INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.94

Exploring metacognitive processes in design ideation with text-to-image AI tools

Hao-Yu Chang and Jo-Yu Kuo ✉

National Taipei University of Technology, Taiwan

✉ jyk@ntut.edu.tw

Abstract

This research aims to explore the existence of metacognition during the use of text-to-image generators in the design ideation stage. We recruited five participants with a design background to use Midjourney as an ideation tool and to produce three sketches at the end of their task. Through semi-structured interviews and retrospective verbalization, we collected data on their thought processes. The qualitative analysis revealed clear indications of metacognitive engagement, such as monitoring and evaluating, which opens the path for future research into the impact of AI on design cognition.

Keywords: idea generation, design cognition, metacognition, image generator, qualitative analysis

1. Introduction

The subject of AI has consistently held significant interest across various disciplines. In 2022, with the rapid advancement of technology, the emergence of AIGC (Artificial Intelligence Generated Content) not only has led to changes in the structures of various industries, but it has also become a highly promising tool in different fields. In design, the emerge of text-to-image AI can generate corresponding images with simple instructions. Moreover, it can also enhance visual communication and creative ideation efficiency (Liu et al. 2023). Therefore, several studies have been investigating the use of AI and its application (Ploennigs and Berger 2022; Vartiainen and Tedre 2023). However, design is regarded as a discipline not just about producing work, but also a complex process involving thinking, analysis, and decision-making (Kavousi et al. 2020a). In psychology, we mentioned it as "Metacognition". Not only it plays a significant role in design education and the design ideation (Ball and Christensen 2019), the improvement of creativity is achieved through the training process of metacognitive thinking. Hence, in this paper, instead of discussing the application of AI integrating in design, we aim to have a deeper understanding of its impact on the design field.

1.1. Motivation

As mentioned above, design ideation involved metacognitive process, such as creative thinking, evaluating, decision-making and text-to-image AI tools facilitate the unexpected finding of ideas and foster a creative mindset, enhancing the design process (Paananen et al. 2023). Therefore, we seek to understand whether metacognitive processes are still actively engaged when designers interact with AI tools. To specify, our study aims to explore the thinking processes of designers when using AI as an ideation tool during the conceptualization stage of design.

2. Literature review

2.1. AI text-to-image generation in design

Text-to-image AI is capable of generate novel images for inspiration in design ideation stage (Liu et al. 2023). Not only being applied in different fields of design, included art, architecture, visual communication, product design etc, it brings about new changes in education realms. Dehouche and Dehouche (2023) conducted an experiment, using a group of 72,980 Stable Diffusion prompts and classified into different categories, to assess the potential of teaching history of art, aesthetic, and technique. In the study (Vartiainen and Tedre 2023), the researcher recruited 15 craft teachers and teacher educators to discuss their thoughts in semi-structure interview about text-to-image AI in design education after the experiment using Midjourney to generate images in 90 minutes. Apart from research in education, Liu and Hu (2023) used different training method in Stable Diffusion and apply within different stage of product design process to explore how AI demonstrate concept in industrial design.

Numerous studies have indicated that AI could play an important role in stimulating creative ideas during the conceptual ideation phase of design. In other words, AI generation tools can stimulate designers to optimize products and seek innovative ideas by generating various concept images (Daumiller and Dresel 2019; Ploennigs and Berger 2022; Fang 2023; Liu and Hu 2023). Lee and Chiu (2023) launched an experiment about comparing the impact between using AI generation tools and the largest exploration platform, Pinterest, as a visual stimulus in design ideation stage. Although the result did not show a significant different in the performance of the participants, the students held a positive attitude towards the integration of AI. The study further indicates that the uniqueness and ambiguity of AI allow designers to freely get the inspiration they need, making it very suitable for the use of early-stage product design. In another research, Ploennigs and Berger (2022) developed a workflow by analysing 3 different generative models' (Midjourney, DALL-E and Stable diffusion) different-use-cases in the early stage of architecture design process.

From the recent research, we can identify the direction of AI in design field into two parts. The first one is about Prompt Engineering, mainly exploring within different angles on how to write prompts to get better images (Liu and Chilton 2022). The second part is about applying AI generation tools in each design realm, including education, design process, etc. To conclude, we find that AI could continuously refine itself through various training method to provide more accurate images in Prompt Engineering research. Moreover, numerous literatures indicate that the research on text-to-image generators mainly focus on their potential in practical applications of design fields. However, there are seldom research investigate deeply into the thinking process while using AI tools in design industry.

2.2. Metacognition in design thinking

Design thinking is a complicate process that involved initial time to reflect on what the problem is (Ball and Christensen 2019). In the other words, it takes systematic approach to problem-solving in design. The unlimited feature of it often overwhelms students and makes them anxious during the process of thinking. However, a significant characteristic of human cognition is the ability to critically reflect on their thinking process (Kavousi et al. 2020a). We called this kind of behaviour: Metacognition, refers to an awareness of one's own cognitive processes. This concept was first be introduced by Flavell. He defined it to be the ability to think about your own thinking, which plays an important role on self-controlling and self-educating (Flavell 1979). Moreover, several studies have explored the role of metacognition in design education and have found that it plays a significant role in students' design processes. In the research of Sternberg et al. (1996), it indicated that self-monitoring and adjustment are one of the methods that can develop creative thinking. In other words, metacognitive thinking is particularly essential in design idea generation and development, as it contributes to the creative process in design. In the research of Kavousi et al. (2020b), the results show that high performance students spend more time on thinking about the task, which got higher score in Reflective monitoring process in metacognition. In the contrary, Low performance students drive into their work directly in most of the time instead of planning, which got lower score. In the conclusion,

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

metacognition is an essential component of design thinking and can enhance the design process and its outcomes for learners.

Metacognition have been categorized into different ways in several studies. Currently, it is most classified into two parts: Metacognition Knowledge, Metacognition regulation. Metacognition Knowledge refers to how much you know about your own thinking and the strategies you possess. Metacognition Regulation means that the actions you take while learning, included planning, monitoring, and evaluating. The assessment of one's metacognition have be classified into two parts: offline and online (Marra et al. 2022). One is conducted before or after the task. The data mostly gather through questionnaire and semi-structure interview, such as Metacognition Awareness Inventory (Schraw and Dennison 1994). The other one is conducted during the task with thinking-aloud method.

2.3. Qualitative analysis

"Qualitative" typically refers to non-numerical, descriptive data, which often comes from text or transcripts of interviews. The methods include both inductive and deductive ways (Siiman et al. 2023). Coding is a common process in qualitative analysis, where paragraphs and texts are labelled and organized. This helps researchers break down and reassemble data in a meaningful way (Elliott 2018). However, both methods are time-consuming. Therefore, many studies had been exploring the use of AI for coding.

ChatGPT is a generative artificial intelligence developed by OpenAI, a large language model capable of autonomous learning from data. The development of artificial intelligence could categorize complex content, organize themes, and encode quickly through typing prompts. In the research of Rahman et al. (2023), they applied ChatGPT in various stages of their research, including ideation, introduction, literature review, research methodology, and experimental analysis. Their study shows that with transcribed data provided, ChatGPT is capable of delivering satisfactory results for certain qualitative data analyses. Moreover, several research found ChatGPT as a valuable tool in qualitative analysis (Tabone and de Winter 2023). ChatGPT assists researchers in simplifying the coding process of qualitative data, thereby improving the efficiency of coding and uncovering insights that may have been overlooked (Zhang et al. 2023). It challenges and supplement human interpretations.

3. The experiment

The study aims to explore the Metacognition thinking process of designer while using text-to-image AI in design conceptual phase. In the experiment, we recruited 5 participants to attend the study. The reason that we recruited a small number of participants is that we hope to observe whether metacognition emerges in the design process involving AI. If any metacognitive ability is employed during the process of using AI, we will be able to carry out further experiments in the future. In other words, this preliminary study of exploring the existence of metacognition process allow us to continue the future work. During the experiment, each of them must use Midjourney in Discord as a design ideation tool and propose 3 sketches at the end of the task. After the task, we conducted semi-structured interviews with retrospective verbalization to collect the data and analysed the qualitative results with the AI tool ChatGPT.

3.1. Participants

The research recruited participants with more than 4 years of product design background to assure the knowledge of basic design process and have mature design abilities. In addition, the current text-to-image generators are commonly used in English input. To maintain the accuracy of the data, the English proficiency of the participants is all above score of 750 of the contest TOEIC.

3.2. Procedure

The entire experiment was divided into three parts. The first part was the preparation phase, the researcher introduced the basic tips about prompt engineering of Midjourney in 5 minutes. After the guide, participants were asked to prompt whatever they want for warm-up with 15 minutes. The purpose

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

of this phase is to ensure participants understand the rules and be familiar with Midjourney to avoid research errors.
In the second phase, participants were asked to design a home decor item that can be mass-produced. They must propose 3 sketches at the end of the task. The task was told with an open-ended question with no correct answer and encourage them to be creative (Kavousi et al. 2020b). Each participant should at least try refining 5 times of the prompts to get different visual stimuli. It last 60 minutes in the stage.
Finally, semi-structure interview was conducted with audio recorded. This stage last 15-30 minutes. There were 11 questions structured with subjects from different stage of the task and opinion of Midjourney (Figure 1). There are three main aspects of the interview we want to investigate, (a) the thinking process while using Midjourney as an ideal tool in the design task. We asked them to recall their memory with their Midjourney prompts record and tell us what they were thinking while they refine their task. (b) Their opinion upon text-to-image AI as an ideation tool and visual stimulation. (c) How participants will use AI in their future design practice.

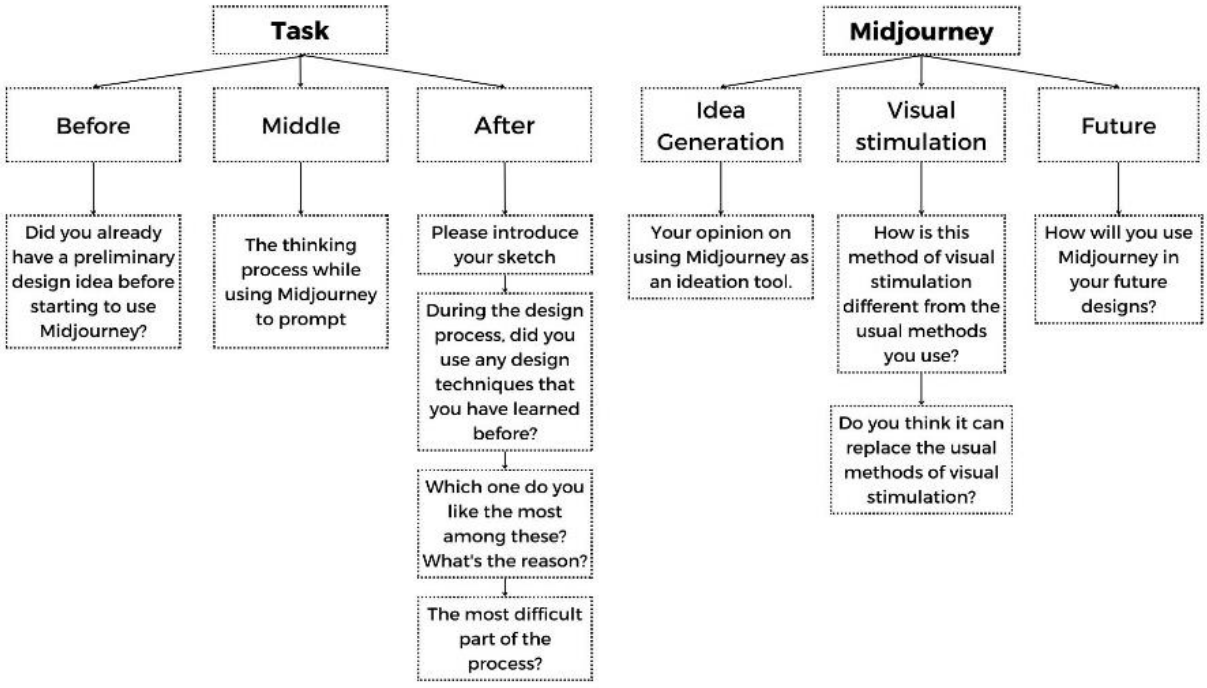

Figure 1. Semi-structured interview questions' structure (source: this research)

3.3. Data coding

To answer the research question "What are the metacognitive process designer used while using AI tool in conceptualization phase", we transcribed the text from the interview about the retrospective verbalization of thinking process while using Midjourney to prompt from the structure to examine the frequency and sequence of the metacognitive process emerge from the design task.
In this study, we used retrospective verbalization to collect data of Metacognition and ChatGPT as a tool for qualitative data analysis. We referred to the classification of metacognition in the article of Kavousi et al. (2020b) and categorized each data into 5 groups, Reflective process knowledge (RPK), Reflective process monitoring (RPM), Reflective process control (RPC), Cognitive thought process (CTP) and Other process (OP). The reason to add the group "Cognition" into the theme is to clearly recognize the Metacognitive Process with other processes. To identify, cognitive processes involve students' actions in understanding, planning, and carrying out a design task. Metacognition enters this process when designers review their understanding, evaluate their ideas' creativity, judge their ability to execute these ideas, and check the quality of their end results.

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

Table 1. The definition of each theme

Themes	Definition
Reflective process knowledge	Learner's knowledge regarding how to learn, which could influence the process of learning
Reflective process monitoring	Judgments made by learners regarding the status of learning (how learning is progressing, how learning should progress)
Reflective process control	Decision or actions taken by learners that influence the progress of the learning-task
Cognitive thought process	Include activities that students perform during the interpretation of a learning task, and in the conceptualization and execution of a design in response to that task
Other process	Unrelated of the above themes, domain knowledge, solution, reading

4. Results and discussion

4.1. Experiment results

After the design task, the final sketches from 5 of the participants are shown (Figure 2) and the large number of images generated by Midjourney from each participant are displayed (Figure 3). The purpose of formulating sketches as the method of presenting results is to clearly define Midjourney as an ideation tool. In other words, the images generated by AI from each designer are the visual stimuli being used to inspire them to get better ideas. In the stage of semi-structure interview, the total amount of words and duration are organized, and we calculated the number of times each participant modified the prompts (Table 1). The average number of the frequency each participant refines their prompts is 9. Some of the examples of prompts are included:

- a floor lamp, home style, minimalist, futuristic, warm color, concept design, product design, original, highly detailed, realistic, 8K, 3D render.
- cushion, round square shape, color warm green, rough texture, product design, realistic photo, perspective angle display.
- cushion, random shape, on a sofa, color warm, smooth touch, fluffy, product design, realistic photo.
- a vase, wooden material, alien, space, light color, geometric, product design, placement on top, render image.
- living room vase, Japanese style, concrete and wood material, product design, product concept, 4k rendering
- tall straight cylinder living room vase, ceramic material, product design, product concept, 4k rendering.

Table 2. The list of each participant's frequency of refining prompts, total amount of words and duration in semi-structured interviews

	Midjourney Task	Semi-Structure interview	
No	Frequency prompts refining	Total amount of words	Duration (mins)
P1	8	3268	28
P2	8	3776	24
P3	7	2018	15
P4	13	3667	20
P5	7	2092	15

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

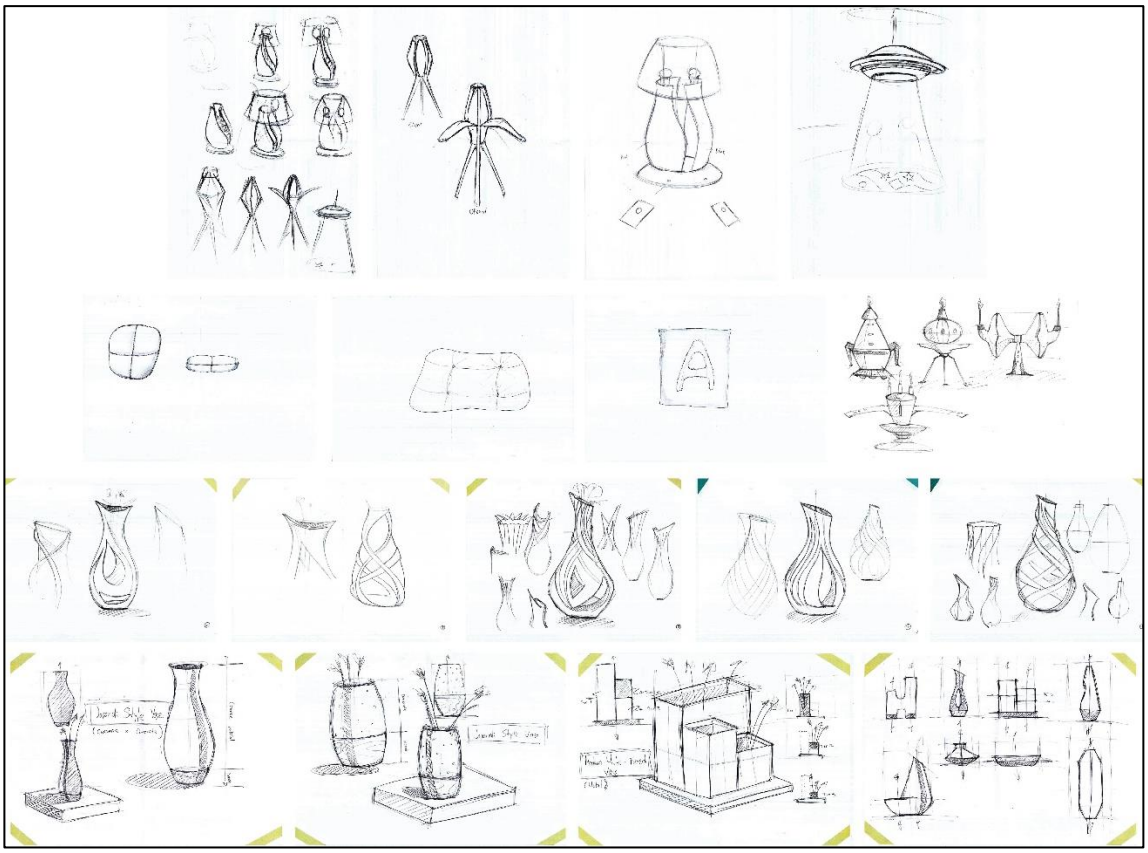

Figure 2. Final sketches from 5 participants

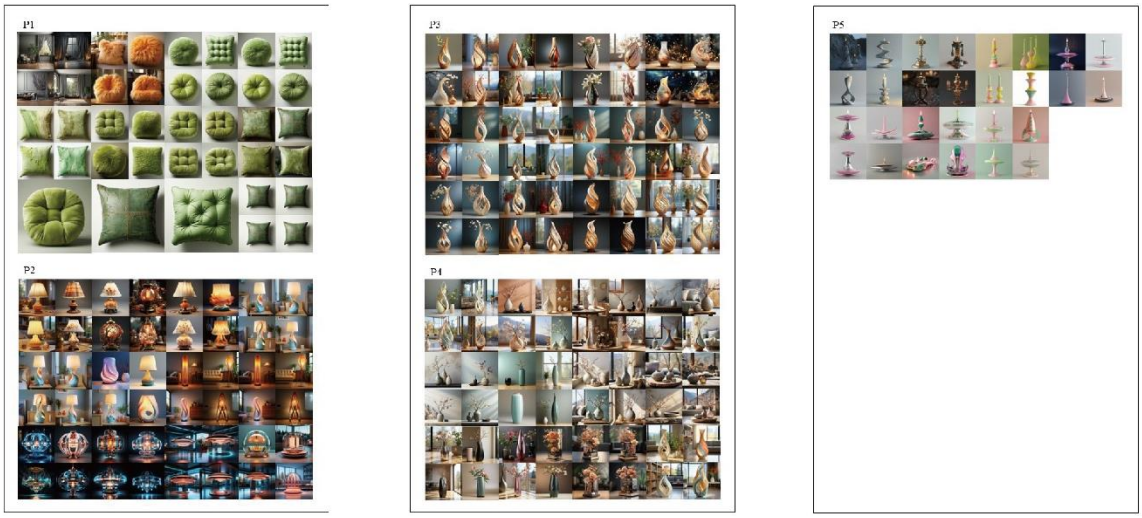

Figure 3. Images generated by Midjourney

4.2. Metacognition results

We used ChatGPT to organize the data. To enhance the quality and reliability of the analysis from ChatGPT, we focused on refining the prompts and used part of the workflow from the study of Zhang et al. (2023) . We started the prompts with a role-playing. Then, we describe the task background, how the task should be conducted and the expected performance. The original prompts were written in Chinese and the examples of the codes are shown in (Table 3).
Here are the prompts:

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

"You are a researcher, and I have posted an excerpt from an interview. This interview content comes from an experiment, which aims to explore the design thinking involved in using Midjourney (a text-to-image generator) as a design ideation tool. You will use the interview content to conduct a qualitative analysis (in research and analysis, 'qualitative' usually refers to non-numerical, descriptive data, which often comes from texts or transcripts of interviews). Please encode each sentence of the interview content (1209 words), excluding the interviewer's questions, according to the five thematic categories of Reflective process knowledge, Reflective process monitoring, Reflective process control, Cognitive thought process, and other process. Below are the explanations of the themes.

1. Reflective process knowledge: Learner's knowledge regarding how to learn, which could influence the process of learning

2. Reflective process monitoring: Judgments made by learners regarding the status of learning (how learning is progressing, how learning should progress)

3. Reflective process control: Decision or actions taken by learners that influence the progress of the learning-task

4. Cognitive thought process: Include activities that students perform during the interpretation of a learning task, and in the conceptualization and execution of a design in response to that task

5. Other process: Unrelated of the above themes, domain knowledge, solution, reading

Please remember to encode the entire context that I required and encoded in the order of the conversation."

Table 3. The list of themes and examples

Themes	Evidence/Examples
Reflective Process Knowledge	"Considering the feasibility of mass production and manufacturing, I directly deleted three and four."
Reflective Process Control	"So, at that time, I entered the prompt to test since I want to first understand their perspective on the prompt of 'vase'." "I am not satisfied with the result, so I removed 'fluffy', as I believed that 'fluffy' was the reason for that outcome."
Reflective Process Monitor	"The next thing I realized was that this did not give me any inspiration to design the vase I originally wanted, so I continued to adjust the material."
Cognitive thought process	"I started to try different locations to see how they would affect the design of the vase, combined with changes in style." "Then I wanted to design another product with a different style. Since I just designed a desk lamp, I want to design a floor lamp."
Other process	"Because it indeed is an attractive thing, I played around with it a bit." "Besides that, I made no other changes, just transformed it into a floor lamp."

We organized the data and developed the color-coded map (Figure 2) of students' thought process (Kavousi et al. 2020b). Reflective process knowledge refers to the red areas, which happened in the beginning of the task. Reflective process control refers to the yellow areas. Reflective process monitor refers to the orange areas. Cognition process refers to the grey areas, which take most of the time. And Other process refers to the black areas.

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

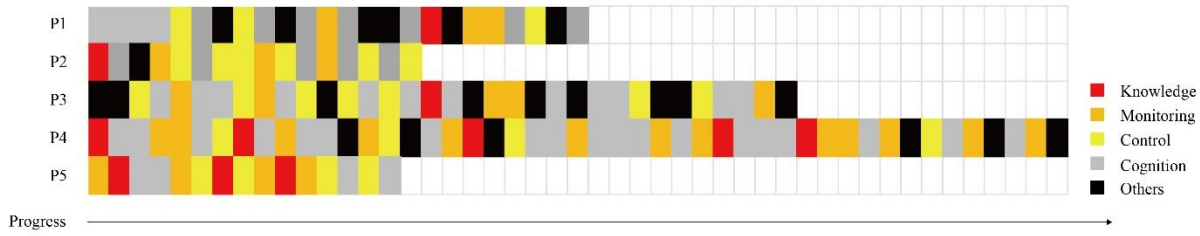

Figure 4. Color-coded map of students' thought process

Another source of insights about metacognition, we calculated the number of each theme that emerged in the analysis (Figure 5). In the chart, although the number of cognitive thought process is the most, we can see that there are numbers of metacognitive process emerge in designers' thinking. In addition, we calculated each participant's metacognitive and cognitive thought processes' percentage.

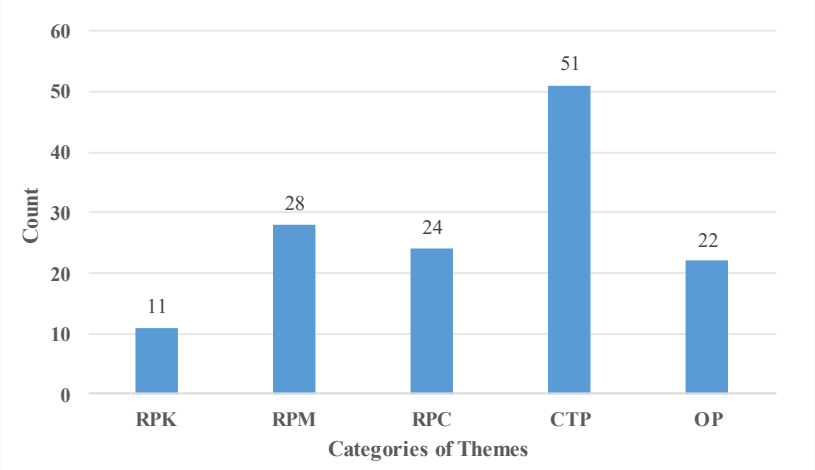

Figure 5. Chart of the number of each theme that emerged in the analysis

Table 4. Participant's metacognitive, cognitive, and other thought processes' percentage

No	Metacognitive thought process	Cognitive thought process	Other process
P1	29%	46%	25%
P2	28%	35%	27%
P3	38%	35%	6%
P4	47%	40%	13%
P5	73%	26%	0%

4.3. Discussion about text-to-image AI

According to the records of semi-structured interview, to answer the questions about their opinion upon text-to-image AI as an ideation tool and visual stimulation:

> *"I think it serves as an excellent tool for ideation. I believe this is a great practice for students, not to copy but to use AI to generate numerous ideas. I think it can save them a lot of time and help them come up with even more ideas. At the same time, it trains students to develop their ability to narrate something."*

> *"I do think it's suitable as a tool for ideation. On the positive side, it can provide a very clear image, a good render, a great visual representation. On the other hand, its downside is that it's too visual. If you rely entirely on it, your work will end up feeling very hollow, like an empty shell. Based on my experience, that's how I see it."*

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

> *"It should be used in combination because conventional visual stimulation methods provide you with diverse adjectives, more colourful ideas, or thoughts about materials, especially since the image appears right in front of you. In contrast, with Midjourney, you need to think of specific words to get stimulated. But this is just one of my answers, and it's also possible that I'm not using prompts frequently enough."*

> *"I might initially still rely on other forms of visual stimulation to find more specific and concrete scenarios. Only after I have a clear idea of the shape and transformation, I'm aiming for would I then turn to Midjourney to explore further variations."*

The result of the interview indicates that most of the participants show a positive attitude towards text-to-image AI as ideation tools. They admire its speed and reaction with numerous ideas generated. In other hands, to serve as a tool for visual stimulation, sometimes they find it too abstract to be use as a reference and it's hard to find words to describe your products. But overall, they all look forward to using it to combine with other tools and applying it to the ideation stage of their future design works.

5. Conclusion and future work

This paper adopted an exploratory research design to explore the possibility of metacognitive process existence while using text-to-image AI as a tool in design ideation stage. The result shows evidence of metacognitive process emerges in the integration of designer and AI tools. In addition, this study discovered designers' opinion towards text-to-image AI as a visual stimulation and ideation tool and highlights the question of over-reliance. It gave an opportunity to discuss the fundamental issue, the importance of one's thinking process in the rapid development of technology and brings out the future investigation opportunities. However, several research indicated that AI does not replace the needs for human, but a complement (Morgan 2023; Siiman et al. 2023). It is still under debate to use only ChatGPT in qualitative research. In the future work, we will recruit more participants to attend the research to investigate the impact metacognition brings while using Midjourney and the potential use of it as a method to train designer's metacognition. Meanwhile, we will integrate human researchers for verifying and enriching the findings from ChatGPT to enhance the reliability of the analysis.

Acknowledgement

This research was supported by Ministry of Education (grant number: PHA1123033) and National Science and Technology Council (grant number: 112-2221-E-027-080-MY2).

References

Ball, L.J. and Christensen, B.T. (2019), "Advancing an understanding of design cognition and design metacognition: Progress and prospects", *Design Studies*, 65, 35-59. https://doi.org/10.1016/j.destud.2019.10.003.

Daumiller, M. and Dresel, M. (2019), "Supporting Self-Regulated Learning With Digital Media Using Motivational Regulation and Metacognitive Prompts", *Journal of Experimental Education*, 87(1), 161-176. https://doi.org/10.1080/00220973.2018.1448744.

Dehouche, N. and Dehouche, K. (2023), "What's in a text-to-image prompt? The potential of stable diffusion in visual arts education", *Heliyon*, 9(6), e16757. https://doi.org/10.1016/j.heliyon.2023.e16757.

Elliott, V. (2018), "Thinking about the coding process in qualitative data analysis", *Qualitative Report*, 23(11), 2850-2861.

Fang, Y.-M. (2023), *The Role of Generative AI in Industrial Design: Enhancing the Design Process and Learning*.

Flavell, J.H. (1979), "Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry", *American Psychologist*, 34(10), 906-911. https://doi.org/10.1037/0003-066X.34.10.906.

Kavousi, S., Miller, P.A. and Alexander, P.A. (2020a), "Modeling metacognition in design thinking and design making", *International Journal of Technology and Design Education*, 30(4), 709-735. https://doi.org/10.1007/s10798-019-09521-9.

Kavousi, S., Miller, P.A. and Alexander, P.A. (2020b), "The role of metacognition in the first-year design lab", *Educational Technology Research and Development*, 68(6), 3471-3494. https://doi.org/10.1007/s11423-020-09848-4.

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press

Lee, Y.-H. and Chiu, C.-Y. (2023), “The Impact of AI Text-to-Image Generator on Product Styling Design”, in Mori, H. and Asahi, Y., eds., *Human Interface and the Management of Information*, Cham, 2023, Springer Nature Switzerland, 502-515.
Liu, M. and Hu, Y. (2023), “Application Potential of Stable Diffusion in Different Stages of Industrial Design”, in Degen, H. and Ntoa, S., eds., *Artificial Intelligence in HCI*, Cham, 2023, Springer Nature Switzerland, 590-609.
Liu, V. and Chilton, L.B. (2022), “Design Guidelines for Prompt Engineering Text-to-Image Generative Models”, in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, New Orleans, LA, USA, Association for Computing Machinery, Article 384, available: https://doi.org/10.1145/3491102.3501825.
Liu, V., Vermeulen, J., Fitzmaurice, G. and Matejka, J. (2023), “3DALL-E: Integrating Text-to-Image AI in 3D Design Workflows”, in *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, Pittsburgh, PA, USA, Association for Computing Machinery, 1955–1977, available: https://doi.org/10.1145/3563657.3596098.
Marra, R.M., Hacker, D.J. and Plumb, C. (2022), “Metacognition and the development of self-directed learning in a problem-based engineering curriculum”, *Journal of Engineering Education*, 111(1), 137-161. https://doi.org/10.1002/jee.20437.
Morgan, D.L. (2023), “Exploring the Use of Artificial Intelligence for Qualitative Data Analysis: The Case of ChatGPT”, *International Journal of Qualitative Methods*, 22, 16094069231211248.
Paananen, V., Oppenlaender, J. and Visuri, A. (2023) “Using Text-to-Image Generation for Architectural Design Ideation”, *arXiv preprint.* https://doi.org/10.48550/arXiv.2304.10182
Ploennigs, J. and Berger, M. (2023) "AI Art in Architecture", *AI in Civil Engineering*, 2(1):8. https://doi.org/10.1007/s43503-023-00018-y
Rahman, M., Terano, H.J., Rahman, M., Salamzadeh, A. and Rahaman, M.S. (2023), “ChatGPT and Academic Research: A Review and Recommendations Based on Practical Examples”, 3, 1-12. https://doi.org/10.52631/jemds.v3i1.175.
Schraw, G. and Dennison, R.S. (1994), “Assessing metacognitive awareness”, *Contemporary Educational Psychology*, 19, 460-475. https://doi.org/10.1006/ceps.1994.1033.
Siiman, L.A., Rannastu-Avalos, M., Pöysä-Tarhonen, J., Häkkinen, P. and Pedaste, M. (2023), “Opportunities and Challenges for AI-Assisted Qualitative Data Analysis: An Example from Collaborative Problem-Solving Discourse Data”, in Huang, Y.-M. and Rocha, T., eds., *Innovative Technologies and Learning*, Cham, 2023, Springer Nature Switzerland, 87-96.
Sternberg, R.J., Williams, W.M., Supervision, A.f. and Development, C. (1996), *How to Develop Student Creativity*, Association for Supervision and Curriculum Development.
Tabone, W. and de Winter, J. (2023), *Using ChatGPT for Human-Computer Interaction Research: A Primer*.
Vartiainen, H. and Tedre, M. (2023), “Using artificial intelligence in craft education: crafting with text-to-image generative models”, *Digital Creativity*, 34(1), 1-21. https://doi.org/10.1080/14626268.2023.2174557.
Zhang, H., Wu, C., Xie, J., Lyu, Y., Cai, J. and Carroll, J.M. (2023), “Redefining qualitative analysis in the AI era: Utilizing ChatGPT for efficient thematic analysis”, *arXiv preprint.* https://doi.org/10.48550/arXiv.2309.10771

https://doi.org/10.1017/pds.2024.94 Published online by Cambridge University Press