Aalto University

Aaltodoc
OPEN ACCESS

This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Author(s): Björklund, Tua A.

Title: Initial mental representations of design problems: Differences between experts and novices

Year: 2013

Version: Post print

Please cite the original version:

Björklund, Tua A. 2013. Initial mental representations of design problems: Differences between experts and novices. Design Studies. Volume 34, Issue 2. 135-160. ISSN 0142-694X (printed). DOI: 10.1016/j.destud.2012.08.005.

Rights: © 2013 Elsevier BV. This is the post print version of the following article: Björklund, Tua A. 2013. Initial mental representations of design problems: Differences between experts and novices. Design Studies. Volume 34, Issue 2. 135-160. ISSN 0142-694X (printed). DOI: 10.1016/j.destud.2012.08.005, which has been published in final form at http://www.sciencedirect.com/science/article/pii/S0142694X12000609.

All material supplied via Aaltodoc is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Initial mental representations of design problems: differences between experts and novices

Tua A. Björklund
Aalto University Design Factory, Finland

Defining and structuring wicked design problems has a major influence on subsequent problem solving, and demands a considerable level of skill. Previous research on mental representations in design is scarce, and has been largely based on students or individual experts. This study explored the differences in the initial mental representations of real-life product development problems between advanced product development engineering students and recommended, professional experts. Expert mental representations were found to demonstrate superior extent, depth and level of detail, accommodating more interconnections and being more geared towards action. The results indicate that targeting relevancy perceptions to locate interconnections and promote proactivity can be a key factor in developing product development education to better match the requirements faced by professionals.

Keywords: expertise, product development, design problems, design cognition, specification

Expertise, i.e. superior performance in representative tasks in the field of expertise (Ericsson & Smith, 1991; Ericsson & Lehmann, 1996), has been studied in diverse domains and numerous professions, and systematic differences have long been demonstrated between expert and novice problem solving performance (Ericsson, *et al*., 2006; Chi, Glaser & Farr, 1988). However, limited research has been conducted on product development expertise (Cross, 2003; Defazio, 2008; Lawson, 2004), and in general, expertise and decision making research has tended to focus on fields with relatively well-defined problems, such as games and sports. While well-defined tasks are associated with a clear initial state, goal state, and set of rules (Reitman, 1965; Simon, 1973), many of the problem parameters are vague or unknown in the ill-structured creative problems faced in creative knowledge work. Indeed, previous design researh has identified that it is not only the domain that distinguishes design from other fields, but also the process in which it is carried out (Gero, 1990). The design process seems to fundamentally differ from the scientific method (Lawson, 1979). Whereas a strategy of analysis and synthesis works for well-defined problems (Reitman, 1965; Simon, 1973), the exploration process of ill-structured problems is targeted at both goal and decision variables (Gero, 1990). The problem must first be transformed or structured into a clear mental representation of the current situation and goal state by the problem solver (Simon, 1973). In addition, fruitful actions need to be recognized from irrelevant ones from a seemingly unlimited pool of possible options (Schunn, McGregor & Saner, 2005). As creative knowledge-work professionals such as product developers need to routinely deal with these "messy situations" (Schön, 1983), how the problems are perceived and represented are of particular interest (Lawson, 2004).

Coined as wicked problems in design literature (Rittel & Webber, 1973; Buchanan, 1992), there is no "right" way to represent such vague problems. Rather the problem representation develops hand in hand with the solution, and the "information needed to *understand* the problem depends upon one's idea for *solving* it" (Rittel & Webber, 1973, 161, italics original). How the problem is perceived influences which solutions are considered as relevant (Getzels, 1975), and thus finding the solution requires the problem to be formulated in a fruitful way (Getzels, 1979). Indeed, the creation or adaption of a fruitful *frame* has been indentified as a key practice in design and design thinking (Dorst, 2011; Paton & Dorst, 2010; Drews, 2009; Beckman & Barry, 2007), as well as in creative work in general (Hargadon & Bechky, 2006; Schank & Abelson, 1977). Framing refers to the creation of a standpoint from which a problem can be successfully tackled (Dorst, 2011), and requires a process of structuring and formulating the problem (Cross, 2004). Whereas design problems can have some inherent structure, for example in terms of the number of main issues or amount of dependencies between issues (Dorst, 1996), problem structuring refers to the psychological process of forming a mental, subjective representation reflecting the perceived problem state and desired outcome (Simon, 1973). The significance of the mental representation that is formed by the designer is further highlighted by the nature of design briefs in development work – at the starting point of a project, the client's initial expression of the design problem is reframed by the product developer and the client in a process of briefing in order to create a fruitful and actionable view of the project (Schön & Wiggins, 1992; Valkenburg & Dorst, 1998; Hey, Joyce & Beckman, 2007; Paton & Dorst, 2010). In other words, designers must interpret the input they receive or collect regarding a design project in order to create a first representation of the problem at hand (Visser, 2006). As the requirements co-evolve with the solution (Dorst & Cross, 2001; Kolodner & Willis, 1996; Suwa, Gero & Purcell, 2000) and affect its quality (Chakrabarti, Morgenstern, & Knaab, 2004; Walz, Elan, & Curtis, 1993), the first representation created by the product developer has a significant impact on the entire subsequent development project, and posits itself as both a meaningful and an intriguing research arena. However, despite the rise of expert mental representation research in other fields (Bläsing, Tenenbaum & Schack, 2009), the majority of product development research has been able to provide limited insight on how the type of problems that development professionals face are successfully represented (Visser, 2006). Much empirical research on design has ignored considerations of expertise (Lawson, 2004), even though expertise is strongly associated with successful framing (Akin, 1990; Cross, 2004b; Lawson & Dorst, 2009; Paton & Dorst, 2010). In fact, design research has tended to study either groups of design students (Defazio, 2008) or individual professional designers (Cross, 2004b), working on simplified tasks and in simplified conditions (Lawson, 2004). This study aims to address this gap by exploring how expert and novice first mental problem representations differ from each other in product development, utilizing a novel, resource-efficient methodology for investigating real-life product development problems.

1 Previous research on expert mental problem representations

The study of mental representations has recently become a focal point in studying expertise and learning (Bläsing, Tenenbaum & Schack, 2009). Expertise is mediated by superior mental representations (Ericsson, 2003), which have a bidirectional relationship with knowledge (Alibali, Phillips & Fischer, 2009). In contrast to the external representations such as sketches and models utilized in design, mental representations are temporary internal cognitive structures modeling the problem (Chi, Feltovich & Glaser, 1981; Dixon & Boncoddo, 2009) that are constructed implicitly and automaticly by the problem solver (Bickhard, 2001). Mental problem representations lie at the juncture of conceptual knowledge and procedural actions (Rittle-Johnson, Siegler & Alibali, 2001), allowing the selection and evaluation of effective information (Bläsing, Tenenbaum & Schack, 2009). Although there are numerous options in how any given design problem is represented, and how the problem is mentally represented by the problem solver has a significant impact on subsequent solving efforts (Cross, 2004b; Gero, 1990; Rittel & Webber, 1973), there is little research conducted on constructing mental representations in design (Visser, 2006).

Numerous problem reconstruction and perception studies in many other fields of expertise have revealed that experts can better recall meaningful, relevant information in their domains (Chase & Simon, 1973; Charness, 1976; Randel, Pugh & Reed, 1996; Smyth & Pendelton, 1994; Starkes, *et al*., 1987). These differences have been linked to larger integrated knowledge structures in the memory (Gobet, *et al*., 2001), demonstrated also by design experts (Popovic, 2004). In addition to differences in the extent of mental reprepresentations, information priorization seems to occur already on a perceptual level, as the location of attention has been demonstrated to vary between experts and novices in sports and games (De Groot & Gobet, 1996; Rowe & McKenna, 2001; Saariluoma, 1985). Systematic differences have also been found in how experts and novices group together presented problems, reflecting differences in the quality of the initial problem representations: Whereas novices focus on surface features (such as pulley problems in physics), experts group problems based on their deep structure, organizing problems with the same underlying principles together in physics (Chi, Feltovich & Glaser, 1981), forming algorithms or data structures in programming (McKeithen, *et al*., 1981), and organizing diagnostic hypotheses according to major patho-physiological issues in medicine (Feltovich, *et al*., 1984; Johnson, *et al*., 1981). However, research has not yet tackled which features of product development problems capture experts' attention, or if there are some specific characteristics in design mental representations (Visser, 2006).

Futhermore, in addition to producing different mental problem representations, experts and novices also differ in the process of forming them. Here research in design expertise is more available. First of all, design experts are more cognitively active and productive compared to novices (Kavakli & Gero, 2001, 2002). A large amount of this greater cognitive activity is spent on understanding the initial, ill-defined design specification and framing the problem (Goel & Pirolli, 1992; Cross, 2004b). The process of problem framing or structuring may even take longer than actually solving the structured problem (Simon, 1973). Designers tend to treat even more well-defined problems as if they were design problems, wanting to reframe them (Cross, 2007, Paton & Dorst, 2010). Indeed, in contrast to expertise in well-defined problems, Cross (2004; Cross & Clayburn Cross, 1998) suggests that creative experts treat problems as harder than what novices do. For example, experts demonstrate a more comprehensive and higher level awareness of the contextual constraints of the problem (Eteläpelto, 2000). Experts in other fields also spend more time considering the information in the problem and are more likely to incorporate relevant knowledge (Chi, Feltovich & Glaser, 1981). In addition, experts request higher-level task information than novices and are better able to predict what information they will need further on in the problem solving process in the field of finance (Hershey, *et al.,* 1990). Design experts extensively utilize knowledge from previous projects (Ahmed, Wallace & Blessing, 2003; Cross, 2004a), spontaneously producing analogies to specific past cases whereas novices tend to use general principles (Ball, Ormerod & Morley, 2004). More experienced design students gather and use more information related to the problem at hand (Atman, *et al*., 1999; Christiaans & Dorst, 1992; Cross, Christiaans & Dorst, 1994; Popovic, 2004), and design experts seem to approach the problem information more critically – unlike novices, experts question data, are aware of limitations and relationships between issues, and differentiate between important and less important issues (Ahmed, Wallace & Blessing, 2003). Also more successful design students make priority judgments early on (Christiaans & Dorst, 1992). In addition to evaluating the available information, design experts also tend to evaluate the solution more and earlier than novices (Ahmed, Wallace & Blessing, 2003; Ball, *et al.,* 1997), and engage in more reflection in general (Schön, 1983; Crakett, 2004; Petre, 2004). Design experts engage in more problem decomposition, creating more sub-goals (Ball, *et al*., 1997) and using explicit problem decomposing strategies (Ho, 2001, based on a protocol study comparing a single expert and novice).

Research in other fields of expertise further indicates that experts create mental representations that are more closely linked to subsequent action (Klein, 1998) and emphasize their own active role in information seeking, as opposed to novices perceiving themselves as passive recipients of information (Prince & Salas, 1998).

Thus one of the differences that can be expected to manifest between product development experts and novices is the display of differing levels of proactive behavior. Defined as taking anticipatory action to impact oneself or one's environment (Grant & Ashford, 2008), proactive behavior is change-oriented (Bateman & Crant, 1993) and active (Crant, 2000) by nature. Given the recent demonstrations of the importance of proactivity for successful work behavior (Baer & Frese, 2003; Frese, *et al.*, 2007; Koop, De Reu & Frese, 2000; Seibert, Crant & Kraimer, 1999) and innovativeness (Binnewies, Ohly & Sonnentag, 2007; Frese, Teng & Wijnen, 1999; Ohly, Sonnentag & Pluntke, 2006; Seibert, Kraimer & Crant, 2001), proactiveness presents itself as a critical ingredient for success, especially in creative domains such as product development. Thus whether proactivity differences between experts and novices can be traced back to the initial mental representations or problem structuring and framing stage of product development problem solving becomes an interesting question. However, the connection between product development expertise and proactivity has not been studied, and little is known about the role of knowledge, skills and abilities in proactive behavior in any domain (Grant & Ashford, 2008; Crant, 2000).

Finally, naturalistic decision making research suggests that expert responses are centered around recognizing or constructing adequate responses based on experience and critical features of the problem, rather than exhaustively analyzing options to produce normatively optimal responses (Klein, 1997a,b; Patel, Kaufman & Arocha, 2002). In this type of decision making, "the burden of difficulty is on assessing the nature of the situation rather than on comparing alternative courses of action" (Klein, 1997, 341). Empirical support for the usage of such approaches has been gained from a variety of time-critical professions (Carvalho, dos Santos & Vidal, 2005; Klein, 1998; Klein, Calderwood & Clinton-Cirocco, 1989; Kushniruk, Patel & Fleiszer, 1995), but Zannier, Chiasson and Maurer (2007) also found that the less structured a design problem was, the more the participants focused on naturalistic approaches to solving it. As a result, experts do not tend to consider more options than novices, but rather immediately produce higher quality options (Klein, *et al.*, 1995; De Groot, 1946/1978). Domain-based experience and the resulting well-developed schemas (abstract knowledge structures) enable experts to automatically recognize classes of problems (Chi, Feltovich & Glaser, 1981) and patterns (Lesgold, *et al*., 1988), and directly produce reasonable options (Klein, *et al*., 1995). Also design experts have been demonstrated to automatically recognize familiar types of problems and solutions (Ball, Ormerod & Morley, 2004). In addition to considering a limited amount of options, experts in many fields seem to choose a preferred option rather early on (Joseph & Patel, 1990), with empirical results suggesting that experts possess adaptive developments supporting the recognition of patterns and preventing excess resource-consuming search through irrelevant information and false hypotheses (Patel, Kaufman & Arocha, 2002). Thus the importance of the initial mental representation formed in the beginning of problem solving process is further highlighted, especially in the case of fields with vague, ill-defined problems such as product development.

After reviewing research on design expertise, Cross (2004) concludes that problem framing is frequently identified as a key feature of design expertise, and understanding the capacity of designers to create new frames is a key goal for current design research according to Dorst (2011). However, while it is clear that differences in problem framing exist between design experts and novices, many questions regarding the origins and significance of the few empirically observed differences remain. In addition to the general lack of research, the usage of students and individual professionals further limits the reliability of the obtained knowledge on the psychological processes of product development. As Lawson (2004, 457) states, "we should explore perception of design situations and in particular how they are recognised and classified". In order to do this, this study further explores the very initial mental problem representations of expert product developers and product development students, aiming especially to identify any differences between the two groups when dealing with actual real-life design briefs instead of simplified well-defined development sub-problems.

2 Method

2.1 Participants

A total of seven product development experts (referred to as E1-E7) and seven product development students (referred to as N1-N7) took part in the study. The study participants were all Finnish, and all but one expert were male, minimizing differences resulting from factors unrelated to differences in the level of expertise. In the absence of objective criteria, such as Elo ratings in chess (Elo, 1978), social reputation and length of experience are typical identification criteria for experts (Chi, Glaser, & Farr, 1988). Thus the experts were chosen based on nominations from product development managers for especially capable product developers within their department (E1-E3) or from peers for especially capable, design award-winning product development colleagues (E4-E7). The expert participants came from two companies, both of which provided product development and design services for other organizations. The experts thus worked in partially or completely outsourced projects of varied companies, and had accrued experience from several fields. The experts had work experience in product development from 8 to 15 years, and all of them had participated in a minimum of 13 product development projects. The expert average of 25 projects and 11 years of experience can be compared to Defazio's (2008) minimum of 10 successful products or publications for design experts, or Ahmed, Wallace and Blessing's (2003) minimum of 8 years of experience for experienced engineering designers. The ages of the experts ranged from 32 to 41, averaging at 36, whereas the ages of novices ranged from 24 to 29, averaging at 26 years.

The novices in the study all had product development as their major subject in the same Finnish university of technology, and had a maximum of one year until their graduation. In order to ensure that the novices did not approach the experts in skill level, the amount of working experience was controlled. The novices reported having a minimum of 6 months of work experience, and having spent a maximum of three years as part-time workers in the field of product development (compare to, e.g., the limit of 2.5 years for novices in Ahmed, Wallace & Blessing, 2003).

2.2 Testing materials

In order to facilitate knowledge elicitation (Klein, Calderwood & MacGregor, 1989) and ensure that the expert participants could utilize their expertise (Ericsson, 2006b), the study aimed to investigate familiar, representative tasks of the domain. Data collection was built around five design briefs, comparable to the successful approaches of using clinical cases in studying medical expertise (e.g. Lesgold, *et al.*, 1988). The utilized five design briefs were based on five real product development cases from five different companies and five different projects. Generated test cases typically aim for being prototypical of the field, providing a range of difficulty, or providing a range of different types of cases (Hoffman, *et al.*, 1995). This study aimed to provide a variety of types in order to ensure that the tasks represented the real projects faced by product developers in their professional life, and to improve generalizability to a wider range of physical product development tasks. The aim was to choose design briefs on products from varied fields, but nonetheless ones that were understandable even if the application area was unfamiliar. The five utilized design briefs regarded a polling booth for electric voting**,** a sauna safety device, a coffee package that is easier to open, a wireless charging device, and a bigger half-pipe grinder. All of the design briefs were approximately three fourths of an A4 page in length, with an average amount of 250 words (comparable to other design briefs used in previous research, such as Dorst and Cross', 2001, 427, self-created design brief on a train litter-disposal system). The design briefs were in Finnish, the native tongue of the participants.

2.3 Data collection

Expert mental representations have been previously investigated in a number of ways, including recall tasks, perception tasks, and verbal reporting (Chi, 2006). One of the most common methods of studying expertise in general has been protocol analysis, a type of verbal reporting based on concurrent verbalization or thinking aloud while solving a problem (Ericsson, 2006a; Ericsson & Simon, 1993; Coley, Houseman & Roy, 2007; Houseman, Coley & Roy, 2008). However, solving product development problems typically require at least several weeks of work and collaboration with a wide host of different stakeholders and professionals. Indeed, many of the participant experts reported that their next step in proceeding with the design briefs would have been talking to other specialists, clients, or users. While protocol analysis in this case would have provided valuable information on the problem represention and solving process if a realistic setting would have been provided, arranging several expert and novice participants to work for several weeks on the same problem would be extremely challenging. Thus rather than use unrealistically simple and well-defined problems, it was decided to utilize initial reflections of real product design problems prompted by means of interviewing the participants. Structured interviews are considered to provide a more systematic coverage of the domain (Cooke, 1994), and were consequently deemed more appropriate to investigate representational differences than unstructured interviews. In addition, structured interviews, in which the questions were always presented in the exact same order and form, ensured that any observed differences between the experts and novices were not prompted by the interviewer and allows for easier comparison between participants. While the choice of questions influences which result categories can be formed from the data, they however do not have an effect on the within category differences found in the data between the expert and novice participants. As standardized questions allow for more systematic and easier comparisons between the responses of different participants, the more constrained scope of possible answers was considered as an acceptable limitation. In order to minimize the constraints and make the questions applicable to all five design briefs, open-ended (Shaw & Woodward, 1990) and generic (Hoffman, *et al*., 1995) interview questions were utilized. The following six questions were asked for each design brief:

1. Describe in a few sentences what the design brief was about.
2. Was there some information missing? If yes, what?
3. Was there some needless information? If yes, what?
4. What was important information?
5. How would you continue from this point?
6. Are there any problems or challenges to be expected?

Comparable to the cognitive probe question of “What information did you use in making this decision, and how was it obtained?” utilized for eliciting knowledge in critical decision interviews (adopted in naturalistic decision making research; Klein, Calderwood & MacGregor, 1989), the questions probe both in an explicit fashion and in a more indirect manner for the information the participants include in their initial mental representations. Thus while previous studies have utilized problem reconstruction to study mental representations (e.g. Chase & Simon, 1973; Siegler, 1976), the questions of this study effectively deconstruct the problem. The six questions were deemed to provide sufficient details on the participants' mental representations while limiting or directing the participants' answers as little as possible to any particular set of knowledge or behavior in advance.

Data were collected in 14 structured interviews, which were carried out individually and by the same interviewer. The interviews were held in Finnish, the mother tongue of the participants (therefore all the excerpts presented in this paper have been translated into English). The participants read the five design briefs, presented in a varied order, one at a time, and each design brief was followed by a structured interview of six questions. Although the participants were able to anticipate the interview questions after a few design briefs, there was no systematic increase or decrease in any result category according to the design brief presentation order. The participants were informed in advance that they could spend as much time as they wished with the design briefs and interview questions, and none voiced concerns during or after the interviews. In total, the interviews lasted from 30 to 66 minutes, the experts spending an average of 47 minutes and the novices an average of 37 minutes. Dealing with one design brief typically took the participants approximately one and a half minutes to read the design brief and four to six minutes to answer the interview questions. The interviews were audio-recorded.

2.4 Analysis of the interviews

The audio-recordings of the interviews were transcribed, after which every interview was segmented (Chi, 1997) into propositions, each of which was considered to represent a separate idea. The typical length of an individual segment was one sentence. In total, 1760 segments were produced by the participants.

The coded segments of transcribed verbal reports can be judged for both content and frequency (Chi, 2006). When the interview questions do not restrict the content of the responses, analysis of the data can benefit from a data-driven, grounded approach (Cooke, 1999). Although grounded theory (Bryant & Charmaz, 2007) was not utilized in this study, as the purpose was not to develop new concepts or conceptual models, bottom-up thematic coding was chosen in order to include any potential differences between the novices and experts, rather than to limit the focus on a predetermined set of representational aspects. Thus categories were created based on reoccurring themes in the problem-related knowledge types, such as identified sub-goals and requirements. A segment could belong to more than one category, for example the segment *"And of course [it is a challenge], how an individual voter can be sure that the vote is recorded, that it's recorded as it has been given"* was classified as both a challenge and a new requirement for the end product or solution to fulfill.

After all of the segments had been coded, similar codes were merged, and all of the segments were reanalyzed with the produced final list of categories. Only categories containing more than 15 segments were included in the analysis, thus producing 14 main categories (see Table 1). Furthermore, subcategories (again, all containing more than 15 segments) were identified for three categories: important information, how to proceed with the problem, and defining the problem.

Table 1. Produced categories for the segments

Class	*Category*	*Description*	*Example*
I Needed information	1. Missing information	Information identified as missing or needed in order to continue working on the case, questions about the product	" I don't know, this didn't say, are the competitors' product patented, so that that's why they can't be copied, or do they just not want to make the same kind." (E3)
	2. Important information	Information explicitly identified as important by the participant	
	a. feature or quality of the product	a feature or quality of the product mentioned in the design brief	"it needs to be cheap." (N5)
	b. other information in the design brief	information aside from product features or qualities stated in the design brief	"And that size of the largest list of candidates (ballot) is essential." (E5)
	c. deduced context	information regarding the context of the project, deduced by the participant	"That it is likely a pretty small sample, to base the development on."(E7)
	3. Outside information	Utilization of information not found in the design brief (personal experiences or know-ledge of the world)	"And as at the same time especially the voting enthusiasm of the youth is pretty low, it could actually be quite good to freshen up the voting environment a bit." (E6)

II Problem structuring	4. Definition	Defining or limiting the problem-space	
	a. product	related to the product	"This probably... likely these are targeted for private apartments." (E1)
	b. project	related to the project	"This would be a technology development project, if it were initiated." (E3)
	5. New requirement	Identifying a new requirement (not mentioned in the design brief) for the product	"Electronic voting, so places for power sources (outlets) are required there." (E5)
	6. Sub-goal	Identifying a sub-goal	"We would need to keep the centre of gravity a bit lower and more to the centre." (E1)
	7. Initial idea generation	Developing or mentioning some specific ideas for the product	"Maybe you could ease the opening by some small extra material slip, make a better grip, from which you can tear it open." (E1)

III Process	8. Specific source of information	A specific source of knowledge or information identified	" And insurance companies. They could surely provide information on sauna fires, how they have begun." (E2)
	9. What next	Explicit statements of what the participant would do next	
	a. generic	of a generic nature	(I would) "...set up meeting with the client" (N5)
	b. case- specific	specific to the project at hand, more detailed	"I would go watch in the field when they [snowboarders] make them [half-pipes] entirely by hand." (N1)
	10. Project evaluation	Evaluating the project (or the information in the design brief)	"This was more, just gather the people and start doing. Very simple thing, that you surely can vary easily enough options." (N5)
	11. Challenges	Identified challenges relating to the product development problem and project	"It might require more work than estimated." (E2)
IV Presentation of the problem	12. Design brief text evaluation	Evaluating the form or presentation style of the design brief	"It could be better structured, that, in what order the information is presented." (N6)
	13. Needless information	Information presented in the design brief but explicitly identified as useless by the participant	"There are these appendices of the sizes of the candidate lists." (…that I wouldn't need) (N1)
	14. Task clarification questions	Problem perceived as unclear, answers to questions sought from the client	(I would need to...) "discuss a bit, do they want to actually do something" (N2)

The 14 categories could be grouped into four larger classes: all of the categories were related to either needed (or used) information, problem structuring, the problem solving process or the presentation of the problem.

Due to the aim of the study, differences between experts and novices across the resulting categories (problem knowledge dimensions) were of more interest than the themes of the categories as such (indeed, any amount of different coding schemes might have been developed from the same data). The amount of segments that each participant had produced to each class was counted, omitting segments in which a participant repeated the comment within the same design brief discussion. However, repetition across different design briefs was not controlled in order to improve the reliability of the results by giving less emphasis to features that emerged only in relation to a particular design brief. Thus the amount of segments in a category reflect the amount of distinct ideas expressed by the participant in relation to each of the five design briefs, giving an overall view of all of five the representations.

2.5 Statistical methods

To analyze the reliability of classification, an independent coder re-classified 10% of the segments (interview sections regarding design brief 5). Inter-coder reliability (Cohen's Kappa) was calculated separately for each category. The values of Kappa for all the categories and subcategories ranged from 0.86 to 1, which was considered satisfactory.

A two-tailed Mann-Whitney U-test was used to assess the significance of the differences in the total number of segments in Classes I-IV between experts and novices. The resulting p-values were adjusted for multiple comparisons by the Bonferroni method; i.e., since four pairwise tests were performed, the p values were considered statistically significant if they were smaller than the adjusted alpha of .05/4=.0125.

3 Results

The total amount of segments produced by expert participants ranged from 109 to 297, whereas novices produced 61 to 97 segments in total. No design brief elicited systematically more or less segments from the participants, and, furthermore, the total of segments elicited by each design brief was of similar magnitude. The study did not allow for any conclusive findings on the effect of the presentation order of the design briefs.

On the average, experts produced more segments that novices (34.1 vs. 16.2 per design brief, respectively). Productivity differences became even more marked when segments related to the presentation of the problem (class IV) were considered separately. Segments in classes I to III, identifying needed information, structuring the problem and regarding the solving process, were directly related to the problem at hand, and could be considered as productive, and the experts had higher amounts of segments in each category of these classes (see Table 2). On the other hand, the productivity of evaluating the presentation of the design brief (class IV) was questionable. Experts spent only 13 out of 1192 (1,1%) segments to class IV, whereas novices spent an average of 8.1% of their segments in the class.

Table 2. The number of segments belonging to each class produced by experts and novices.

Class	*Category*	*Average no. of segments (sd)*	
		Experts	*Novices*
I Needed information	1. Missing information	28.6 (15.1)	10.4 (5.1)
	2. Important information	18.9 (8.9)	11.7 (2.7)
	a. feature or quality of the product	4.7 (2.6)	3.9 (3.4)
	b. other information of the product	7.0 (4.9)	7.4 (2.9)
	c. deduced context	8.7 (3.8)	0.4 (0.5)
	3. Outside information	10.3 (10.0)	2.7 (2.1)
	Total	**57.7 (26.7)**	**24.9 (5.9)**
II Problem structuring	4. Definition	12.0 (7.1)	4.0 (4.5)
	a. product	6.9 (4.9)	1.7 (3.3)
	b. project	5.1 (4.9)	2.3 (2.0)
	5. New requirement	7.1 (5.6)	1.6 (1.9)
	6. Sub-goal	3.9 (4.0)	0.9 (1.2)
	7. Initial idea generation	9.4 (10.3)	3.0 (4.2)
	Total	**32.4 (19.2)**	**9.4 (5.5)**
III Process	8. Specific source of information	5.1 (3.4)	0.9 (0.7)
	9. What next	14.7 (6.4)	9.9 (3.1)
	a. generic	6.0 (2.8)	5.3 (2.7)
	b. case-specific	8.7 (5.1)	4.6 (2.1)
	10. Project evaluation	17.4 (14.1)	7.0 (5.6)
	11. Challenges	15.3 (8.3)	8.0 (4.1)
	Total	**52.6 (27.1)**	**25.7 (9.8)**
IV Presentation of the problem	12. Design brief text evaluation	0.7 (1.1)	1.6 (2.)3
	13. Needless information	1.0 (1.8)	2.3 (1.4)
	14. Task clarification questions	0.0 (0.0)	2.7 (2.8)
	Total	**1.7 (2.1)**	**6.6 (5.4)**
Segments in total[1]		**170.3 (65.6)**	**81.1 (12.3)**

[1] including repeated segments and the segments that did not fit the final 14 categories

Class I – Needed information

Experts had an average of 57.7 segments in the first class, identifying needed information, compared to the novice average of 24.9 segments (p=0.004; statistically significant after adjustment for multiple comparisons). The largest category of the class, missing information, contained segments that were questions and identified information as missing or needed in order to continue working on the case, where the participant had an active role in finding the information – as opposed to category 14, which contained questions to which the design brief provider was expected to find the answer. In the missing information category, experts had an average of 28.6 segments (range 13 to 48), whereas novices only had an average of 10.4 segments (range 4 to 17). For example in the case of the half-pipe grinder, the most common items identified as missing by the experts were more specific measurements (E1, E3, E4, E5, and E6), information on the attachment of the device to the operating machine (E1, E2, E3, E5, and E6), information on the half-pipe (E2, E3, and E6) and further information on the content of the mentioned FIS-standard (E1, E4, and E7). The novice segment content was much more limited, but did include some of the questions raised by the experts as well (N3 and N7 on the measurements, N1 and N3 on the attachment, and N1, N6 and N7 on the half-pipe).

In addition to experts producing more segments regarding missing information, a difference in the level of processing could be detected in information explicitly identified as important by the participants (category 2). Experts identified deduced context information as important from 3 to 13 times, while the seven novices made only three such statements in total. For example, expert 3 commented that the most important thing to know in one design brief was that "*it's only in deliberation, the bill, so there isn't yet any defined setting to make it [the electronic polling booth] into*" and in the case of sauna safety solutions that the product was to be made "*to a different use and a different environment, but that it's not... there already exists some kind of technology, so we're not starting from zero*". This can be contrasted to the other two important information subcategories, which contained information on the product or context mentioned already in the design brief. In the case of coffee packages, for example, the most common aspects identified as important in these subcategories were that the price should not increase (E1, E3, E5, E6, N3, and N7), the package should be easy to open (E2, E3, E6, N1, N5, and N6), have good logistical qualities (E3, E6, N1, and N7) and take into account coffee preservation considerations (E6, N1, N6, and N7).

Experts also had a higher average of segments referring to knowledge not included in the design brief, or outside information (10.3 vs. 2.7, category 3). Both novices and experts referred to outside knowledge of the product, its usage and its context – for example voting systems in Finland and elsewhere (N4, N6, E3), and current discussions in Finland about the possibility of voting at home (N7) and the low voting percentage of youth (E6). Both groups also referred to general outside knowledge, such as material prices (N6), design for all principles (N5), software functioning principles (E3) and physics (E5). However, experts also had several references to product development project experiences and utilized knowledge on analogous products instead of just knowledge on the target product and environment: paint tins were compared to coffee packages (E6), chain saws to the half-pipe grinder (E5), electric tooth brushes in wireless charging (E3), and phone booths, flap charts, lecterns and ATMs were drawn on in the case of electronic voting booths (E3, E5, and E6).

Class II – Problem structuring

Experts had more segments than novices on problem structuring (class II, p=.017; not statistically significant after adjustment) and each of the related categories. The most marked difference between novices and experts within the class of problem structuring was found in the number of new requirements identified (category 5): experts had an average of 7.1 new requirements, whereas novices only had an average of 1.6 new requirements. Both experts and novices had physical requirements for the products, such as small size for the wireless charging solution (E1 and E3) and for the sauna safety device (N2 and N6). However, numerous expert requirements were related to the appearance of the product (especially the wireless charging solution; E1, E3, E6, and E7) and to the compatibility of the solution with other products and environments (E1, E2, E3, E6, and E7), whereas the novices produced no such requirements. Furthermore, all of the experts had at least one requirement related to the use or context of the product, such as increasing production speed in the case of coffee packages (E5) and fulfilling snowboard competition requirements in the half-pipe shape (E3), whereas only three novices produced such segments.

Experts had more segments in the largest problem structuring category, defining the problem at hand, producing an average of 12.0 compared to 4.0 segments in category 4. For example, E7 concluded that the electronic polling booth design task was limited to the polling booth (rather than including the electronic voting system), and E5 came to the conclusion that the total system would weigh approximately 50 kilograms. In addition, all experts identified at least one sub-goal (category 6), whereas four novices had no segments in this category. Both experts and novices identified sub-goals that were related to both the product and the project aspects of the design brief, although experts had some sub-goals that were more specific. For example, the E1 would have first determined the required amount of coolant in the sauna safety system, measured the required opening strength and determined an acceptable level in the easy-to-open coffee packages, and aimed to increase the bearing capacity without increasing material amount in the half-pipe grinder. These can be contrasted with the six novice segments in the category: determining what the intelligent system would monitor and what would trigger it in the sauna safety system (N1), designing a new structure (N2) for the half-pipe grinder, and in the case of wireless charging, promoting collaboration with device manufacturers (N1) and mid-size furniture companies (N3), and determining the driving force (e.g. furniture companies, cell phone manufacturers) on the market (N4).

Experts had a higher average of idea generation segments (category 7). There was also a qualitative difference between the experts' idea generation and that of the novice producing the highest amount of idea generation segments, N5. Unlike the experts, N5 did not generate ideas based on the goals and requirements set by the design brief, but from what he felt was a more fruitful viewpoint or goal. Thus whereas he can be said to have engaged in problem structuring in the initial idea generation, the clients' (design brief point-of-view) needs and requirements were not taken into consideration.

Class III – Process

The experts had more process-related segments than the novices (class III, p=.017; not statistically significant after adjustment). Experts identified an average of 5.1 sources for information and potentially needed collaborators (category 8), whereas novices identified either none or only one. Furthermore, the majority of expert segments regarded bringing the input from a variety of product development related professionals: industrial designers (E1, E4, and E7), usability specialists (E4 and E7), electricity-related professionals (E1, E4), interior designers (E3), architects (E3), strength calculators (E6), "machinery people" (E4), engineers (E6) and a expert in electronic safety systems (E6). The novices, on the other hand, did not refer to any other development specialists, but both experts and novices would have consulted stakeholders related to the manufacturing (N6, E1, and E3), and the use of the product (N2, N3, and E5). A few references were also made to other outside information sources in both groups – insurance companies (E2), rescue departments (E2), machine design standards (E4) and sauna fire case reports (E7) in the case of experts, and voting laws in the case of novices (N3 and N7).

The experts identified an average of 15.2 challenges that they might encounter in the project proposed by the design brief, compared to the average of 8 challenges identified by novices. As in the information identified as important, indication of differences in the level of processing could be detected in the identified challenges. The novice-identified challenges were directly related to the design problem and the context, such as compatibility with different saunas (N1), rough weather-conditions (N2), gaining partners (N3), and changing a highly optimized process without changing anything (N5), types of challenges that were also found in the expert segments. However, all experts had also challenges resulting from the consequences of development requirements or scope decisions, such as "*if you try to make a version [of the electronic polling booth] for the bus, it probably would require a detachable bottom or else, that you would need to be able to unfasten parts, but that easily makes it [the solution] too complicated*". The novices had no such statements.

A similar difference in processing level could also be detected in how to proceed with the projects: the experts were more customized in their proposed proceedings (subcategory 9b). For example, E5 would have gathered a bunch of batteries and familiarized himself with them in the case of wireless charging, whereas the more general subcategory 9a included more vague plans such as checking out competitors (N1, N3, N4 and N6).

Class IV – Presentation of the problem

Unlike in the previous three classes, novices produced more segments regarding the presentation of the development problem than experts (class IV, p=.026; not statistically significant after adjustment). The experts had no task clarification questions (category 14), whereas all but one novice had at least one, and up to eight, segments. One task clarification question was targeted at the electronic voting booth (N5), four questions were targeted at the sauna safety solution (N5 and N7) and wireless charging solution (N4, N5, and N7), each, and five questions were targeted at both the half-pipe grinder (N4, N5 and N6) and the coffee package design brief (N2, N3, N4, and N7). The questions were targeted towards the nature and extent of the desired solution and to the relative priorities of the expressed requests, for example that the design brief had "*requirements in so many directions, so they could express a lot better, that what are the most relevant things and which are less relevant*" (N6), and "*what is the most biggest problem, is it the opening or the re-closing, or is it that the vacuum can break and the coffee goes bad, which one of them is the most important [problem]*" (N2).

Novices also had a higher average of segments evaluating the design brief presentation and explicitly identifying irrelevant information (categories 12 and 13). Only three experts and three novices offered an evaluation of the design brief texts (category 12), and these segments were mainly targeted at the design briefs of the sauna safety solution, the coffee package and the wireless charging solution (each receiving four mentions). The experts criticized the informal tone of the sauna safety solution (E5), and the tone and terminology of the wireless charging solution (E6 and E7). The novices, on the other hand, produced some evaluating segments in relation each design brief, criticizing for example their emphasis on background information (N7) and poor structure (N5 and N6). The novices also found something needless (category 13) in each design brief, typically too detailed information. The majority of segments were related to the electronic voting booth, sauna safety solution and wireless charging solutions. Expert 5 found a few details in the voting booth and sauna safety solution needless, and would have preferred more requirement information related to the products themselves, and several novices found needless information in these design briefs as well (N2, N3, N4 and N7). Experts 3 and 4 on the other hand found the wireless charging solution design brief to present too much background information, and novices N3, N5 and N7 felt the design brief presented self-evident information.

4 Discussion

Representations have a key role in design, and learning to construct, interpret and use different types of representations is an essential part of design education (Visser, 2006, 225). As expertise can be achieved through deliberate practice (Ericsson & Lehmann, 1996), differences in how expert product developers and shortly graduating product development students approach problems can provide useful guidance for training in both educational institutes and organizations. Identifying underlying cognitive processes and skills allows targeting deliberate practice efforts, and new problem solving strategies can improve mental problem representations (Alibali, Ockuly & Fischer, 2009). Meta-cognitive strategies (Cohen, Freeman & Thompson, 1997), critical cues (Klein & Wolf, 1995) and studying expert problem solving cognitions (Abernathy & Hamm, 1995) can also assist novices in their development towards expertise. Aiming to explore differences in the mental representations of real product development problems, the design brief interpretations of seven experts and seven novices were investigated in this study. While the limited amount and type of participants and design tasks utilized in the study certainly cautions against freely generalizing the results across different fields, the novel and resource-efficient task was able to reveal several differences between the experts and novices.

The results suggest that product development experts do indeed view problems as harder than novices (Cross, 2004), in the sense that experts reported needing more information in order to tackle the presented problems successfully. As could be expected (Kavakli & Gero, 2001, 2002), the experts were more productive, producing much higer amounts of segments than novices, even though both groups were promted by the exact same stimuli. In addition to sheer volume differences, the expert segments also demonstrated more depth and width in the scope of their mental representations. The experts perceived a wider range of requirements and drew from a wider range of outside information in their reflections. Previous studies suggest that such differences begin to manifest early on in the learning process, as already more experienced design students cover a larger portion of the problem-definition space and use more information (e.g. Adams, Turns & Atman, 2003; Atman, *et al*., 1999; Popovic, 2004).

In fact, the results indicate that experts accommodate for a higher degree of interconnections both within the mental representations and between the problem representations and outside knowledge. The experts reported deduced context information as highly significant for solving the problems, and identified challenges resulting from the scope and requirement decisions of the design briefs (i.e. making interconnections within the problem information). Furthermore, only experts were found to utilize infromation from previous projects and analogous products, novices were limited to the target product context in connecting the problem at hand to previous knowledge. These results concur with previous design studies reporting increased awareness of contextual constraints (Eteläpelto, 2000), and utilization of previous and analogous experiences (Ahmed, Wallace & Blessing, 2003; Ball, Ormerod & Morley, 2004; Cross, 2004a; Visser, 1995) in the design problem solving processes of experts. The findings of this study suggests that a possible source for the observed differences in the depth and detail lies in more developed relevancy perceptions and perceptions of interconnections in the problem representations of design experts. As relevancy perceptions involve judging the importance of a piece of information, evaluating how promising the implied direction is (Bereiter & Scardamalia, 1993) and choosing the appropriate level of abstraction that should be utilized in solving the problem (Feltovich, Prietula & Ericsson, 2006), they can determine which pieces of information seem connected to eachother. Similar findings of the importance of interconnections have been obtained by Randel, Pugh and Reed (1996) in the field of electronic warfare, noting that while low and high performers did not significantly differ in the considered cues, knowledge and imagery, the more skilled participants "put these elements together" or integrated them in a superior manner. As previous research has demonstrated mental problem representations to be influenced by strategies and actions taken during the problem solving process (Alibali, Ockuly & Fischer, 2009; Dixon & Boncoddo, 2009), explicitly instructing novice product developers to pay more attention to the interconnections, consequences and context of the problem as a meta-cognitive strategy (Cohen, Freeman & Thompson, 1997) might help them to develop more effective mental problem representations.

Furthermore, the findings also indicate that experts are able to identify more points of leverage for solving the design problems. The experts created more numerous and specific sub-goals, as well as more specific and customized plans for proceeding with the problem solving. They also utilized a wider array of outside information sources, and frequently reported that they would consult or collaborate with other development professionals in specific matters of the project (the importance of which Visser, 1995, has demonstrated in the actual process of expert design problem solving). Indeed, the experts seemed to be much more attuned to the information needs they would face in subsequent solving efforts and how to tackle these needs. In addition, the experts restricted their efforts towards solving the problem, i.e. productive work, whereas novices spent a proportion of their already more limited activity on evaluating the presentation of the problem. Similar results on the focus of activity have been previously obtained in software design, where moderate performers produce more task-irrelevant cognitions than high performers (Sonnentag, 1998). Finally, only novices seemed to demand ready answers for their questions from the clients, whereas experts saw themselves as having more active roles in seeking the needed information, identifying both more information needs and more information sources.

Previous research in other fields has demonstrated experts to be more active in information gathering (Prince & Salas, 1998) and situational awareness (Endsley,

2006) in the actual problem solving process, and the passive-active distinction can also be found in learning foci (Cleary & Zimmerman, 2001). The results of this study demonstrate a more proactive stance towards the problem solving process already in the mental problem representation and structuring stage. As little is known about the role of knowledge, skills and abilities in proactive behavior (Grant & Ashford, 2008; Crant, 2000), such a finding is a significant one. The mental representation of the problem has key implications for subsequent action, as more comprehensive mental representation of the problem at hand increases the likelihood of proactive behavior via increasing the amount of identified options and opportunities. As more advanced mental representations allow high performers to identify better points of leverage and to target their efforts toward more fruitful actions, they can also favorably affect the the impact of any pursued proactive behavior. This can produce a virtuous cycle of increasing proactivity where initial success further encourages more proactive behavior, as self-efficacy, the belief in the successful impact of one's efforts, has been found to be an important antecedent for proactive behavior (Grant & Ashford, 2008; Parker, Williams & Turner, 2006; Frese, Garst & Fay, 2007; Frese & Fay, 2001). While further experiments with larger participant sample sizes will provide valuable insights regarding the magnitude and statistical significance of the observed expert-novice differences, the present results suggest that not only do better initial mental problem representations have a direct impact on development expertise, but they also promote successful problem solving via increased proactivity. On the other hand, the frequent passiveness demonstrated by novices should be alarming for educators aiming to train successful professionals, as proactivity is becoming a key requirement of working life in any field, and particularly in creative domains such as design.

5 Conclusions

The difficulty of solving ill-structured design problems often lies in operationalizing the initially vague problem and creating fruitful problem solving actions. Although there is widespread agreement on the significance of the initial mental representation or successfully framing of the problem on subsequent performance, little is yet known about mental representations in product development. Furthermore, much research on product development problem solving has been based on studying the behavior of design students or, at best, individual designers (Cross, 2003; Cross, 2004b; Defazio, 2008). This study addresses the gap in knowledge by exploring the differences in initial mental problem representations and reflections on real-life product development problems between advanced product development students and recommended, professional product development experts. The results reveal that experts have superior extent, depth and detail in their representations, accommodate for more interconnections both within the problem information and between the problem and previous knowledge, and approach the problem in a more proactive manner. Design experts seem to perceive both more information needs and more information sources relevant to the problem at hand. Thus the results of this study indicate that forming comprehensive mental representations based on wide relevancy perceptions should be considered as a performance and proactivity enhancer in design along with previously identified cognitive-motivational issues. Especially accommodating for interconnections in the mental representations offers a promising venue for further research on promoting product development expertise and proactivity in solving product development problems – in other words, increasing both the capability to address professional problems successfully, and the tendency to act on these capabilities.

References

Abernathy, C.M. & Hamm, R.M. (1995). *Surgical intuition: What it is and how to get it*. Philadelphia: Hanley & Belfus.

Adams, R.S, Turns, J. & Atman, C.J. (2003). Educating effective engineering designers: The role of reflective practice. *Design Studies,* 24(3), 275-294.

Ahmed, S., Wallace, K.M. & Blessing, L.T.M. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design,* 14*,* 1-11.

Akin, M. (1990). Necessary conditions for design expertise and creativity. *Design Studies,* 11(2), 107-113.

Alibali, M.W., Phillips, K.M.O. & Fischer, A.D. (2009). Learning new problem-solving strategies leads to changes in problem representation. *Cognitive Development,* 24, 89-101.

Atman, C.J., Chimka, J., Bursic, K.M. & Nachtmann, H.L. (1999). A comparison of freshman and senior engineering design processes. *Design Studies*, 20, 131-152.

Baer, M. & Frese, M. (2003). Innovation is not enough: climates for initiative and psychological safety, process innovations, and firm performance. *Journal of Organizational Behavior,* 24*,* 45-68.

Ball, L.J., Evans, J. St. B.T., Dennis, I. & Ormerod, T.C. (1997). Problem-solving strategies and expertise in engineering design. *Thinking & Reasoning,* 3, 247-270.

Ball, L.J., Ormerod, T.C. & Morley, N.J. (2004). Spontaneous analogising in engineering design: a comparative analysis of experts and novices. *Design Studies,* 25*,* 495-508.

Bateman, T.S. & Crant, J.M. (1993). The proactive component of organizational behavior. *Journal of Organizational Behavior*, 14, 103–118.

Beckman, S.L. & Barry, M. (2007). Innovation as a learning process: Embedding design thinking. *California Management Review*, 50(1), 25-56.

Bereiter, C. & Scardamalia, M. (1993). *Surpassing ourselves. An inquiry into the nature and implications of expertise*. Chicago: Open Court.

Bickhard, M.H. (2001). Why children don't have to solve the frame problems: cognitive representations are not encodings. *Developmental Review*, 21, 224-262.

Binnewies, C., Ohly, S., & Sonnentag, S. (2007). Taking personal initiative and communicating about ideas: What is important for the creative process and for idea creativity? *European Journal of Work and Organizational Psychology,* 16(4), 432-455.

Bläsing, B., Tenenbaum, G. & Schack, T. (2009). The cognitive structure of movements in classical dance. *Psychology of Sport and Exercise*, 10, 350-360.

Bryant, A. & Charmaz, K. (2007). Introduction grounded theory research: Methods and practices. In A. Bryant & K. Charmaz (Eds.), *The Sage Handbook of Grounded Theory* (pp. 1-28). Thousand Oaks: Sage Publications.

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues*, 8(2), 5-21.

Carvalho, P.V.R., dos Santos, I.L., & Vidal, M.C.R. (2005). Nuclear power plant shift supervisor's decision making during microincidents. *International Journal of Industrial Ergonomics,* 35, 619-644.

Chakrabarti, A., Morgenstern, S., & Knaab, H. (2004). Identification and application of requirements and their impact on the design process: a protocol study. *Research in Engineering Design*, 15(1), 22-39.

Charness, N. (1976). Memory for chess positions: resistance to interference. *Journal of Experimental Psychology: Human Learning and Memory,* 2, 641-653.

Chase, W.G. & Simon, H.A. (1973). The mind's eye in chess. In W.G. Chase (Ed.): *Visual Information Processing* (pp. 215-308). New York: Academic Press.

Chi, M.T.H. (1997). Quantifying qualitative analyses of verbal data: a practical guide. *Journal of the Learning Sciences*, 6, 271-315.

Chi, M.T.H. (2006). Laboratory methods for assessing experts' and novices' knowledge. In K.A. Ericsson, N. Charness, P.J. Feltovich & R.R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.167-184). New York: Cambridge University Press.

Chi, M.T.H., Feltovich, P.J. & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121-152.

Chi, M.T.H., Glaser, R. & Farr, M.J. (Eds.) (1988). *The nature of expertise*. Hillsdale, NJ: Erlbaum.

Christiaans, H. & Dorst, C. (1992). Cognitive models in industrial design engineering: a protocol study. In D.L. Taylor & D.A. Stauffer (eds.): *Design Theory and Methodology -DTM92*. New York: American Society of Mechanical Engineers.

Cleary, T.J. & Zimmerman, B.J. (2001). Self-regulation differences during athletic practice by experts, non-experts, and novices. *Journal of Applied Sport Psychology,* 13, 185-206.

Cohen, M.S., Freeman, J.T., & Thompson, B.B. (1997). Training the naturalistic decision maker. In C. Zsambok & G. Klein (Eds.), *Naturalistic decision making* (pp.57-268). Mahwah, NJ: Lawrence Erlbaum Associates Inc.

Coley, F., Houseman, O. & Roy, R. (2007). An introduction to capturing and understanding the cognitive behaviour of design engineers. *Journal of Engineering Design,* 18(4), 311-325.

Cooke, N.J. (1994). Varieties of knowledge elicitation techniques. *International Journal of Human-Computer Studies,* 41, 801-849.

Cooke, N.J. (1999) Knowledge elicitation. In FT Durso, R.S. Nickerson, R.W. Schvaneveldt, S.T. Dumais, D.S. Lindsay & M.T.H. Chi (Eds.), *Handbook of Applied Cognition* (pp.479-509). Chichester: John Wiley & Sons.

Crakett, R. (2004). 'He's different, he's got 'Star Trek' vision': supporting the expertise of conceptual design engineers. *Design Studies,* 25, 459-475

Crant, J.M. (2000). Proactive behavior in organizations. *Journal of Management,* 26(3), 435-462.

Cross, N. (2003). The expertise of exceptional designers. In N. Cross and E. Edmonds (Eds.), *Expertise in Design* (pp.23-35). Sydney, Australia: Creativity and Cognition Press, University of Technology, Sydney.

Cross, N. (2004a). Creative thinking by expert designers. *Journal of Design Research*, 4. DOI: 10.1504/JDR.2004.009839

Cross, N. (2004b). Expertise in design: an overview. *Design Studies,* 25, 427–441.

Cross, N. (2007). *Designerly Ways of Knowing*. Basel, Switzerland: Birkhauser.

Cross, N., Christiaans, H. & Dorst, K. (1994). Design expertise amongst student designers. *Journal of Art and Design Education*, 13, 39-56.

Cross, N. & Clayburn Cross, A. (1998). Expertise in engineering design. *Research in Engineering Design,* 10, 141-149.

De Groot, A.D. (1946/1978). *Thought and choice in chess*. Oxford, England: Mouton (2nd ed.). Originally published 1946.

De Groot, A.D. & Gobet, F. (1996). *Perception and memory in chess: Heuristics of the professional eye*. Assen: Van Gorcum.

Defazio, J. (2008). The identification of design experts. *Journal of Design Research, 1*, 84-96.

Dixon, J.A. & Boncoddo, R. (2009). Strategies and problem representations: Implications for models of changing cognitive structures. Commentary on "Learning new problem-solving strategies leads to changes in problem representation" by M.W. Alibali, K.M. Ockuly and A.D. Fischer. *Cognitive Development,* 24, 102-105.

Dorst, K. (1996). The design problem and its structure. In N. Cross, H. Christiaans & K. Dorst (Eds.), *Analysing Design Activity* (pp.15-34). Cichester, England: Wiley.

Dorst, K. (2006). Design problems and design paradoxes. *Design Issues,* 22(3), 4-17.

Dorst, K. (2011). The core of 'design thinking' and its application, *Design Studies*, 32(6), 521-532.

Dorst, K. & Cross, N. (2001). Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 22, 425-437.

Drews, C. (2009). Unleashing the full potential of design thinking as a business method. *Design Management Review*, 20(3), 39-44.

Elo, A. E. (1978). *The rating of chess players past and present*. New York: Arco.

Endsley, M.R. (2006). Expertise and situation awareness. In K.A. Ericsson, N. Charness, P.J. Feltovich & R.R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.633-651). New York: Cambridge University Press.

Ericsson, K.A. (2003). The search for general abilities and basic capacities: theoretical implications from the modifiability and complexity of mechanisms mediating expert performance. In R.J. Steinberg & E.L. Grigorenko (Eds.), *The psychology of abilities, competencies and expertise* (pp. 93–125). New York, NY: Cambridge University Press.

Ericsson, K.A. (2006a). Protocol analysis and expert thought: Concurrent verbalizations of thinking during experts' performance on representative task. In K. A. Ericsson, N. Charness, P. Feltovich, and R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.223-242). New York: Cambridge University Press.

Ericsson, K.A. (2006b). The influence of experience and deliberate practice on the development of superior expert performance. In K. A. Ericsson, N. Charness, P. J. Feltovich & R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.683-703). New York: Cambridge University Press.

Ericsson, K. A., Charness, N., Feltovich, P. & Hoffman, R. R. (Eds.) (2006). *The Cambridge Handbook of Expertise and Expert Performance*. New York: Cambridge University Press.

Ericsson, K.A. & Lehmann, A.C. (1996). Expert and exceptional performance: Evidence of maximal adaptation to task constraints. *Annual Review of Psychology,* 47, 273-305.

Ericsson, K.A., & Simon, H.A. (1993). *Protocol analysis: Verbal reports as data.* Cambridge, MA: Bradfordbooks/MIT Press. Revised edition.

Ericsson, K.A. & Smith, J. (1991). Prospects and limits in the empirical study of expertise. In K. A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise: Prospects and Limits* (pp.1-38). Cambridge: Cambridge University Press.

Eteläpelto, A. (2000). Contextual and strategic knowledge in the acquisition of design expertise. *Learning and Instruction,* 10, 113–136

Feltovich, P.J., Johnson, P.E., Moller, J. & Swanson, D. (1984). The role and development of medical knowledge in diagnostic reasoning. In W. Clancey & E. Shortliffe (Eds.), *Readings in medical artificial intelligence: The first decade* (pp. 275-319). Reading, MA: Addison Wesley.

Feltovich, P.J., Prietula, M.J. & Ericsson, K.A. (2006). Studies of expertise from psychological perspectives. In K. A. Ericsson, N. Charness, P. J. Feltovich & R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.41-67). New York: Cambridge University Press.

Frese, M. & Fay, D. (2001). Personal initiative: An active performance concept for work in the 21st century. *Research in Organizational Behavior,* 23, 133-187.

Frese, M., Garst, H. & Fay, D. (2007). Making things happen: Reciprocal relationships between work characteristics and personal initiative in a four-wave longitudinal structural equation model. *Journal of Applied Psychology,* 92, 1084-1102.

Frese, M., Krauss, S., Keith, N., Escher, S., Grabarkiewicz, R., Luneng, S., Heers, C., Unger, J., & Friedrich, C. (2007). Business owners' action planning and its relationship to business success in three African countries. *Journal of Applied Psychology,* 92, 1481-1498.

Frese, M., Teng, E., & Wijnen, C.J.D. (1999). Helping to improve suggestion systems: Predictors of making suggestions in companies. *Journal of Organizational Behavior,* 20*,* 1139-1155.

Gero, J.S. (1990). Design prototypes: A knowledge representation schema for design. *AI Magazine,* 11(4), 26-36.

Getzels, J.W. (1975). Problem-finding and inventiveness of solutions. *Journal of Creative Behavior*, 9, 12-18.

Getzels, J.W. (1979). Problem finding: A theoretical note. *Cognitive Science*, 3(2), 167-172.

Gobet, F., Lane, P.C.R., Croker, S., Cheng, P.C.-H., Jones, G., Oliver, I. & Pine, J.M. (2001). Chunking mechanisms in human learning. *TRENDS in Cognitive Sciences,* 5(6), 236-243.

Goel, V. & Pirolli. P. (1992). The structure of design problem spaces. *Cognitive Science,* 16, 395-429.

Grant, A.M. & Ashford, S.J. (2008). The dynamics of proactivity at work. *Research in Organizational Behavior*, 28, 3-34.

Hargadon, A.B. & Bechky, B.A. (2006). When collections of creatives become creative collectives: A field study of problem solving at work. *Organization Science*, 17(4), 484-500.

Hershey, D.A., Walsh, D.A., Read, S.J. & Chulef, A.S. (1990). The effects of expertise on financial problem solving: Evidence for goal-directed, problem-solving scripts. *Organizational Behavior and Human Decision Processes,* 46, 77-101.

Hey, J.H.G., Joyce, C.K. & Beckman, S.L. (2007). Framing innovation: Negotiating shared frames during early design phases. *Journal of Design Research*, 6(1–2), 79-99.

Ho, C.-H. (2001). Some phenomena of problem decomposition strategy for design thinking: differences between novices and experts. *Design Studies,* 22, 27-45.

Hoffman, R.R., Shadbolt, N.R., Burton, A.M. & Klein, G. (1995). Eliciting knowledge from experts: A methodological analysis. *Organizational Behavior and Human Decision Processes*, 62(2), 129-158.

Houseman, O., Coley, F. & Roy, R. (2008). Comparing the cognitive actions of design engineers and cost estimators. *Journal of Engineering Design,* 19(2), 145-158.

Johnson, P.E., Duran, A.S., Hassebrock, F., Moller, J., Prietula, M.J., Feltovich, P.J. & Swanson, D. B. (1981). Expertise and error in diagnostic reasoning. *Cognitive Science*, 5, 235-283.

Joseph, G.-M. & Patel, V.L. (1990). Domain knowledge and hypothesis generation in diagnostic reasoning. *Medical Decision Making,* 10, 31-46.

Kavakli, M. & Gero, J.S. (2001). Strategic knowledge differences between an expert and a novice. In J.S. Gero & K. Hori (Eds.), *Strategic knowledge and concept formation III* (pp.55-68). Sydney: Key Centre of Design Computing and Cognition, University of Sydney, Australia.

Kavakli, M. & Gero, J.S. (2002). The structure of concurrent cognitive actions: a case study on novice and expert designers. *Design Studies*, 23, 25-40.

Klein, G. (1997a). Developing expertise in decision making. *Thinking and Reasoning,* 3(4), 337-352.

Klein, G. (1997b). The recognition-primed decision (RPD) model: Looking back, looking forward. In C.E. Zsambok & G. Klein (Eds.), *Naturalistic decision making* (pp.285-292). Mahwah, NJ: Lawrence Erlbaum Associates Inc.

Klein, G. (1998). *Sources of power*. Cambridge, Massachusetts: MIT Press.

Klein, G., Calderwood, R., Clinton-Cirocco, A. (1989). Rapid decisionmaking on the fireground. *Proceedings, Human Factors and Ergonomics Society 30th Annual Meeting*, Dayton, Ohio 1, 576-80.

Klein, G., Calderwood, R. & MacGregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on Systems, Man, and Cybernetics,* 19(3), 462-472.

Klein, G., & Wolf, S. (1995). Decision-centered training. *Proceedings of the 39th Annual Meeting of the Human Factors and Ergonomics Society,* San Diego, CA. Human Factors and Ergonomics Society, Inc: Santa Monica, CA.

Klein, G., Wolf, S., Militello, L. & Zsambok, C. (1995). Characteristics of skilled option generation in chess. *Organizational Behavior and Human Decision Processes,* 62, 63-69.

Kolodner, J.L. & Wills, L.M. (1996). Powers of observation in creative design. *Design Studies*, 17, 385-416.

Koop, S., De Reu, T., & Frese, M. (2000). Sociodemographic factors, entrepreneurial orientation, personal initiative, and environmental problems in Uganda. In M. Frese (Ed.), *Success and failure of microbusiness owners in Africa: A psychological approach* (pp.55-76). Westport, CT: Quorum.

Kushniruk, A.W., Patel, V.L., & Fleiszer, D.M. (1995). Complex decision making in providing surgical intensive care. *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society* (pp. 287-292). Hillsdale, NJ: Lawrence Erlbaum.

Lawson, B. (1979). Cognitive strategies in architectural design. *Ergonomics,* 22, 59-68.

Lawson, B. (2004). Schemata, gambits and precedent: Some factors in design expertise. *Design Studies*, 25(5), 443-457.

Lawson, B. & Dorst. K. (2009). *Design expertise*. Oxford, UK: Architectural Press.

Lesgold, A., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., & Wang, Y. (1988). Expertise in a complex skill: Diagnosing X-ray pictures. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp.311-342). Hillsdale, NJ: Erlbaum.

McKeithen, K.B., Reitman, J.S., Reuter, H.H. & Hirtle, S.C. (1981). Knowledge organization and skill differences in computer programmers. *Cognitive Psychology,* 13, 301-325.

Ohly, S., Sonnentag, S. & Pluntke, F. (2006). Routinization, work characteristics and their relationships with creative and proactive behaviors. *Journal of Organizational Behavior,* 27, 257-279.

Parker, S.K., Williams, H.M. & Turner, N. (2006). Modeling the antecedents of proactive behavior at work. *Journal of Applied Psychology,* 91*,* 636-652.

Patel, V.L., Kaufman, D.R, & Arocha, J.F. (2002). Emerging paradigms of cognition in medical decision-making. *Journal of Biomedical Informatics*, 35, 52-75.

Paton B. & Dorst K. (2010). Briefing and Reframing. In K. Dorst, S. Stewart, I. Staudinger, B. Paton & A. Dong (eds.): *DTRS8 Interpreting Design Thinking – Symposium Proceedings* (pp. 317-336). Sydney, Australia: DAB Documents, University of Technology Sydney, Australia. ISBN 978-0-9808622-2-5.

Petre, M. (2004). How expert engineering teams use disciplines of innovation. *Design Studies*, 25, 477-493.

Popovic, V. (2004). Expertise development in product design - strategic and domain-specific knowledge connections. *Design Studies*, 25, 527-545.

Prince, C., & Salas, E. (1998). Situation assessment for routine flight and decision making. *International Journal of Cognitive Ergonomics*, 1, 315-324.

Randel, J.M., Pugh, H.L. & Reed, S.K. (1996). Differences in expert and novice situation awareness in naturalistic decision making. *International Journal of Human – Computer Studies, 45,* 579-597.

Reitman, W. R. (1965). *Cognition and thought*. New York: Wiley.

Rittel, H. & Webber, M. (1973). Dilemmas in a general theory of planning. *Policy Sciences,* 4, 155-169.

Rittle-Johnson, B., Siegler, R.S. & Alibali, M.W. (2001). Developing conceptual understanding and procedural skill in mathematics: An interactive process. *Journal of Educational Psychology,* 93, 346-362.

Rowe, R.M. & McKenna, F.P. (2001). Skilled anticipation in real-world tasks: Measurement of attentional demands in the domain of tennis, *Journal of Experimental Psychology: Applied,* 7(1), 60-67.

Saariluoma, P. (1985). Chess players' intake of task-relevant cues. *Memory & Cognition,* 13, 385- 391.

Schank, R., & Abelson, R.P. (1977). *Scripts, Plans, Goals, and Understanding: An Inquiry into Human Knowledge Structures*. Hillsdale, NJ: Lawrence Erlbaum.

Schunn, C.D., McGregor, M.U. & Saner, L.D. (2005). Expertise in ill-defined problem- solving domains as effective strategy use. *Memory & Cognition,* 33, 1377-1387.

Schön, D. (1983). *The Reflective Practitioner: How Professionals Think in Action*. London: Basic Books Inc.

Schön, D.A. & Wiggins, G. (1992). Kinds of seeing and their function in designing. *Design Studies*, 13(2), 135-56.

Seibert, S.E., Crant, J. M., & Kraimer, M. L. (1999). Proactive personality and career success. *Journal of Applied Psychology,* 84, 416-427.

Seibert, S.E., Kraimer, M.L. & Crant, M.J. (2001). What do proactive people do? A longitudinal model linking proactive personality and career success. *Personnel Psychology,* 54, 845-874.

Shaw, M. L. G., & Woodward, J. B. (1990). Modeling expert knowledge. *Knowledge Acquisition*, 2, 179-206.

Siegler, R.S. (1976). Three aspects of cognitive development. *Cognitive Psychology*, 8, 481-520.

Simon, H.A. (1973). The structure of ill structured problems. *Artificial Intelligence,* 4, 181-201.

Smyth, M.M. & Pendelton, L.R. (1994). Memory for movement in professional ballet dancers. *International Journal of Sport Psychology*, 25, 282-294.

Sonnentag, S. (1998). Expertise in professional software design: A process study. *Journal of Applied Psychology,* 83, 703-715.

Starkes, J.L., Deakin, J.M., Lindley, S. & Crisp, F. (1987). Motor versus verbal recall of ballet sequences by young expert dancers. *Journal of Sport Psychology*, 9, 222-230.

Suwa, M., Gero, J. & Purcell, T. (2000). Unexpected discoveries and S-invention of design requirements: important vehicles for a design process *Design Studies*, 21, 539-567.

Valkenburg, A. & Dorst, K. (1998). The reflective practice of design teams. *Design Studies*, 19, 249-271.

Walz, D. B., Elan, J. J., & Curtis, B. (1993). Inside a software design team: knowledge acquisition, sharing, and interaction. *Communications of the ACM*, 36(10), 63-77.

Visser, W. (1995). Use of episodic knowledge and information in design problem solving. *Design Studies*, 16(2), 171-187.

Visser, W. (2006). *The cognitive artifacts of design*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

Zannier, C., Chiasson, M. & Maurer, F. (2007). A model of design decision making based on empirical results of interviews with software designers. *Information and Software Technology,* 49, 637-653.