# Exploring Dual-Processes of Iteration in Conceptual Design\*

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Conceptual design has been modeled as a loop cycling from design entities that stimulate cognitive processes that produce design operations that in turn generate design entities, continuing iteratively. In order to deepen our understanding of this iterative process and therefore enhance design training, the cognitive processes of design iteration can be further broken down in terms of a spectrum of thinking informed by dual-process theory and Cognitive Continuum Theory. This spectrum ranges from purely intuitive to purely analytical processes and encompasses a number of modes of thinking in between. Built on this framework, we discuss results from mapping cognitive processes from the design realm onto this continuum and observe that some iterative loops stay in the analytical mode, some in the intuitive mode, while others quickly oscillate back and forth. A relationship between the character of ideas generated and cognitive mode is explored, as mapped by linkography, a visual representation of the connections between design entities in a task. Potentially, ideas that are generated during analytical loops are more derivative while ideas generated during intuitive loops or intuitive-analytical oscillations are more unique. To conclude, implications for design education based on this analysis are proposed.

Keywords: dual-process theory; design cognition; iteration; intuitive thinking; conceptual design

# 1. Introduction

It has been observed that students become less divergent over the course of a four-year engineering education [1]. As many models and methods of creativity [2–8] emphasize the importance of intuitive, unconscious, and stochastic thought in the creative process, we believe that the engineering curriculum's heavy emphasis on analytical thinking may be inadvertently hindering students' creative abilities by teaching them out of their intuitively creative habits, and therefore limiting the effectiveness of design education. This sentiment is best summarized as, "inductive and deductive reasoning do not suffice to reproduce the phenomenon of creative behavior" [3]. As an example, in jazz improvisation, the lateral prefrontal regions (associated with planning, sequences, problem-solving, and focused attention) deactivate [9]. Nevertheless most would deem the musical outcome of jazz improvisation to be highly creative, and it is the product of largely automatic processing. It has been shown that creative idea generation can be improved to a certain extent for example using Synectics, a simple but intuitive method to stimulate abstract thinking using a variety of stimuli and forced associations [10]. Should we incorporate more of these intuitive approaches into the education and practice of engineering design?

Even in technical design, creative ideas are often the result of stochastic associations between external stimuli and experiences that are often random and open to a wide range of influences such as past experience, cognitive biases, and the nature of the designer's surroundings. Most existing conceptual design models, such as Geneplore [11], Design by Analogy [12, 13] and Generate-Stimulate-Produce (GSP) [14], do not effectively take into account or distinguish this non-analytical component of creative idea generation. Thus, there is a noticeable lack of understanding of what role intuitive thinking plays, and how important it is in engineering.

In this paper, we present an analysis that is a step closer toward understanding the unique contributions of intuitive and analytical processes to the design process. With this understanding, it is hoped that techniques can be developed in the future to stimulate intuitive and analytical thinking as necessary to enhance creative idea generation and student education.

# 2. Related work

# 2.1 The dual-systems approach

Dual-process theory is an established model from cognitive psychology that divides cognitive processes into two camps: Type 1 and Type 2 [15]. Type 1 processes are fast, intuitive, heuristics-based, and emotional, and answer simple questions like "What is  $2 \times 4$ ?" or when one reads the emotion on a colleague's face. Conversely, Type 2 processes are slow and analytical, and answer more difficult questions like "What is  $34 \times 17$ ?" and also kick in if they detect an error is about to be made [16, 17].

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Engineering education is focused on producing analytical, thoughtful individuals, effectively stimulating and honing Type 2 processes, which are necessary for convergent problem-solving tasks. However, much of the creative methodology literature seems to focus on developing Type 1 processes (e.g. consider the importance of empathy in design thinking [7]). It is very likely that Type 1 processes will prove to be stronger contributors to the creative design process than Type 2 processes alone.

The authors have made a first attempt to distinguish the independent roles of Type 1 and Type 2 processes in the engineering design process of students [18, 19]. This analysis looked at the processes associated with the generation of individual ideas, and compared the novelty of the ideas to the contribution of Type 1 and Type 2 processes. In the first pilot study [18], supported by additional data and analysis [19], it was found that Type 1 thinking was more prevalent in the earlier stages, and Type 2 processes were more prevalent in the later stages. This is to be expected, as ideation naturally involves taking advantage of quick thinking, like unexpected associations, and later stages involve more convergent thinking and solution analysis. However, it was found in our study that the most novel ideas were generated through a balanced combination of Type 1 and Type 2 processes, suggesting that both fast and slow thinking are desired for optimal results. Building on these findings, in this paper we seek to understand how and why the cognitive modes switch back and forth and how these oscillations may contribute differently to the design process. Unlike the previous studies, in this analysis we omit comparing idea novelty to process outcome. Ideas are plotted later as points on linkographs to juxtapose the time evolution of cognitive oscillations and character of ideas generated without linking them to corresponding creativity or novelty measures. Such a linkage will be the subject of future work.

# 2.2 Understanding creativity with the dual-process lens

A correlation has been found between dependence on intuitive thinking and creative potential [20, 21], and we ideally look to explore and expand on this result in the engineering context. Hogarth [22] explored the interaction of intuitive and analytical thinking in general problem solving, based on the complexity and potential for bias, such as experience and characterization of problem environment. He suggests that for problems with low complexity but high potential for bias, analytical approaches are favored over intuitive approaches. Conversely, for problems with high complexity, but low potential for bias, intuitive approaches are favored over analytical approaches. For problems with high complexity and high potential for bias (such as a first year design student approaching their first design problem), it is unclear whether intuitive or analytical approaches are superior. In our experience, an analytical approach to design problems is naturally preferred by students, and in doing so inexperience may keep an individual from isolating the critical information required to solve a problem, and as a result fixate on irrelevant or misleading information. This coincides with Smith and Linsey's [23] definition of fixation.

There is plenty of evidence demonstrating both the value and the danger of using Type 1 (heuristicsbased) reasoning. It is most beneficial in a benign environment that supports the use of heuristics through experience and implicit learning [24]. It has been found in certain instances, Type 1 processes can perform better than Type 2 thinking [25]. Pretz [26] found that intuitive methods worked better for novice problem-solvers, perhaps because they do not know exactly what information is relevant to a problem and should be analyzed, and this method avoids fixating on extraneous information. In his eight stages of creative process model, Sawyer [27] found that dual-process is constantly on display in these stages. At the same time, much effort has been spent demonstrating how Type 1 reasoning breaks down in more complicated situations [16, 28 - 30].

Potentially, intuitive processes are able to implicitly abstract behavior and patterns in a way that is more pragmatic than analytical thinking. By thinking in parallel, memories and ideas can be stored, processed, and retrieved much more quickly than analytical, logical processes. With experience and abstraction of knowledge comes various levels of confidence, as "high self-esteem at the conscious, rational level may coexist with low self-esteem at the experiential level" [5]. This is perhaps why selfefficacy (or creative confidence) is important in the context of training students to be competent designers, as belief in one's abilities could be nearly as important as the abilities themselves when it comes to creative output [31].

It is important to note that intuitive and analytical approaches are not mutually exclusive, and both sets are necessary to complete design tasks. On the Cognitive-Experiential Self-Theory (CEST), another dual-process model that differs slightly from Stanovich and West's, Epstein [5] notes, "even when people believe their thinking is completely rational, it is often biased by their experiential processing." The intuitive system is an "adaptive, associative learning system" that generates first round responses to stimuli and questions that are subsequently processed slowly by the rational system. Epstein also notes, "The rational system (or Type 2 processes) can also induce the experiential system (or Type 1 processes) by providing the understanding that allows a person to train the experiential system so that its initial reactions are more appropriate," such as overcoming an irrational fear. Intuitive and analytical processes are not functioning independent of each other but rather are highly intertwined, and are continually oscillating back and forth.

From this background literature, it is clear what is described as the intuitive, Type 1, or experiential system generates the automatic response to any given (especially ill-structured) problem or stimulus. The rational, Type 2, logical system often generates a second, delayed reaction after the brain has done some processing, but this response is still guided to some extent by the intuitive system. However, over time, training of the rational, analytical system can in turn inform the intuitive responses to stimuli. Therefore it is valuable to understand the positive, negative, or neutral role that intuitive processing plays in the design process. For instance, Type 1 processes influence the accessibility of stimuli and domain knowledge; it has been found that by priming subjects by writing sentences related to the domain they are studying, accessibility of domain knowledge increases [32]. Conversely, through cognitive biases such as confirmation bias and selective attention, the accessibility of stimuli and domain knowledge could be reduced. In a situation where nervous emotions may interfere with performance, such as giving an important presentation, the intuitive emotional response often overwhelms the rational response. The nature of the intuitive contributions to the design process is not well understood, and is explored in this paper.

### 2.3 Cognitive continuum theory

Cognitive Continuum Theory, or CCT, [33] uses the same dual-process building blocks as above, but describes the outcome of cognition, rather than the process [34]. Using varied combinations of analytical and intuitive thinking, six modes of inquiry are mapped on a continuum ranging from pure analytical thought to pure intuitive thought (intuitive judgment, peer-aided judgment, system-aided judgment, quasi-experiment, controlled trials, and scientific experiment). Quasirationality [35] lies in the middle of the continuum, and is a combination of both rational and intuitive thought. In Hammond's theory, well-structured tasks trigger analysis and ill-structured tasks trigger intuition. In addition, thinking can oscillate between these varied modes of cognition [33, 36]. We believe that this oscillation is a fundamental aspect of the iterative nature of conceptual design that has yet to be captured by existing models. Cognition changes not only on short time scales, as analytical and intuitive processes continuously influence each other, but also on longer time scales, as the demands of a design task change over time. That is, engineering design problems are ill-structured and open-ended, which triggers various modes of cognition, but through abstraction, the problems are decomposed into smaller well-structured problems, so that the analytical mind is used later in the design task. Such cognitive oscillations are explored in this analysis.

#### 2.4 An improved model of conceptual design

With the addition of CCT, we propose an expansion of the Generate-Stimulate-Produce (GSP) model that maps cognitive processes onto Hammond's intuitive and analytical spectrum, as shown in Fig. 1. Our previous model of creative stimulation in conceptual design [14, 37] was based on Finke, Ward and Smith's Geneplore model [11]. The Geneplore model consists of the generation of preinventive structures and then the exploration and interpretation of these structures. The generation is the divergent phase of the creative cycle, whereas exploration is the convergent phase. Benami [37] expanded the model of Finke et al. to the conceptual design process. His basic model consisted of design entities (raw ideas and mature concepts that include the standard descriptions of form, function, and behavior), which stimulate cognitive processes (memory retrieval, association, transformation, problem analysis and solution analysis), which produce design operations (actions that bring design entities into a design context such as sketching, questioning, and suggesting) which generate new design entities, as shown in Fig. 1. The cycle turns preinventive structures into mature ideas and knowledge until a final design is reached, or can be terminated if the designer is unable to obtain a satisfactory design. By expanding this model, we shed new light on the conceptual design process,



Fig. 1. Expanded GSP model incorporating CCT.

incorporating a more realistic representation of mental cognition.

Based on the GSP model, we have also explored iteration in conceptual design [38]. The iteration design process model consisted of four key tasks (analyze problem, generate idea, compose concept, evaluate concept) and three loops (problem redefinition, idea stimulation, concept reuse). In this work we found that increased iteration frequency corresponds with increased quality, variety, and quantity of ideas, but has a mixed effect on novelty. However, increased problem redefinition frequency may in fact decrease novelty, which suggests that a highly analytical approach might suppress novel ideas [38].

# 3. Experimental approach

### 3.1 Guiding question

Q1: Is it observable in the design process that the early design phase be dominated by oscillations favoring intuitive processes, and they will slowly diminish until overtaken by primarily analytical processes at the end of the task?

This question is based on our prior analysis [18] that suggests students generate ideas with more Type 1 thinking during the first third of the design process, and generate ideas with more Type 2 thinking during the last third of the design process. We expect the cognitive processes to mirror this, which logically follows from the divergent and convergent thinking that naturally governs creative idea generation [39].

#### 3.2 Retrospective protocol analysis

Two different methods, concurrent and retrospective, were tested to reveal internal thoughts during the collaborative design task. The retrospective approach was most effective, as concurrently thinking aloud and interacting with a team proved to be too much for one designer to process. This allowed for the observation of both private and shared thoughts. In addition, Simonton [4] argues concurrent think aloud methods can interfere with unconscious processes that may benefit creative and divergent thinking. Also, retrospective protocols have been found to have similar accuracy to concurrent protocols [40]. Subjects self-reported that they were able to remember 90% or greater of their thoughts in a design process lasting under thirty minutes. But, as there is no certain way to determine exactly how much information is missing, it is hard to quantify how large an issue memory recall may be. In general, protocol analysis also presents the issue that not all thoughts may be verbalized [41]. However, this method is the best available to design researchers to explore cognitive interactions.

### 3.3 Subjects

Subjects for this experiment consisted of ten senior and master's students in mechanical engineering at the University of Southern California divided into five groups of two. The team assignment was random, except for one team. All students were in engineering design classes and had group projects in those classes. Therefore, they were familiar with participating in collaborative design and had been taught basic engineering design methodologies. However, the participants were novice designers as all had less than a year of industry work experience. The subjects were compensated by being entered in a drawing for an iPod Nano and gave consent when arriving at the study. The study was reviewed and approved by the institutional review board.

#### 3.4 Procedure

When first arriving at the study, participants were given individual training in verbalizing their thoughts. The training started with verbalizing a simple process, and continued to become more difficult until the subject was verbalizing their performance during a practice design problem.

After training, the designers were put in pairs and provided with pencil, paper, and the design problem statement (given in the appendix) that asked them to develop a device that would securely store skateboards to prevent students from stacking them up against classroom walls. The designers were then video recorded as they collaboratively worked through the design problem. They were given as much time as they needed to complete the problem, as time constraints could interfere with the natural design process.

Immediately after the subjects completed the design problem, they were asked to retrospectively verbalize their thoughts from the design process. This was done while watching a video of the design problem providing verbal and visual cues. The retrospective verbalizations were recorded in an audio file for later transcription and association with the live verbalizations.

# 4. Analysis

#### 4.1 Protocol analysis

The classification of Type 1 and Type 2 processes was accomplished by almost fully building on a preceding analysis' collaborative stimulation protocol coding. In this collaborative stimulation study, the design entities, cognitive processes and instances of collaborative stimulation were first identified. The data from each group's experiment session consisted of two audio files and a video file. A coding scheme was employed to analyze the data, identifying design entities, cognitive processes, and collaborative stimulation. The coding scheme was checked using inter-coder reliability, and an agreement of 85% was found.

A design entity was identified as a potential or partial solution having a form, function, and/or behavior. Any time a form, function, or behavior was mentioned in the transcript, it was classified as a design entity. Sometimes sketches accompanied design entities, making them easier to identify. After the design entities were identified, the cognitive processes occurring in the transcript were identified. Generative cognitive processes consisted of *memory retrieval*, when an experience or design entity which existed in the past is remembered, association, when connections are drawn between two design entities, transformation, when a design entity is altered or changed, problem analysis, when the design problem is explored in more detail, and solution analysis, when the fitness of a design solution is compared to the problem. Then the collastimulation processes borative (prompting, clarifying, seeding, and correction) were identified by examining how cognitive processes came about, and if they could be attributed to a collaborative stimulation.

#### 4.2 Cognitive continuum theory analysis

In applying CCT to the collaborative stimulation data, the classification of processes and statements coincided with the hallmarks of fast, intuitive Type 1 thinking and slow, logical Type 2 thinking, as in our previous work [18, 19]. Memory retrieval, association, prompting, and correcting were categorized as Type 1, as these processes often happen quickly and without much logical, conscious mental computation. Problem analysis, solution analysis, seeding, and clarifying were categorized as Type 2, as these processes often require slower, serial, logical thinking. We believe transformation to be a combination of both and falls into the quasirational category. Consequently, as seeding, clarifying, prompting, and correction were often observed simultaneously with transformation, we categorize those as quasirational as well (see Table 1). After this analysis, the processes were mapped onto a continuum, ranging from 1 (intuitive) to 9 (analytical), with 5 (transformation), representing the rough dividing line between predominantly intuitive and analytical modes. These processes were then plotted against time. Some segments were associated with more than one process, and so the primary one was chosen to represent the segment. Because this mapping was direct from the original collaborative stimulation coding, it maintains the same intercoder reliability as the original study. Note that the intention of this mapping is not to

 Table 1. Cognitive Continuum Coding

Category	Coding	Process
Intuitive	1	Association
Type 1	2	Memory Retrieval
Quasi- rational	3 4 5 6 7	Prompting Clarifying Transformation Seeding Correcting
Analytical	8	Problem Analysis
Type 2	9	Solution Analysis

arbitrarily categorize cognitive categories but rather to holistically understand processes in a new way. The mapping could arguably be modified in the future.

# 5. Results

The following figures show the cognitive oscillations observed over the course of a design task as predicted by Hammond's [33] continuum theory for two groups who participated in the study (Figs. 2, 3, 5, and 6). Also shown are the corresponding linkographs for the groups showing the genealogy of ideas (Figs. 4 and 7). The solid lines mark the movement between identified cognitive processes and the dotted line marks quasirational transformation as the approximate dividing line between intuitive (bottom of chart) and analytical (top of chart) modes of thinking. Figs. 2 and 5 chart the individuals' retrospective discussion of their ideas over the design task, and Figs. 3 and 6 chart the live video protocol discussion between the two collaborators, without differentiation between the two individuals.

In the video protocols (Figs. 3 and 6), we observe larger oscillations between loops of intuitive and analytical thinking throughout each group's design process. Similar patterns are found in the individual retrospective data sets (Figs. 2 and 5) however due to the retrospective nature of the individual verbalizations, transcripts are heavily biased towards analytical thinking and memory retrieval, as likely subjects were consciously relating information in the video transcript to their final solutions. This produces more erratic movement in the data. Interestingly, transformation and the other quasirational processes surrounding it (prompting, clarification, correcting, and seeding) seem to often bounce cognitive processes back to the same mode of thinking from whence they came, thereby maintaining the intuitive or analytical loops. Also, we observe larger cycles that mirror the GSP model. For example, in Figure 3 (Group 4) the subjects began with problem analysis (coded as 8), which generated ideas through an intuitive series of



Fig. 2. Cognitive Oscillations-Individual Retrospective Protocol (Group 4).



Fig. 3. Cognitive Oscillations-Live Video Protocol (Group 4).



Fig. 4. Group 4 Linkograph.

prompting (3) and association (1), which then stimulated ideas through transformation (5) and eventually produced ideas that were related to the original problem through problem analysis (8) and solution analysis (9). This is a natural progression for designers, oscillating between intuitive to analytical thinking, which can be seen repeatedly throughout the task.

Larger examples of intuitive and analytical loops can be seen for instance in time segments 30–69 (analytical) 94–99 (intuitive) in Figure 3. The large number of data points at numbers 8 and 9 are because the frequency of problem (8) and solution (9) analysis was very high in this study, as is common with engineering students. It is the home base that often the discussion will return to, to make sure that any proposed idea will fulfill the desired requirements.

At the beginning of the task, mostly analytical thinking is observed as the subjects analyze the problem. Moving forward, there is a period of both analytical and intuitive thinking, and then at the end there is less intuitive thinking at the end of the task as the proposed solution is fine-tuned. Over the experiment (e.g. about 23 minutes for Group 4) both intuitive and analytical modes of thinking are clearly observed.

The linkographs [42, 43] for each group presented



Fig. 5. Cognitive Oscillations-Individual Retrospective Protocol (Group 1).



Fig. 6. Cognitive Oscillations-Live Video Protocol (Group 1).



Fig. 7. Group 1 Linkograph.

are below the cognitive oscillation charts, and are purposefully aligned with increasing time on the horizontal axis to highlight an intriguing difference between the nature of ideas generated by each cognitive mode. When the subjects used analytical processes, the ideas were much more likely to be linked to previous ideas. When the subjects used more intuitive processes and/or completed intuitiveanalytical oscillations, the ideas were more unique, and were less likely to be connected to or derived from previous ideas. For instance, in the first third of Figure 4, there is a high degree of interconnectivity between ideas, as well as predominantly analytical thinking in the corresponding time period in Figure 3. In the middle third of Figure 4, there is very little interconnectivity between ideas, corresponding with quick oscillations between intuitive and analytical modes. This can also be seen to a lesser extent in Figs. 5 and 6. The final phases of design, primarily problem and solution analysis, do not follow this pattern.

Note that linkographs analyze *ideas*, while the cognitive oscillations analyze *cognitive processes*. Ideas on the horizontal axis are represented by numbers, as the only result we wish to discuss is the general pedigree of ideas generated by intuitive and/or analytical thinking. No connection to novelty can be drawn from this analysis. Also note

that ideas are presented sequentially, not spaced relative to time stamps, as in the oscillation charts. As such, specific ideas cannot be associated or traced to the cognitive mode that generated them in this work. In addition, specific claims cannot be made comparing the intuitive and analytical approaches of different individuals. For such analyses, see Moore, Sauder, and Jin [18, 19]. This observation is offered without any numerical analysis for intellectual interest and an avenue for future study.

# 6. Discussion

# 6.1 Guiding question analysis

Our original guiding question was answered with a qualified "no" but the data are nevertheless intriguing. The burst of intuitive thinking that was predicted at the beginning is instead often observed part way into the design task and is also coupled with frequent oscillations to the analytical mode, likely to compare proposed features and ideas to the problem and solution. The long string of analytical thoughts at the beginning is during the period that subjects worked to understand the problem first. However, intuitive thinking did subside towards the end of the task as predicted. To this end, we can offer no statistical basis at this time, but simply analysis by inspection for the given cases.

# 6.2 Oscillations and idea generation

These results suggest the oscillations in cognitive modes of thinking exist throughout the design process as theorized by Hammond [33]. Subjects used both intuitive/experiential/Type 1 and analytical/rational/Type 2 processes throughout the design process, and the varied combination of both modes manifests itself in the range of cognitive processes displayed. There is oscillation on longer and shorter time scales, with some sequences predominantly staying in one cognitive mode and after some time moving to another, as well as rapid movement between modes. There is a frequent return to analysis of the problem or potential solution, which we believe leads to premature judgment of ideas, as is commonly taught to be avoided in brainstorming and other creative idea generation methods such as Synectics and design thinking [7, 8]. This analytical mode of thinking is more metabolically demanding than the intuitive mode, which may also account for the frequent oscillations between modes. The intuitive and analytical loops are consistent with the iterations in Jin and Chusilp's [45] model of iteration in conceptual design.

The oscillations along the cognitive continuum further articulate the iterative loops described by the

GSP model, with some iterations associated with analytical thinking, some with intuitive thinking, and others somewhere in between. The next natural questions are: what causes such different iterations and how do they impact design results? The explicitly observable oscillations together with the answers to these questions will give more resolution to the original GSP model for future pedagogical development. For instance, the quality and number of these loops could be triggered by internal or external stimuli, environment, background experience, or personality. These factors, if clearly identified, can be blended into design training programs. It is unknown why quasirational processes bounce thinking back to the mode from which it came, but this intriguing phenomenon warrants further exploration.

The correlation between cognitive mode and idea source is the strongest evidence yet we have found that intuitive processes under our definition are uniquely generative, and therefore an important part of the design process. It is far from surprising that analytical thinking would produce more logically connected ideas. Nor is it surprising that intuitive thinking (encompassing association and memory retrieval in this analysis) diversifies idea sources by bringing in external stimuli and ideas such as past experiences and memories.

#### 6.3 Implications

The observation of cognitive oscillations between intuitive and analytical modes in the design task is intriguing, and the future lines of research are promising. This work is another step in understanding the unique contributions of each cognitive mode, particularly the intuitive, which are not well understood in the design process. Engineering likely instills well the analytical mode through mathematical problem solving techniques and fundamental physics. However as intuitive thinking is an important contributor to generation of innovative ideas, we believe that the intuitive mode thinking should be understood, addressed, and trained during an engineer's education, either by incorporating new material into engineering design classes or through extracurricular activities such as performing arts, or both. The ideal contribution of intuitive and analytical thinking in the design process is not yet known, and may enable educators to give students quantifiable feedback on their design process and present opportunities for improvement. For instance, the frequent return to analytical thinking, in particular solution analysis, may be damaging to students' creative potential, and this can be demonstrated to students. This constant questioning is at once productive and inhibiting and is a hallmark of the analytical Type 2 processes (see "feeling of rightness" [44]) we commonly see in engineering students.

Understanding the interaction of these two modes of thinking may also help to understand and mitigate the phenomenon of fixation. Fixated students could be stuck in analytical loops where they have exhausted the information available to them that has been built on previous concepts, much in the way an industrious child experimenting with LEGOS may pause when she runs out of bricks within reach. To mitigate this, students should be directed to an intuitive mode of thinking to explore unrelated concepts and stimuli and then relate them back to the problem at hand. This would create a new set of possible connections on the linkograph from which to evolve further concepts.

#### 6.4 Limitations

It should be noted that this mapping of cognitive processes onto Hammond's cognitive continuum does not have the resolution to divide explicitly between the theorized six modes of thinking well summarized in Cader, Campbell, & Watson [46]. This analysis is only meant to give a rough picture of the design process for future dual-process analyses and design method creation. The mapping also has a level of subjectivity that should be taken into account. For instance, clarifying (4) is coded as being less intuitive than prompting (3). It is coded as such due to the authors' best judgment, and could arguably be switched. Furthermore, association is coded as the most intuitive process only based on the authors' reading of the protocols in which most associations reflected quick connections between thoughts. There could be associations that require Type 2 reasoning to bring up relevant thoughts. Instead of a stratified continuum, processes could be cataloged into three discrete bins: intuitive, analytical, and quasirational. However, such a categorization could arguably oversimplify the explored phenomenon. There is very likely a spectrum of intuitive and analytical thinking in play in the design process, it is just not fully understood. Future experiments will have to be carried out to analyze the design process to a higher resolution if the exact amount of intuitive and analytical processes in each design process is desired. Perhaps Hammond's six modes of cognition can be applied.

#### 6.5 Future work

The future work will look into the possible causes of various observed intuitive-analytical oscillations. One direction of this line of research would be an inventory or test, possibly including but not limited to the Rational-Experiential Inventory [47], that students could take to determine his or her use of analytical and intuitive thinking in a design task. Such an inventory would be valuable to see how students' approaches to design change over the course of their education. This inventory would be more valuable if calibrated with the approaches and linkographs of expert designers. Or feedback could be given based on protocol analysis of design tasks. This would help students to understand the nature of their native design process, and allow educators to offer avenues for improvement. The authors believe that an ideal oscillation chart would appear as highly intuitive at the beginning of the task, which would theoretically generate a plethora of unique concepts. This would be followed by intuitive and analytical oscillations, which would build on and refine the concepts into more concrete ideas. The corresponding linkograph of the task would likely be highly interconnected, with links between ideas at the end to ideas at the beginning of the task.

Future studies can add additional resolution to the mapping of cognitive processes onto the continuum, more accurately identifying the six modes of cognition predicted by the theory in cognitive processes identified in design, as well as more accurately determining the hierarchy of processes on the intuitive-analytical spectrum. By comparing the oscillations and cognitive continua of different designers (including their specific field, background, personality type, dependence on rational or intuitive thinking, etc.) it may be possible to determine the ideal set of oscillations that trigger the most novel and creative ideas in a given domain. The analytical mode is naturally the way that engineers are trained to approach problems, and is invaluable for more convergent tasks such as problem solving. However, harnessing intuitive thoughts and delaying judgment of ideas in a design task should help students to create more unique concepts. Future work should also look at how the triggers of intuitive and analytical thinking influence the quality of generated ideas. These triggers, including cognitive biases such as selective attention, can influence accessibility of stimuli and knowledge, and could heavily influence the creativity of final products.

The relationship between cognitive oscillations and character of ideas on linkographs highly warrants further study and quantification. It may be useful for designers to understand how cognitive approaches produce different ideas—some being more unique and others more derivative of earlier thoughts. But this analysis can make no predictions as to the varied novelty of these approaches. However it may also be the case that creativity of ideas is linked to oscillations between analytical and intuitive modes.

# 7. Conclusions

This work is a promising step in developing a validated dual-process model of conceptual design, and the first step towards mapping Cognitive Continuum Theory onto the engineering design process and modeling the mental iterations and oscillations between intuitive and analytical modes of thinking. Hammond's Cognitive Continuum Theory uses the same building blocks as dual-process theory to explain the outcome of cognitive processes on a cognitive continuum, rather than the process itself, which is more readily observed in protocol analysis.

With this knowledge, pedagogical techniques can be developed to balance the overwhelmingly analytical techniques currently taught in engineering education. Students may lose the confidence to depend on intuitive thinking, but this confidence may be developed in other ways, perhaps through performing arts. We hope that engineering educators will take advantage of the creative value of intuitive thought so that students will have the skill and the confidence to innovate in an increasingly competitive and globalized world.

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**Design problem statement:** Skateboards are one of the most popular forms of transportation at USC. Unfortunately though, when students come to class, the only current method for skateboard storage is to line them up against the wall. However, this has the potential to mark up the wall and skateboards can fall over in a domino effect if one is accidently bumped. A larger problem is that in large lecture halls, where there are often 2-3 rows of skateboards stacked up against the back wall. With so many boards, it can be hard to find yours, or even worse, it provides the opportunity for someone to steal one unnoticed. Design a device which will safely and securely hold skateboards while students are in class. This device could either be located in the hallway or outside the building, but not in the classroom due to space constraints.

**Dylan Moore** recently received his M.S. in Mechanical Engineering from the University of Southern California as a Rose Hills fellow and member of the IMPACT Laboratory. He received a B.S. in Engineering Physics and B.A. in Music from the University of California, Berkeley, where he helped to develop *Sense and Sensibility and Science*, an interdisciplinary course on human rationality and how the tools of science can be used to improve individual and societal decisions. His research interests in engineering design creativity grew out of this course to include bridging the pedagogical gap between fields traditionally viewed as creative, such as music, and fields traditionally viewed as technical, such as mechanical engineering, using an integrative dual-process approach. Dylan was a finalist at the 2014 USC Graduate Research Symposium. He also presented at the 2014 ASME Design Theory and Methodology Conference (IDETC), the Design Creativity Workshop at Design, Computing, and Cognition 2014, and the Mudd Design Workshop IX. Dylan is a practicing musician and has sung with the renowned USC Thornton Chamber Singers and Gay Men's Chorus of Los Angeles among other Los Angeles and Bay Area ensembles. Dylan is continuing his studies as a Ph.D. student in Mechanical Engineering at Stanford University.

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