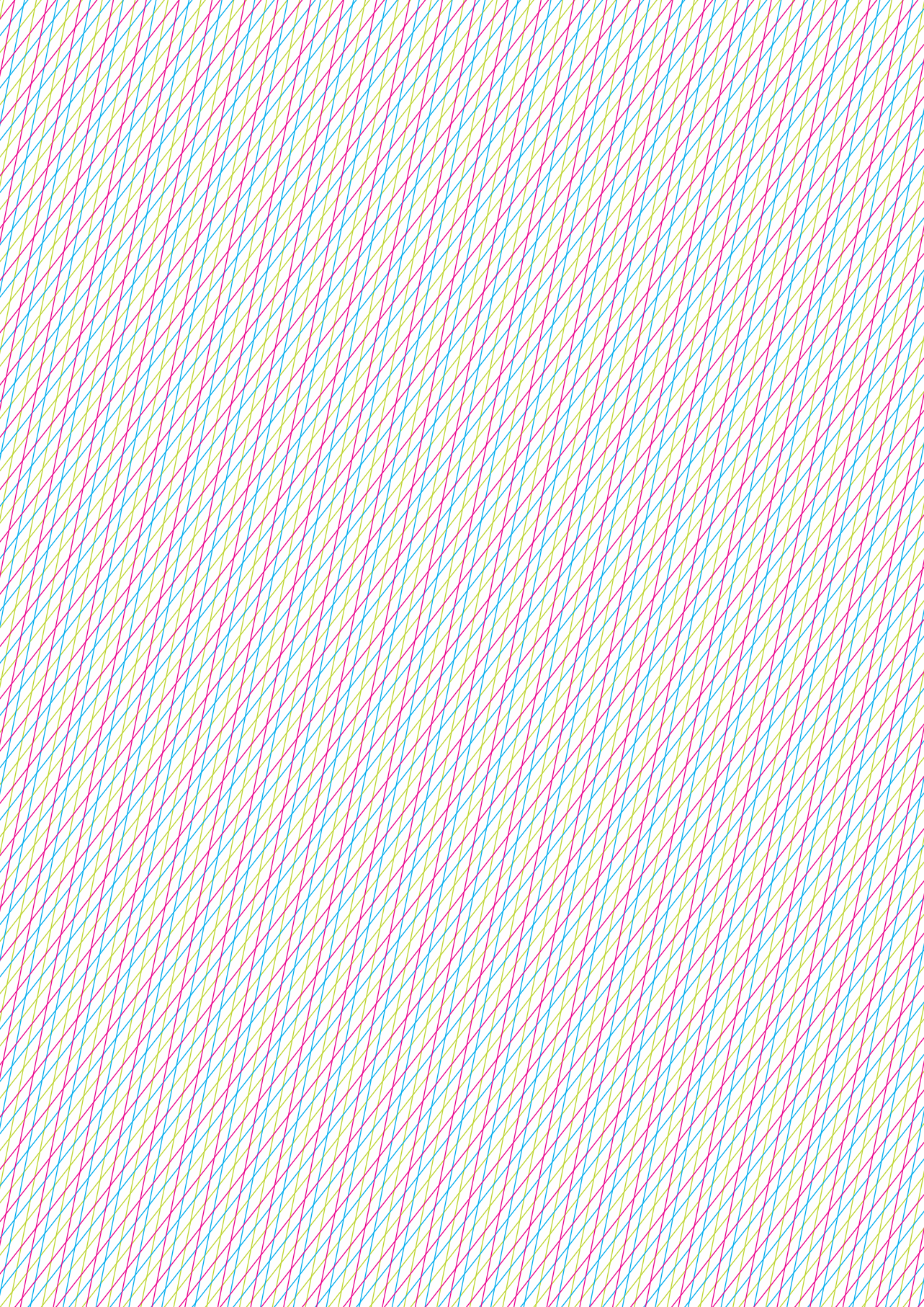
I am grateful to my friend Antje, for your always open ears, your empathy and infectious enthusiasm for the little joys of life.

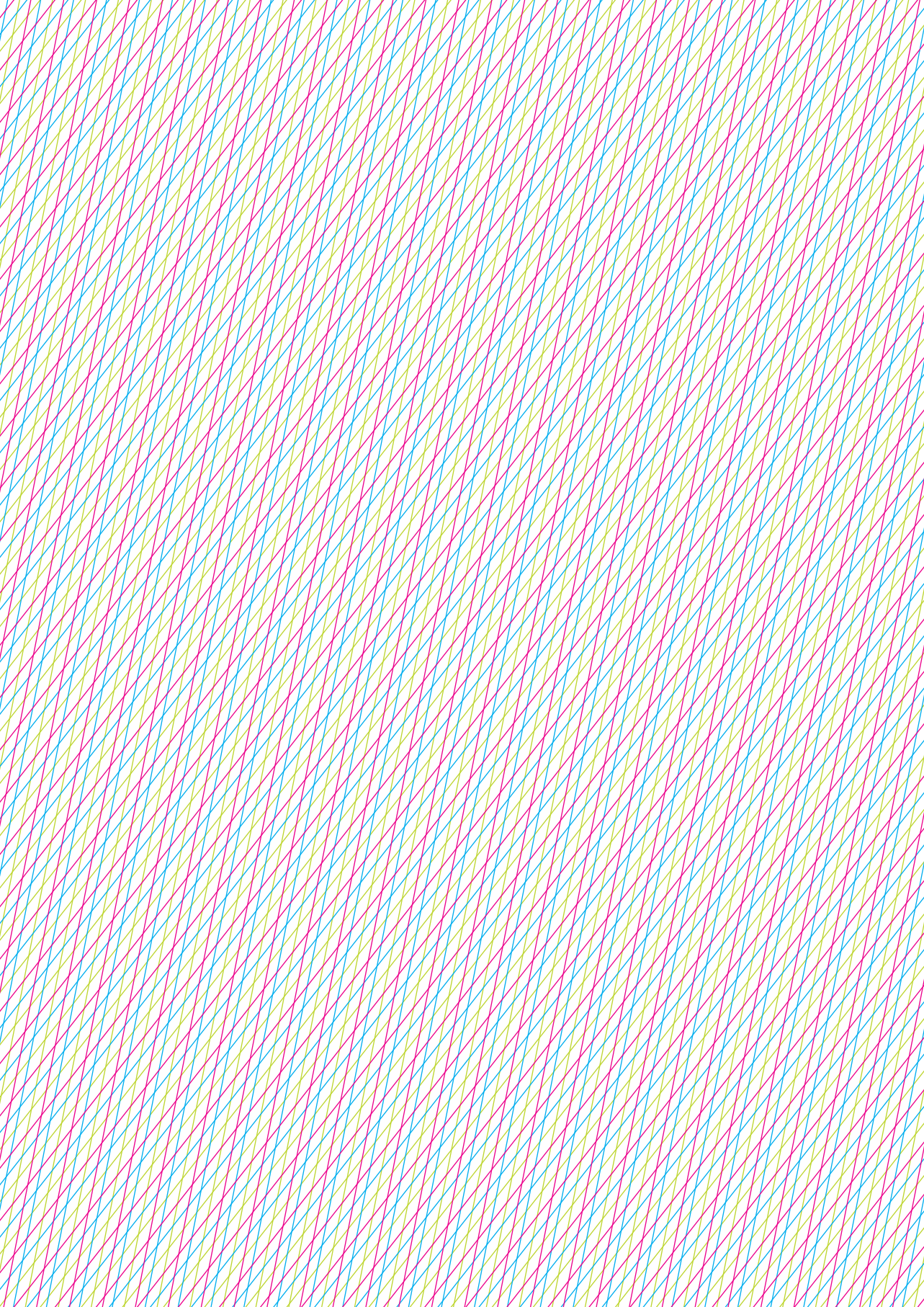
Dear thanks also to Carolin, for your insightful, practical, and cheerful advice in all of life's situations. Your support has been incredibly empowering and your enthusiasm contagious!

I am also thankful to Diego, our inspiring design discussions and your endless advice and support I could always count on. Your tips on making sourdough, your magical powers in formatting in Word and solving computer problems were invaluable.

I thank my grandmother Margarete and my sister Stephanie for their constant encouragement. Barbara and Günter, my parents, thank you, I have always been safe in the knowledge that you are there for me at any time. Your support and love have carried me.

Most important and closest to my heart is my family – my children Amalia and Ana and my husband Edgar – they deserve my greatest thanks. You have supported me, pushed me, believed in me, done without me, you´ve given me courage and fire and always stood cheering on the sidelines – you mean the world to me! It is to you that I dedicate this work.





ISBN 978-94-6419-900-0