Exploring Dual-Processes of Iteration in Conceptual Design

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Abstract

Conceptual design has been modeled as an iterative loop cycling through design entities that stimulate cognitive processes that produce design operations that in turn generate design entities, and the cycle continues. 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 intuitive to analytical processes and encompasses a number of modes of thinking. 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 linkography and cognitive mode is also explored. 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.

I. Introduction

We have observed that students become less divergent over the course of a four-year engineering education. As many models and methods of creativity [1-7] emphasize the importance of intuitive, unconscious, and stochastic thought in the creative process, we believe that engineering curriculum's heavy emphasis on analytical thinking may be inadvertently hindering creative abilities by teaching students 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" [2]. For instance in jazz improvisation, the lateral prefrontal regions (associated with planning, sequences, problem-solving, and focused attention) deactivate [8]. Nevertheless most would deem the musical outcome of improvisation to be highly creative. 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 [9]. The question arises: 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 including past experience, cognitive biases, and the nature of the designer's surroundings. Most existing conceptual design models, such as Geneplore [10], design by analogy [11, 12] and Generate-Stimulate-Produce (GSP) [13], 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 why it is so important 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, techniques can be developed in the future to stimulate intuitive and analytical thinking as necessary to enhance creative idea generation and student education.

II. Related Work

A. 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 [14]. Type 1 processes are fast, intuitive, heuristics-based, and emotional, and answer simple questions like, "What is 2 x 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 x 17?" and also kick in if they detect an error is about to be made [15, 16]. 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 [6]). It is very likely that Type 1 processes will prove to be stronger contributors to the creative design process than Type 2 processes alone.

Hogarth [18] explored the balance 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. While the analytical approach seems to naturally be preferred by students, it is possible that 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 [19] definition of fixation.

There is plenty of evidence demonstrating both the value and the danger of using Type 1 reasoning. Heuristics-based (Type 1) reasoning is most beneficial in a benign environment that supports the use of heuristics through experience and implicit learning [20]. It has been found in certain instances, Type 1 processes can perform better than Type 2 thinking [21]. Pretz [22] 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. In his eight stages of creative process model, Sawyer [23] 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 [15, 24-26].

On the Cognitive-Experiential Self-Theory (CEST), another dual-process model that differs slightly from Stanovich and West's, Epstein [4] 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. 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.

A correlation has been found between dependence on intuitive thinking and creative potential [17], and we look to explore and expand on this result. Another study performed by Eubanks et al. [27] supports the idea that intuition and creativity are correlated. Type 1 processes are able to 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 logical, serial Type 2 processes. With experience and abstraction of knowledge comes confidence. Epstein [4] notes, "From the perspective of CEST it is necessary to recognize that high self-esteem at the conscious, rational level may coexist with low self-esteem at the experiential level." This is perhaps why self-efficacy (or creative confidence) is important in the context of training students to be competent designers, as belief in one's abilities in creative idea generation could be as important as the abilities themselves when it comes to creative output [28].

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 [29]. 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 a presentation, the intuitive emotional response overwhelms the rational response. The nature of the intuitive contributions to the design process is not well understood, and is explored in this paper.

B. Cognitive Continuum Theory

Cognitive Continuum Theory, or CCT, [30] uses the same dual-process building blocks as above, but describes the outcome of cognition, rather than the process [31]. Using varied combinations of analytical and intuitive thinking, six modes of inquiry are described on a continuum ranging from pure analytical thought to intuitive thought. Quasirationality [32] 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 [30, 33]. We believe that this oscillation is a fundamental aspect of the iterative nature of conceptual design. Engineering design problems are initially ill-structured and open-ended, but through abstraction, the problems are decomposed into well-structured problems, so that the analytical mind is used for much of the design task, even though the nature of design would call for an intuitive approach by students. This oscillation is explored in our analysis.

C. Previous Work

Our previous model of creative stimulation in conceptual design [13, 34] was developed based on Finke, Ward and Smith's [10] Geneplore model. 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, where as exploration is the convergent phase. Benami [34] expanded Finke et al.'s model to the engineering 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 Figure 1. As preinventive ideas become mature ideas and knowledge, the cycle continues until a final design is reached, or can be terminated if the designer is unable to obtain a satisfactory design. With the addition of CCT, we propose an expansion of the model that maps cognitive processes onto the intuitive and analytical spectrum, as shown in Figure 1.

Based on the GSP model, we also explored iteration in conceptual design [35]. 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 decrease novelty. This model suggested that the default analytical approach might have suppressed novel ideas [35].

The authors made a first attempt to distinguish the dual-process roles of Type 1 and Type 2 processes the in the design process of students [36]. 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. The work reported in this paper differs in that we examine the processes exclusively, without comparing the

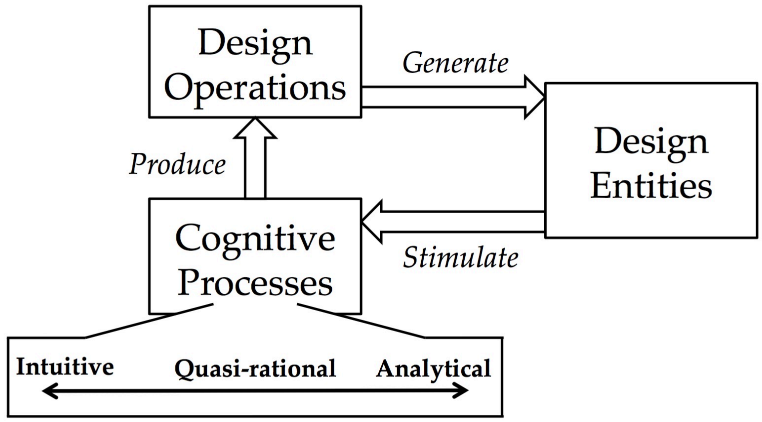

Figure 1: Expanded GSP model incorporating CCT.

novelty of ideas. The ideas are only presented in the linkography as a point of comparison to the oscillation of the cognitive processes. In the previous pilot study, which been supported by additional data and analysis [37] 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 some quick thinking, like unexpected associations, and later stages involve more convergent thinking and solution analysis. The most novel ideas in our study were generated through a balanced combination of Type 1 and Type 2 thinking. Continuing on these preliminary findings, we seek to understand exactly how intuitive and analytical thinking contribute to and operate differently in the design process.

III. Experimental Approach

A. Hypothesis

H1: The early design phase will be dominated by oscillations favoring intuitive processes, and these will slowly diminish until overtaken by primarily analytical processes at the end of the task.

This hypothesis is based off of our prior analysis [36] 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. This logically follows from the divergent and convergent thinking that naturally governs creative idea generation [38].

B. 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 [3] 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 [39]. 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 [40]. However, this method is the best the design available to researchers to explore cognitive interactions.

C. Subjects

Subjects for this experiment consisted of ten senior and master's students in mechanical engineering at the University of Southern California, who were 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.

D. 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 a group 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.

IV. ANALYSIS

A. 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 collaborative stimulation were first identified. The data from each groups 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 collaborative stimulation processes (*prompting, clarifying, seeding,* and *correction*) were identified by examining how cognitive processes came about, and if they could be attributed to a collaborative stimulation.

B. Cognitive Continuum Theory Analysis

In applying CCT to the collaborative stimulation approach, the classification of processes and statements coincided with the hallmarks of fast, intuitive Type 1 thinking and slow, logical Type 2 thinking. 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 quasirationality 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 to 9 (5 being transformation, which represented the rough dividing line between intuitive and analytical modes) and 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.

Table 1: Cognitive Continuum Coding

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

It should be noted that this mapping

does not have the resolution to divide explicitly between the six modes of thinking in CCT well summarized in Cader, Campbell, & Watson [41]. This analysis is only meant to give a rough picture of the design process for future dual-process analyses and design methods. The coding 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. 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 thinking in each design process is desired

V. Results

The following figures display the cognitive oscillations discussed earlier as predicted by Hammond's [30] continuum theory for two groups who participated in the study (Figures 2, 3, 5, and 6). Also shown are the linkographs for the corresponding groups that show the genealogy of ideas (Figures 4 and 7). The solid lines mark the movement between cognitive processes throughout the design task, and the green dotted line marks quasirational transformation (incorporating elements of both intuitive and analytical thinking) as the dividing line between intuitive (bottom of chart) and analytical (top of chart) modes of thinking. Figures 2 and 5 chart the individuals' retrospective discussion of their ideas over the design task, and Figures 3 and 6 chart the live video protocol discussion between the two collaborators, without differentiation between the two individuals.

In the video protocols (Figures 3 and 6), we observe oscillations between loops of intuitive and analytical thinking throughout each group's design process. Because of the nature of the task (remembering what they were thinking at the time), individual retrospective transcripts are heavily biased towards analytical thinking and memory retrieval, as likely subjects were consciously relating everything in the video transcript to their final solutions. This produces more erratic oscillations in the data.

Transformation and the other quasi-rational processes surrounding it (prompting, clarification, correcting, and seeding) seem to play a key role, often bouncing cognitive processes back go 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 though an intuitive series of association (1) and prompting (3), which then stimulated ideas through transformation (5) and eventually produced ideas that were related to the original problem through problem (8) and solution (9) analysis. This is a natural progression in the design task, oscillating between intuitive to analytical thinking, which can be seen repeatedly throughout the design 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.

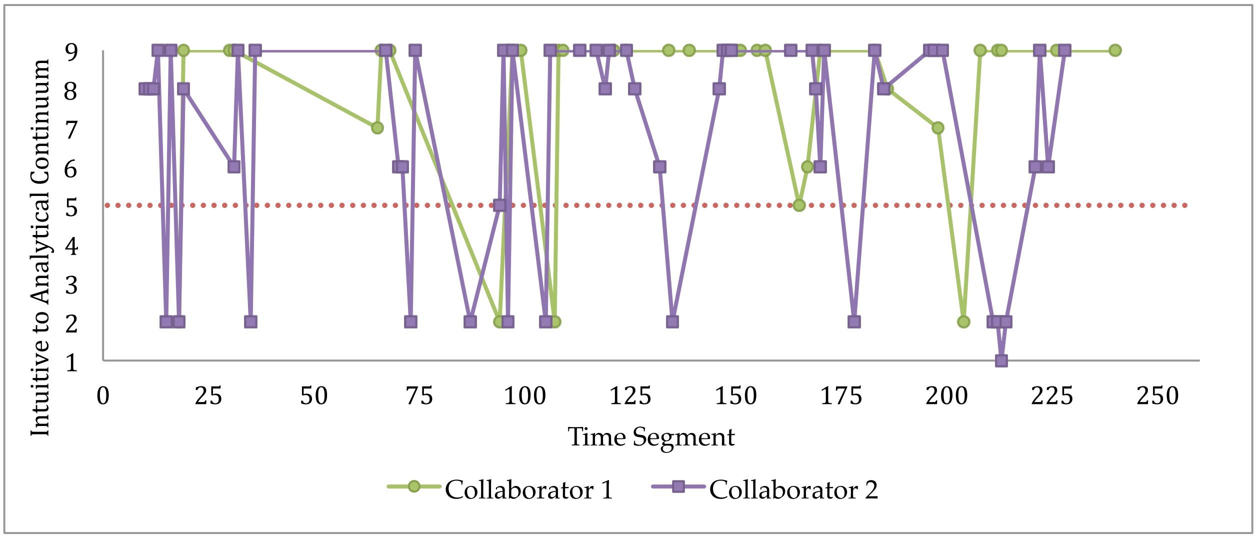

Figure 2: Cognitive Oscillations – Individual Retrospective Protocol (Group 4).

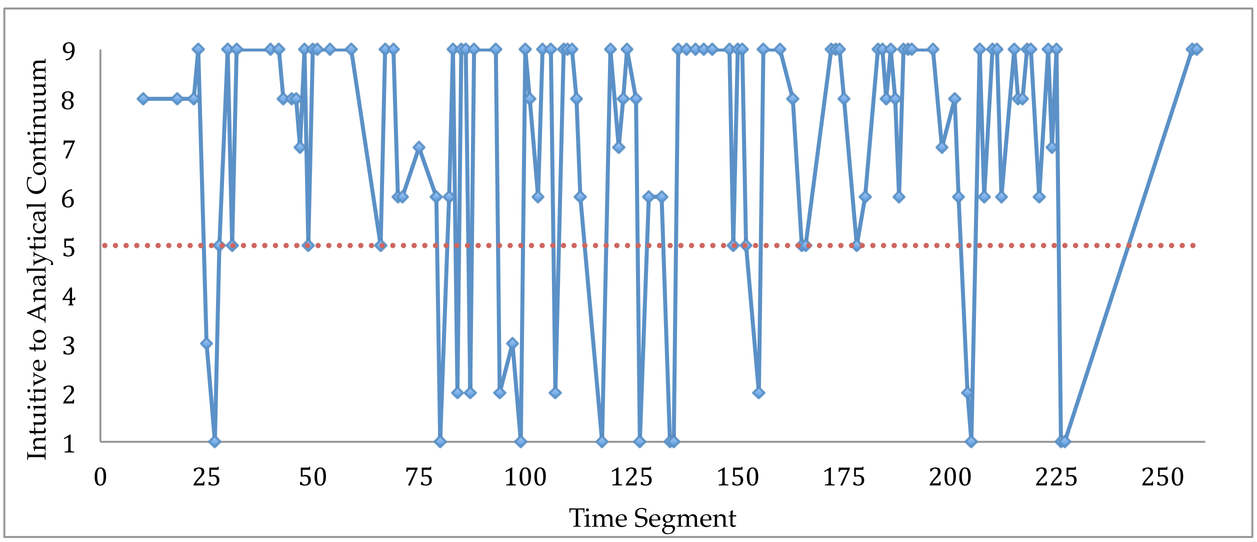

Figure 3: Cognitive Oscillations – Live Video Protocol (Group 4).

Figure 4: Group 4 Linkograph.

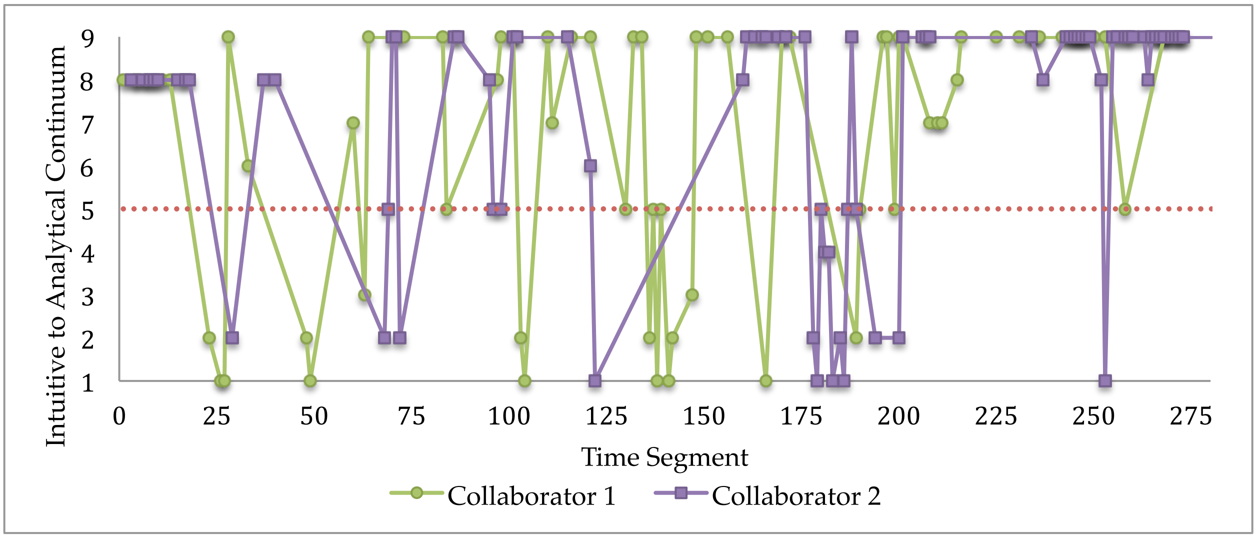

Figure 5: Cognitive Oscillations – Individual Retrospective Protocol (Group 1).

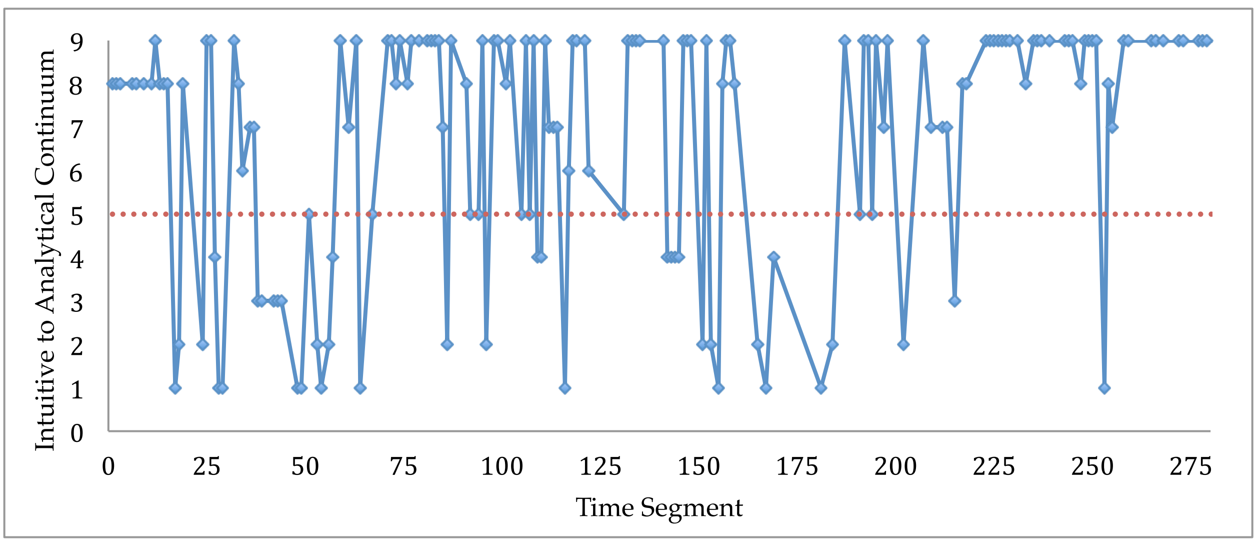

Figure 6: Cognitive Oscillations – Individual Retrospective Protocol (Group 1).

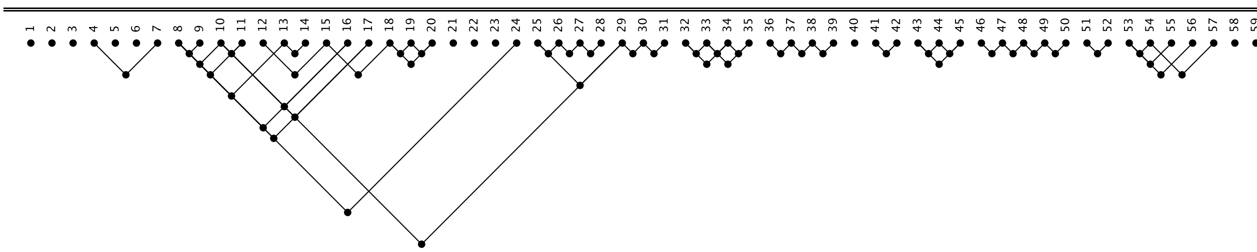

Figure 7: Group 1 Linkography.

Over the experiment, which for group 4 shown in figure 3 lasted about 23 minutes, at the beginning of the task, both intuitive and analytical modes of thinking are observed, but mostly analytical thinking as the problem is analyzed. 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.

The linkographs [42, 43] for each group presented are below the cognitive oscillation charts, and are rotated to highlight an interesting relationship. Ideas are only represented by numbers, nothing more, as the only result we wish to discuss has to do with the complexity of the pedigree of ideas generated by intuitive and/or analytical thinking. Note that linkographs analyze ideas, while the cognitive oscillations analyze cognitive processes. In addition, the 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. Only general conclusions may be drawn. For such analysis, see Moore, Sauder, and Jin [36, 37]. Only the general trend is presented without any numerical analysis for intellectual interest and an avenue for future study. We correlate the linkographs and oscillations via time, as each chart's horizontal axis is correlated with increasing with time.

By inspection, there is an intriguing difference between the character of ideas generated by each cognitive mode. When the subjects used analytical thinking, the ideas were much more likely to be linked to previous ideas. When the subjects used more intuitive thinking and/or intuitive-analytical oscillations, the ideas were more unique, and were less likely to be derived from or connected to 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 approximately 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 Figures 5 and 6. The final phases of design, of primarily problem and solution analysis, do not follow this pattern.

VI. Discussion

A. Hypothesis Analysis

Our hypothesis H1 was not confirmed, but the data are nonetheless 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 large 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, but simply analysis by inspection for the given cases.

B. Oscillations and Idea Generation

These results suggest the oscillations in cognitive modes of thinking throughout the design process as suggested by Hammond [30]. Subjects use both intuitive, experiential, Type 1 and analytical, rational, Type 2 processes throughout the design process, and the combination of both modes manifests itself in the range of cognitive processes displayed.

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 [6, 7]. This analytical mode of thinking is more metabolically demanding than the intuitive mode, which may account for the frequent oscillations between modes. The intuitive and analytical loops are consistent with the iterations in Jin and Chusilp's [44] model of iteration in conceptual design.

The iterative loops described by the GSP model can be informed by the cognitive continuum we proposed, with some iterations associated with analytical thinking, and others with intuitive thinking. Moreover, the quality and number of these loops could be triggered by internal or external stimuli, environment, background experience, or personality and will be the subject of future research. It is unknown why quasirational processes bounce thinking back to the mode from which it came, but this phenomenon warrants further exploration.

The relationship between the character of ideas and number of oscillations and intuitive mode is also intriguing and warrants future study. The idea that analytical thinking would produce more logically connected ideas is not surprising. Nor is it surprising that intuitive thinking (encompassing association and memory retrieval in this analysis) generates more unique ideas by bringing in external stimuli and ideas such as past experiences and memories. This is the strongest evidence yet we have found that confirms the intuitive processes under our definition are uniquely generative, and therefore an important part of the design process.

C. Implications

As intuitive thinking is generally agreed to be the source of innovative ideas, we believe that the intuitive mode thinking should be understood, addressed, and trained over the course of an engineer's education, either in engineering classes or through extracurricular activities such as performing arts. In the authors' opinion, these modes of thinking, particularly the intuitive, are not well understood in the design process. 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 for students' creative potential, and this can be demonstrated to students. This doubt is a hallmark of the analytical Type 2 processes we see throughout engineering education.

One possible contribution of this line of research would be an inventory or test, possibly including the Rational-Experiential Inventory [45] that students could take to determine his or her dependence on analytical and intuitive thinking in a design task. 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 for much of the beginning of the task, which would theoretically generate a plethora of unique ideas. This would be followed by intuitive and analytical oscillations, which would build on the existing ideas. The linkograph of this task would likely be highly interconnected, with links between ideas at the end to ideas at the beginning of the task.

An understanding of the interaction of these two modes of thinking may help to understand 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. To mitigate this, students should be directed to explore an intuitive mode of thinking to explore unrelated concepts and stimuli and then eventually 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.

VII. Summary and Future Work

This work is the next step in developing a dual-process model of conceptual design, and the first step towards mapping Cognitive Continuum Theory onto the engineering design process, 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 (intuitive Type 1 and analytical Type 2 thinking) to explain the outcome of cognitive processes on a cognitive continuum, rather than the process itself.

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. 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.

With this knowledge, pedagogical techniques can be developed to balance the overwhelmingly analytical techniques 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 powers of intuitive thought so that students will have the skill and the confidence to innovate in an increasingly competitive and globalized world.

VIII. Acknowledgements

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X. Appendix

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.

XI. Author Biographies

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 supervised by Dr. Yan Jin. 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 traditionally technical fields, 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) and Design Creativity Workshop at Design, Computing, and Cognition 2014. 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.

Dr. Jonathan Sauder received is Ph.D. in Mechanical Engineering from the University of Southern California in 2013, where his thesis was on "Collaborative Stimulation in Group Design Thinking". Prior to the Ph.D. he received a Masters in Product Development

Engineering from USC and a Bachelors of Science Mechanical Engineering from Bradley University. Dr. Sauder is currently a technologist at NASA's Jet Propulsion Laboratory, in the Technology Infusion Group, which seeks to bridge the TRL “Valley of Death” by implanting innovative, promising technologies on flight missions. He still maintains close ties with the IMPACT Lab at the University of Southern California.

Dr. Yan Jin is Professor of Aerospace and Mechanical Engineering at the University of Southern California. He received his Ph.D. degree in Naval Engineering from The University of Tokyo. Prior to joining USC faculty in the fall of 1996, Dr. Jin worked as a Senior Research Scientist at Stanford University. Dr. Jin is a recipient of National Science Foundation CAREER Award (1998), TRW Excellence in Teaching Award (2001), and Xerox Best Paper Award (ASME International Conference on Design Theory and Methodology (DTM), 2002). He served as Conference Chair (2005) of DTM Conference and currently serves as Editor-in-Chief of AIEDAM Journal, Associate Editor of Design Science Journal, Editorial Board Member of AEI. Dr. Jin is a Fellow of ASME (American Society of Mechanical Engineers).

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