An Exploration of the cognitive processes of design teams to inform design education and practice

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Abstract

While design is associated with novelty and creativity, few studies have explored the cognitive processes employed during team interactions. Design practice is collaborative where designers work in multidisciplinary teams. Along with the cognitive skills involved in designing, designers also need skills to work in teams, share information, and negotiate decisions. The aim of this study is to understand the cognitive processes used by design teams during the early phases of product design. This study uses case studies and applies content analysis to examine the conversations of design teams during the problem definition, ideation, and concept development phases of the design process. Creativity has been described in terms of sudden bursts of ideas described as creative leaps and is associated with creative thinking. The findings in this study shows that while creative thinking is essential to creative teams, other cognitive modes such as knowledge processing, critical thinking, and metacognition are engaged in more frequently. The emphasis of each cognitive process also varies depending on the phase of the design process. These findings have implications for how design students are educated, the skills required and how we promote creativity in design teams.

Keywords

Cognitive processes, creative thinking, critical thinking, metacognition, knowledge processing, design

Background

Creativity is the driver of competitive advantage within organizations to stay ahead of competitors (Parjanen, 2012). While being focused on creativity, contemporary design practice demands collaborative problem-solving skills, made up of critical thinking, creativity and communication (Tang et al., 2020). The front end of product design is typically considered to be highly creative (Bowen et al., 2016; D'souza & Dastmalchi, 2016; Guo et al., 2017). Many problems faced by designers are ill defined and involve techniques beyond what is achievable by one discipline so are typically solved by interdisciplinary teams (Cross, 2006; Jonassen & Hung, 2008). Recently, team design processes have gained greater attention and have focused on the social aspect of design (Bucciarelli, 1994) and on the analysis of language in design, for example, (Dong et al., 2005; Dong et al., 2013; Lloyd, 2000).

In design education, studios provide an important environment for collaborative learning where students learn to experiment and work together, using each other as a resource to iteratively generate and refine design solutions (McMahon & Kiernan, 2011; Park, 2020). Students also experience collaboration through periodic reviews known as critiques with both tutors and other group members (Gunday Gul & Afacan, 2018). However while there are efforts to provide collaborative projects both within and outside of the design studio, there is no agreed approach on how interdisciplinary teamwork should be implemented (Chou & Wong, 2015; Kiernan & Ledwith, 2014) facilitated or assessed within design education (Self & Baek, 2017). Newell and Bain (2020) found that while collaboration and teamwork is recognised as being important in design education, many design educators were not knowledgeable of the cognitive and social skills required or the structures and processes necessary to facilitate collaborative team practice.

Chou and Wong (2015) argue that design education must facilitate dialogue to encourage knowledge sharing and experience, to solve more complex design challenges and generate holistic solutions. However, the management of dialogue has had limited focus in education (Mercer and Littleton 2007). Examples of such studies are; an analysis and comparison of the conversation activities between experts and novice design teams, (Kiernan et al., 2020), a framework developed by Xun and Land (2004) using question prompts to promote peer interaction and a scaffolding discourse developed by Ferreira and Lacerda dos Santos (2009) to facilitate collaboration in design projects. However the study by Ferreira and Lacerda dos Santos (2009) showed that when students interact the dialogue is not necessarily constructive. Even when the discourse is effective students are unable to repeat the strategies as they do not readily recognise the elements of the discourse that were effective (Fredrick 2008). Park (2020) argues that a strategically designed studio structure combined with collaboration strategies are essential to give students successful learning experiences.

To develop effective approaches to team engagement, educators will need to be able to assess the collaboration process. This in turn means that the conversations and interactions of teams will require greater attention. This study explores the conversations of creative design teams to understand the cognitive processes employed by design teams and how they are engaged with, over three phases of the design process.

The cognitive processes in design teams

Three phases of the front end of design were defined for this study in line with the Design Council's model (Design-Council, 2007): problem definition, ideation and concept development. The problem definition phase involves identifying and researching an opportunity or problem, structuring research data, problem framing and creating patterns from the data that suggest solution directions (Cross, 2011). The ideation phase is focused on creating a breadth of ideas. Ideation is associated with divergent thinking with a wide search across categories of knowledge to explore new ideas (Ferreira & Lacerda dos Santos, 2009; Zhang et al., 2015). At the concept development phase the focus is to narrow the solution options with the comparative analysis and evaluation of solutions (Ulrich et al., 2011).

Group creativity can be defined as the series of interactions, knowledge exchanges and negotiations that lead to new ideas (Parjanen, 2012). While design has been associated with creativity, creativity demands not only divergent thinking, but also convergent thinking (Goldschmidt, 2016). Dong (2007) and Ferreira and Lacerda dos Santos (2009) describes how coherent design concepts come about through cycles of convergent and divergent thinking to create and then analyse and select ideas. Lipman (1989) argues that complex thinking is a combination of critical and creative thinking. He believes that both are embedded in the other and that creative thinking involves critical judgments, while critical thinking involves creative judgments. In building on the convergent and divergent aspects of design, Pacheco and Herrera

(2021) propose that there are three main cognitive processes involved in complex thinking: critical thinking, creative thinking, and metacognition. Further to this Kiernan et al. (2020) include a fourth cognitive process in the form of knowledge processing as interdisciplinary teams require the sharing and the processing of relevant information to the task at hand.

Design is solution oriented and therefore relies on both creative (divergent) and critical thinking (convergent) (Cross, 2006; Dorst, 2011). Design problem-solving, also requires metacognition to reflect on the appropriateness of the knowledge and strategies used to reach the project goals (Andres, 2013; Jonassen, 1997; van Ginkel et al., 2009). The collaborative nature of design requires knowledge processing in the sharing and integration of knowledge (Kleinsmann et al., 2012; McDonnell, 2009). Whilst acknowledging that the processes discussed below are not the only processes, they are central and therefore the focus of this paper. These four cognitive processes are described below.

Creative thinking

Creativity is the novelty and usefulness of ideas regarding products processes and services (Chulvi et al., 2012; Zhou & Shalley, 2011). Creative thinking has been defined as the ability to think divergently and generate several original ideas or solutions (Casakin et al., 2010; Goldschmidt & Tatsa, 2005) and encourages ideas that challenge the status quo (Hatchuel et al., 2017). It is made up of lateral thinking and suspended judgement to create multiple ideas (Harris, 2012; Li et al., 2007). Torrance (1968) outlines four components of creative thinking: fluency in the creation of ideas, originality in the nature of the ideas, elaboration in the expansion of ideas, and flexibility in the different categorisation of ideas. Creative thinking is the ability to view things from different perspectives and combining previously unrelated elements (Shin et al., 2012). While creative thinking is not always synonymous with divergent thinking this mode of thinking has been used to assess creativity. Tests of divergent thinking look to fluency in generating a number of ideas and originality, (Paulus, 2000; Runco & Acar, 2012). As design is solution orientated it has largely been associated with creative thinking during ideation and brainstorming (Runco & Jaeger, 2012). Designers are required to explore several ideas before they fix on one providing the need for creative thinking (Stempfle & Badke-Schaub, 2002). Previous studies assessing design performance have looked to levels of creative thinking as a performance indicator such as Badke Schaub et al. (2010). For the purpose of this paper, creative thinking is defined as:

Divergent thinking to explore and generate alternative ideas and options.

Critical thinking

While creative thinking is important in design it cannot alone address the scope of many of today's design problems. Design problems are complex, ill-defined and un-structured (Goel & Pirolli, 1989). They may have conflicting assumptions, evidence, and opinions requiring alternative solutions (Kitchner, 1983). Solving these problems therefore requires reason, argument and distributed knowledge (Jonassen, 1997; Kitchner, 1983). While creative and divergent thinking are associated with design, convergent thinking though necessary, has limited attention in the design literature (Goldschmidt 2016). It has been shown that design cycles come about through alternative episodes of convergent and divergent thinking (Dong, 2007). This is further described as a process of co-evolution to define and develop both the problem and solution together (Dorst & Cross, 2001). As ideas are created (divergent) this reveals further information or questions to be analysed about the problem (convergent thinking). As non-viable options are evaluated through convergent thinking this prompts the use of convergent thinking to generate further ideas (Ferreira and Lacerda dos Santos 2009; Stempfle and Badke-Schaub 2002; Dorst 2011). Critical thinking is convergent as it is logical and deductive to question and analyse information to make decisions (Choi and Lee 2009; Hung et al. 2008).

Critical thinking is about being able to analyse a problem, justify one's beliefs and theories, the examining of evidence and the ability to offer counter-arguments (Jonassen, 2008; Tang et al., 2020). It is analytical and focuses on essential details, the selection of ideas according to their relevance and being able to deduce options from information (Fung & Howe, 2012). Bezanilla et al. (2019) outline the following six critical thinking skills: 'Analysing/Organising; Reasoning/Arguing; Questioning/Asking oneself; Evaluating; Taking a position/Taking Decisions; and Acting/ Compromising'. Facione (2011) includes the following core skills: analysis, inference, evaluation, and interpretation. For the purpose of this paper, critical thinking is defined as:

Convergent, logical, and deductive thinking to interpret, analyse and judge information.

Metacognition

Metacognition is required for ill-structured problem-solving to plan how to tackle the problem, monitor progress, and evaluate the appropriateness of the strategies used and the knowledge of a team to reach goals and develop solutions (Andres, 2013; Jonassen, 1997; van Ginkel et al., 2009). Metacognition supports the constructing of plausible solutions for the problem and the understanding that the solution may need further evaluation (Cama et al., 2006). Metacognition relies on critical thinking to evaluate and monitor one's own reasoning (Pacheco & Herrera, 2021). Magno (2010) argues that critical thinking occurs when individuals apply metacognitive skills and strategies to produce a desirable outcome. Furthermore a relationship between creativity and metacognition has also been established (Preiss et al., 2019). Magno (2010) found that when participants demonstrated metacognitive skills, they showed higher levels of creative thinking.

For design tasks Schön's (1983) reflective practice theory proposes that design activity is based on actions and the ability to learn and make decisions from those actions. It involves a reflective conversation with the individual, the team, and the elements of the problem. Therefore, to manage their thinking processes and ability to strategise, teams must also apply metacognition which is divided into two main aspects: knowledge of cognition and regulation of cognition (Öztürk & Gürbüz, 2017). Pacheco and Herrera (2021) propose that as part of a complex thinking model, metacognition can be defined as: the knowledge capacity that a person has of their learning, the use of their cognitive abilities and the recognition of their limitations. It is the knowledge they have about when, where, and why to apply learning strategies and how these strategies can be transferred to other contexts. It is also about the recognition of other perspectives and modes of thinking; the activity of monitoring and evaluation of one's own learning and performance in action and an ability to regulate one's cognitive behaviour accordingly. In summary the main elements of metacognitive regulation are: planning, monitoring and evaluating one's problem solving strategies (Flavell, 1979). For the purpose of this paper, metacognition is defined as:

Self-reflection through planning, monitoring, and evaluating oneself or the team.

Knowledge Processing

Creativity is closely related to knowledge and domain-specific knowledge has been found to influences domain-specific creativity (An & Runco, 2016; Huang et al., 2017; Sun et al., 2020). Un-structured problem solving requires access to domain knowledge that is well organized (Jonassen, 2008),and without it solvers use weaker strategies for searching for a path or solution (Chi & Glaser, 1985). Sun et al. (2020) showed that students with a higher level of domain knowledge performed better than those with a low level of domain knowledge during tests of scientific creativity. Studies have shown that while creativity performance is influenced by domain knowledge, it is also positively impacted by creative and divergent thinking skills (Huang et al., 2017; Paek et al., 2016). Creative performance is dependent on domain knowledge and expertise, which acts as a source for creativity (Amabile et al., 2018). Creative and divergent thinking is a process of applying existing knowledge and combining unrelated knowledge in new ways (Marron & Faust, 2018). It is also about the exchange of knowledge between people to create new knowledge (Smith et al., 2005). Smith et al. (2005) found that existing and accessible knowledge impacted a company's ability to create knowledge which, in turn, increased the outputs of product and service solutions. Knowledge from several domains is also required and due to the heuristic nature of the process general process or metacognitive knowledge is also needed (Christiaans & Venselaar, 2005; Pressley & McCormick, 1995). Metacognitive knowledge can also compensate for the absence of relevant domain knowledge (Xun & Land, 2004).

Knowledge processing through collaboration can also develop critical thinking skills as the process fosters 'discussion, clarification, ideas, and evaluation of the ideas of others (Tang et al., 2020). Information processing or the gathering, interpreting and synthesizing of key information is a key process that influences team output (Mol et al., 2015). The cognitive flexibility of a team to process information is influenced by the intra domain knowledge of the team. (Furr et al., 2012). The creative output of a team also stems from diversity and a team's ability to integrate and apply diverse thought processes (Foss et al., 2008). Effective knowledge processing is critical for design teams in creating and sharing information, decision-making and coordinating design tasks to surface and integrate distributed knowledge (Détienne et al. 2012; Chiu 2002). Therefore, creative thinking, critical thinking and metacognition rely on knowledge and the ability to process that knowledge. For the purpose of this paper, knowledge processing is defined as:

The process of elaborating, explaining, clarifying, and exchanging information to co-construct knowledge.

To conclude the above cognitive process are components of what can be described as complex skills. They are both complementary and interdependent. One form of thinking relies on the others, yet they can also stand alone to address the complex problem solving that makes up design activity. However how these cognitive processes are used in the course of a design project and any variation in their use has received limited attention in the literature. By exploring the use of these four cognitive processes across the three phases described above, this study provides an understanding of how these thinking modes are applied by design teams across different stages of the design process.

Method

This research uses case studies to investigate design teams working in their normal environment in the early phases of design and focuses on the dialogue of the participants to understand the cognitive activity of the teams. The research methodology was chosen to understand the context dependent and complex interconnected processes of design. A fundamental aspect of team designing is conversation and verbal communication.

Data Collection

Four cases were selected for the study. Two of these cases had two teams within each case, this is summarised in Table 1. Each case was bounded by the context, the project, and the experience levels of the teams. Therefore, if two teams worked on the same project within the same context and from similar experience levels, they were part of that one case. The first case involved a bio-medical fellowship program (MedDev1), the second was an undergraduate project (Students), the third a professional practice case (Consultants) and the fourth an additional bio-medical case (MedDev2).

Table 1. Case study profile

Case	Project	Team Type	Team Experience
MedDev1 8 Participants (2 teams of 4)	Uncovering opportunities and the design of solutions in the area of cardiology.	Interdisciplinary, engineering (4), medicine (2), business (1) and law (1).	Experienced post-doctoral research Fellows, Industry experience 3 – 10+ years
Students 14 Participants (2 teams of 7)	Design of a crew rest for flight attendants.	Interdisciplinary, product design (10) and digital communication (3) Engineering (1)	Novice undergraduate students, year 3
Consultants 3 Participants (1 team)	Development of a software program with a user-centred approach.	Interdisciplinary interaction design, software engineering and business. Qualifications: Industrial design (2) Psychology (1)	Experienced industry-based consultants. Industry experience 3 – 10+ years
MedDev2 4 Participants (1 team)	Uncovering opportunities and the design of solutions around urology.	Interdisciplinary Bio-medical engineering (2), medicine (1) and design (1).	Experienced post-doctoral research Fellows, Industry experience 5 – 10+ years

The research data used for analyses for each project is summarised in Table 2.

Table 2. Details of data collection

	MedDev1	Students	Consultants	MedDev2
Analysed data	4 hrs of conversation recorded and analysed.	5 hrs of conversation recorded and analysed	1.5 hrs of conversation recorded and analysed	5.5 hrs of conversation recorded and analysed
Meeting durations	*Problem definition:* Team A: 1 hr 40min Team B: 1hr 52min	*Problem definition:* Team A: 40 min Team B: 46 min. *Ideation:* Team B: 1 hr *Concept development:* Team A: 30min	*Problem definition & Ideation:* 1.5 hrs	*Problem definition:* 3 hrs *Ideation:* 1 hr 25min *Concept development:* 1 hr

The data was collected from naturally occurring meetings in their normal setting to avoid the deformations that may be caused by setting a prescribed project. The researcher was present during all meetings where participant observation was applied, as it is suitable for investigating the rich, diverse experiences, thoughts, and activities of people (Jorgensen, 2015). The conversations of the teams were recorded as they engaged in the design process. A reflexive approach was taken to account for the presence of the researcher in the process and to negate it impacting on the research. This required the researcher remaining objective and taking an 'outsider stance' to avoid influencing behaviours or outcomes. The researcher was also a tutor for the student teams and advised all participants that the study did not impact on grading.

All participant names presented, are pseudonyms for the purpose of anonymisation.

Data analysis

Content analysis (CA) was used for the deductive interpretation of the content of text data from conversations, through a systematic classification process of coding and identifying themes or patterns (Hsieh & Shannon, 2005). The method focuses on the characteristics of language as communication, with attention to the content or contextual meaning of the text (Budd et al., 1967; McTavish & Pirro, 1990). The data was first divided into manageable chunks through the identification of topic segments. Topic shifts and changes were considered to be appropriate means of dividing segments for the purpose of analysing team progress as they tend to come about through agreement (Bublitz, 1988). The four cognitive processes identified from the literature (knowledge processing, critical thinking, creative thinking, and metacognition) were assigned to individual utterances of participants. Reliability refers to the degree to which the findings can be replicated if further studies are to be carried out. An inter-rater reliability study was conducted where another coder, coded a section of the data independently to the descriptions of the themes provided. The results show a Kappa coefficient of 0.718.

Table 3 provides an example of a topic segment from the consultant's conversation. The focus was to review a client's software application, review the navigation and information architecture and redesign it with the intended user in mind. In the first utterance, Harry combines knowledge processing to explain a feature of the program, critical thinking to analyse it and metacognition in assessing that the work involved is not a problem for the team as there is not too much information to manage. Faye responds using critical thinking to argue that the user would not have the information that they need on the screen on the initial use. Harry uses knowledge processing to explain this feature. Faye uses creative thinking to propose that they could form “headers” and “expand and contract questions”. Harry uses creative thinking to develop the solution, knowledge processing to explain it to Faye and critical thinking in the evaluation of the solution.

Table 3. Example of cognitive process codes from consultants

Topic segment	Cognitive processes
Harry: This stuff here again it’s all very rough. This is a classic example of unbelievably inefficient space use. You’d get all of this in here and it would still read properly if you designed it properly. You could have all of this in here and the rolled-up stuff and not have this presentation at all. Because this is an amalgamated part of this. So, when you click on this; it pops out that. It asks all the questions and rolls up the figure and you can have all of these states in there as well. It’s no problem, there’s not that much information there.	KP, CT, CRT, MC
Faye: The only problem we have there is if you look at initial use right. What does the user see on the screen when they haven’t filled in the questions?	CT
Harry: The questions? You fill them out and then you roll them up.	KP
Faye: Each one of these would be almost like headers.	CRT
Harry: Yeah CONSENSUS	KP
Faye: Expand and contract questions.	CRT
Harry: Yeah, and you do the questions and it roll ups and when you close it, it reconfigures the header and that gets them away from having to do this save thing which is counter intuitive because you do the questions down and the save up. So, it gets rid of the whole thing.	KP, CT CRT

KP: knowledge processing, CT: Critical thinking, CRT: Creative thinking, MC: metacognition

Findings

The teams applied all four cognitive processes during their verbal interactions to different degrees to support creative problem solving. The proportion of use over all cases was:

1. Critical Thinking (40%)
2. Knowledge Processing (34%)
3. Metacognition (27%)
4. Creative Thinking (7%)

(Note: Total percentage may be more than 100% as some utterances were coded to more than one category.) The limited use of creative thinking during the front end of design is a surprising finding as creative thinking is largely associated with creative activities such as designing. To gain a deeper understanding of how these cognitive processes were employed it is necessary to examine their use at the different phases of the design process.

Table 4 provides the cognitive processes used, in order of frequency, for each phase and Figure 1 shows the distribution at each phase. There were differences in the use of the cognitive processes between the phases. This can be attributed to the different objectives at each phase of the design process. The problem definition phase is focused on structuring the requirements for the task, the ideation phase is focused on divergent thinking to create a breath of ideas while the concept development phase is focused on the evaluation and refinement of ideas. How each cognitive process was used across the design phases is discussed in the next section.

Table 4. The order of ranking the activities for each phase across all of the cases

Problem definition	Ideation	Concept development
Critical Thinking (43%)	Knowledge Processing (36%)	Knowledge Processing (47%)
Metacognition (35%)	Critical Thinking (31%)	Critical Thinking (38%)
Knowledge Processing (31%)	Creative Thinking (23%)	Metacognition (14%)
Creative Thinking (2%)	Metacognition (13%)	Creative Thinking (6%)

Note: Total percentage may be more than 100% as utterances were coded to more than one category

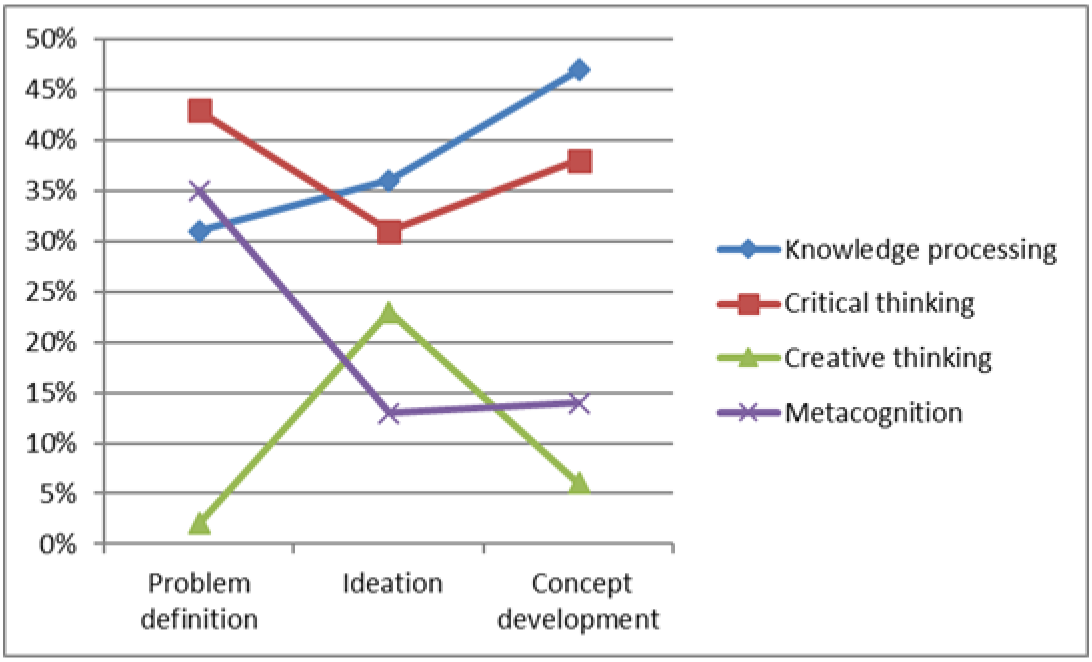

Figure 1. The distribution of the cognitive processes across the design phases

Knowledge processing across phases

Knowledge processing was at significant levels across all phases of projects and levels increased over the phases of projects. This is surprising as the processing of information would have been expected to be at its highest at the beginning of projects as the team members were structuring the requirements. At the concept development phase, knowledge processing was at its highest level to show that knowledge and information exchange is emergent throughout the process. As the team members developed ideas this forced the acquisition of new knowledge in the evaluation and development of solutions. Knowledge processing was also critical in the explanation of solutions to other team members. Below is an example of a topic segment that shows how the Consultants used knowledge processing to share information. During a review of their client's product, Harry externalising his knowledge of the application for the team. The sharing of information by Harry prompts Faye to request further elaboration. Harry responds by providing further knowledge about the client's product showing how knowledge is co-created by the team.

> *Harry: See the competitors here now this screen shot hasn't got one. Basically, those competitors here are not the same as those competitors here, so you know how you add competitors you asked them how do you delete and add competitors? So, it's down there, you put them in down there. It's in the standard opportunity but then they have this field called competitors or main competitors here and it's not them.*

> *Faye: And how do you fill in those main competitors? That's the question I was asking.*

> *Harry: You double click on the little pencil, and you dump them in but it's just text.*

Critical thinking across phases

Critical thinking was at its highest level at the problem definition phase. While it dropped at the ideation phase it was still used significantly, which can be attributed to a co-evolution of developing the problem and solution together. This was reflected in the combined use of both divergent and convergent processes in the form of critical and creative thinking. The teams used critical thinking for further analysis of the problem as ideas posed new questions about the problem space and uncovered emerging sub problems and constraints. For example, ideas proposed with creative thinking could involve a radically new way of doing something leading the team to re-examine new aspects of the problem which required further critical thinking and the processing of information. The following is an example of this co-evolution process from the Students Team B. The team were designing a rest area for airline crews and had established that they needed to provide a changing room for flight attendants.

> *Brian: I think that the space under the stairs is used as storage. We could convert that into some sort of changing room. (Creative thinking)*

> *Lisa: But in reality, we need to get the size of that because there is no point in saying we're putting it in there and then we can't physically get it in there. We need to know the rise of it and the slope. (Critical thinking)*

Brian proposes using the area under the stairs in the crew rest. Upon the creation of the idea the team then recognise that they need to gather more information about this area and analyse it further. Lisa argues that they need to know more about the problem state before they continue to propose solutions (Figure 2).

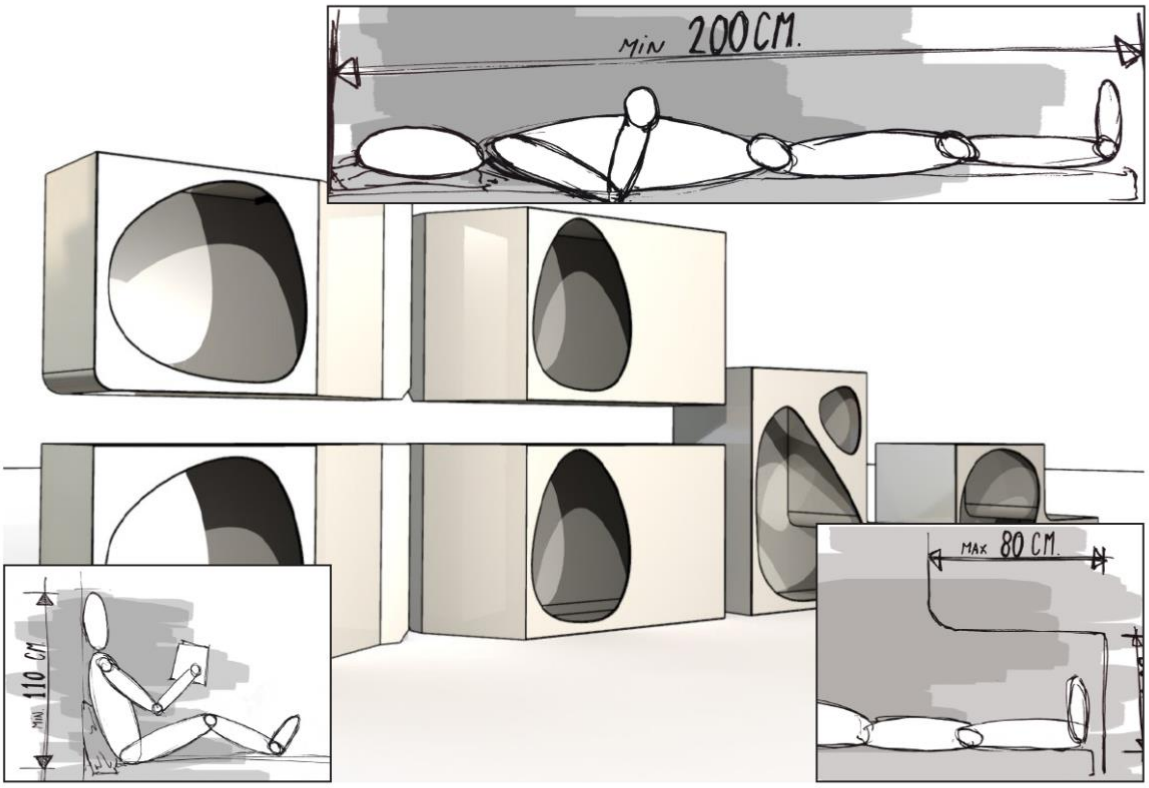

Figure 2. Exploration of crew rest area outputs

Creative thinking across phases

As creative thinking levels increased, critical thinking levels decreased. Creative thinking was at the highest level at the ideation phase while critical thinking was at the lowest level at this phase. These modes of thinking are opposite in nature, so these findings are apt for this stage in the process. The focus at the ideation phase is to create multiple ideas. An overemphasis on critical thinking in the evaluation of ideas could restrict the multiplicity of ideas. At times teams were observed critiquing ideas and discounting them quickly rather than considering how they could be adapted or further explored. Due to space restrictions a member of the Students Team B proposed combining an elevator as a changing room which was critiqued by another member very quickly:

> *Max: It's very hard for it to be an elevator at the same time. If someone is changing and someone else wants to go up or down, that's not possible.*

Runco and Acar (2012) have shown that divergent thinking is synonymous with creative potential. For early idea generation, the aim is to explore and generate a depth and breadth of solutions and withholding judgment on the value of concepts to maximise the potential for optimal solutions (Casakin et al., 2010; Zhang et al., 2015).

Creative thinking had very limited use at the problem definition phase. This is surprising as creative thinking is considered to be a core skill for designers (Kelley, 2001; Stempfle & Badke-Schaub, 2002; Yilmaz & Seifert, 2011). It also had limited use at the concept development phase and was used to revise ideas for solutions upon critical analysis of those solutions. The following is an example of an interchange between knowledge processing, critical thinking, and creative thinking from the MedDev2 team at the concept development phase. Riona uses knowledge processing to explain a proposed concept (Figure 3). Once Liam understands the concept, he analyses it and uses critical thinking to argue that the product may not function correctly. The evaluation prompts Riona to use creative thinking to further build on the idea and develop the solution of a seal.

> *Riona: It comes from the base out to there like this, bear with me. Say this is flush with the skin and then this from the side is protruding out there. (Knowledge processing)*
>
> *Liam: But it still begs the question, I'm just imagining if drips come out here, they are going to be funnelled back. (Critical thinking)*
>
> *Riona: Yeah, there would have to be a seal. Like what you said there, can you bring it out and let it funnel into the bag? (Creative thinking)*

Figure 3. Early prototype

Metacognition across phases

Metacognition was also at highest levels at the problem definition phase dropping significantly over the next two phases. The problem definition phase requires considerable planning and strategising within the team to determine the best approach to working through the project which can account for these levels. The following is an example from the problem definition phase where the MedDev2 team monitored how the team were handling one of the needs/requirements that came from their research findings. There is a difference between Christy and Kieran's interpretation of the requirement. Christy argues that the criteria Kieran uses are not written into the need. He argues why convenience is an important factor in the assessment of the need. Through the application of critical thinking to assess the need and metacognition to monitor and evaluate how the team has managed this need, Christy convinces Kieran to incorporate these "*measurable outcomes*". This managed to elevate the importance of the 'need' amongst the team members.

Christy: You said you want to achieve real time feedback of blood pressure through a non-invasive technique. (Critical thinking, metacognition)

Kieran: Efficiency and convenience, they're the two benchmarks. (Critical thinking)

Christy: Well, that's not how it's written in the needs statement. Are we just assuming that it is, and we score it through non-invasive techniques, to make the procedure more accessible and convenient? (metacognition) In my mind if the need statement was, need a way to provide real time feedback of blood pressure to the clinician, then in my mind it scores at least a three because it's completely inaccessible at the moment, with invasive monitoring. (Critical thinking) There are complications which cost money and it requires a HDU overnight. (Knowledge processing)

Kieran: Fair enough, I think that is where that one was going too. There's no measurable outcome in the needs statement. If we can build those in as measurable outcomes, then you're definitely addressing convenience at least or access. (Metacognition, critical thinking)

Critical thinking and metacognition were often used in combination, while critical thinking was focused on the analysis of the task, metacognition focused on the analysis of the team and individual's performance.

Overall, the findings show that creative team cognition involves a continuous alternation between each of the cognitive processes outlined. Each cognitive process was complementary and interdependent. The findings also show that the emphasis of each cognitive process varied over the design phases and an overuse of some cognitive processes at certain phases could also be counter-productive such as applying critical thinking in the judging of early ideas instead of producing a breath of ideas. In summary, the cognitive processes used were dependent on the objectives at each phase of the design process.

- Knowledge processing increased across the design phases showing that the requirement to agree on new information continues throughout the design process.
- Critical thinking was used extensively across all phases of the design process decreasing only slightly at the ideation phase.
- Creative thinking was the least frequently used cognitive process across all phases rising significantly only at the ideation phase.
- Metacognition was used frequently during the problem definition phase to manage the uncertainty and diversity in perspectives at this phase.

When critical thinking and metacognition (convergent in nature) levels were high creative thinking (divergent in nature) levels were low.

Discussion

Much of the literature in design has emphasised the importance of creativity for designers. For example, both Kelley (2001) and Nussbaum (2013) promote the principle that creativity is a key aspect of designing in teams. It is also an essential component of design education but provides challenges for educators in how to teach it (Wong & Siu, 2012). Creativity has been described in terms of sudden emergent bursts of ideas, described as creative leaps (Dorst & Cross, 2001). These findings problematise such conceptions of creativity suggesting it is important to contextualise creativity constructs within the broader problem-solving process. The data from this study suggest that creativity in design is not just about applying creative thinking. It is as much about knowledge processing, the application of critical thinking to analyse that knowledge, creative thinking to come up with ideas and critical thinking to analyse and refine those ideas. In this way creativity can be conceptualised as a considered process requiring the successful assimilation of several cognitive processes. Through metacognition and reflection on the process teams and individuals can strategise on how to conduct a task, reflect on the effectiveness of those strategies, and revise their course of action where necessary.

What was unexpected in the findings was the level of engagement with each cognitive process. Creative thinking accounted for only 7% of overall cognitive activity. While creative thinking can be associated with creativity and the generation of ideas, idea generation is also stimulated by engaging with other cognitive processes. This study found that design behaviour shifts from divergent behaviour when engaging in knowledge processing and creative thinking, to then convergent and analytical behaviour during critical thinking and metacognition. Critical thinking dominates the process at all stages. Once information was shared, critical thinking was applied in a sense making process where emphasis was placed in finding relationships and patterns between elements. While knowledge processing was used to expand the problem space, critical thinking was used to structure and analyse this information. By questioning and critiquing the problem and reframing it from different perspectives this creates the opportunity to then apply creative thinking to generate solutions. Therefore, by encouraging strong critical thinking ability in design teams this can pave the way for creative solutions.

Knowledge processing accounted for 34% of team activity. Knowledge sharing and integration have been shown to be critical to performance in design (Guo et al., 2017) and in line with the literature a strong relationship between the acquisition of knowledge and creativity was shown (Christiaans & Venselaar, 2005; Sun et al., 2020). Knowledge processing increased across the phases showing that knowledge is emergent throughout the process and not just a focus at the problem definition phase.

Metacognition accounted for almost a third of activity and was frequently used to prepare how to solve the problem and structure disparate information. It involved teams repeatedly reviewing their own progress, recognising gaps in knowledge, and reflecting on the effectiveness of their progress.

The different phases of the design process were found to call for an emphasis on different cognitive processes. Due to the complexity of design problems, teams must first structure the problem before any solution searching can proceed as advocated by Zenios et al. (2009). The problem definition phase was predominantly independent of solution generation and hence creative thinking was at its lowest level. Solution focusing during problem definition could narrow the focus of the problem space too early and limit the scope for new ideas. The findings show that this phase requires mainly critical thinking to analyse and structure the project elements. Metacognition which has been linked to resolving uncertainty was at its highest levels at this phase, this was the phase where the teams were required to consider how to conduct the project and involved cycles of planning tasks, monitoring how the project was being structured and evaluating the result. As expected, creative thinking was highest during ideation, but still used less than knowledge processing and critical thinking. At the ideation phase knowledge processing can be attributed to the co-evolution account in the literature of creative design which is not a ‘creative leap’ from the problem to the solution space but an evolution of both where one informs the other (Maher & Tang, 2003). Critical thinking was used for further analysis of the problem as ideas posed new questions about the problem space and uncovered emerging sub problems and constraints. However, a balance is required as it was found that too much critical thinking at the ideation phase may restrict the fluency of ideas. Studies have also found a correlation between the high amount of ideas and ideation success (Goldschmidt & Tatsa, 2005; Moreno et al., 2014). The concept development phase called for further knowledge processing as the critical analysis of solutions provoked further questions and information seeking. Therefore, as ideas emerge further knowledge is required to understand the impact of solutions.

Recommendations for Design Practice and Design Education

Researchers have argued that educational institutions need to promote complex thinking amongst students (Pacheco & Herrera, 2021). Wong and Siu (2012) argue that design education has been focused on producing creative outputs rather than the processes to arrive at creative outputs. They suggest that the thinking skills of designers requires more focus. With an increase in team work both in industry and education an understanding of the verbal interactions between team members is critical to uncover the thinking engaged with in order to contribute to creative processes as advocated by Gustina and Sweet (2014). This research has contributed to this understanding to reveal the cognitive process used during different phases of the creative design process. The findings confirm that effectiveness of the use of these cognitive process is contingent on good collaboration and communication (Tang et al., 2020). This points to the need for careful facilitation of team discussion to encourage designers to engage in productive dialogue. Tutors or managers can act as facilitators to prompt and scaffold conversation to encourage the cognitive processes outlined. Designers need to be encouraged to be strong critical thinkers by learning to question information and challenge conventional modes of thinking. They need to support this mode of thinking with strong knowledge of a domain (Sun et al., 2020). Knowledge acquisition will continue throughout the project and where the team is lacking in knowledge they will need to consult with experts. Designers also need to be able to be able to alternate on the fly between creative (divergent) and critical (convergent) thinking to firstly explore potential solutions and to then analyse the appropriateness of these solutions. The process can be supported by metacognition to plan, monitor and evaluate progress.

Attention should also be given to the purpose of the phase, for example creative thinking at the problem definition phase may restrict the problem definition stage if the focus is on solution generation rather than problem structuring, while too much critical thinking during the ideation phase could stem the flow of ideas.

The degree and experience and proficiency of educators to implement team work, assessment structures and grading means that educators may place more emphasis on project outputs rather than on the process inputs and the collaborative exchanges required to work effectively within a team (Riebe et al., 2016). The finding of this study can help to provide an understanding for educators of what constitutes productive dialogue while also providing the means and support to implement, facilitate and assess teamwork.

Limitations

Only two cases could be compared for the ideation and concept development phases. This is a limitation of the study and while the findings are not generalisable the questions it raises are generalisable. Only the problem definition phase was captured from the MedDev1 case. The Consultants meeting was predominantly a problem definition meeting and has been defined as such for cross case comparisons. However, due to the nature of the project the team also came up with ideas in this meeting. They did not hold specific ideation meetings and further design developments were done by individuals.

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