ABSTRACT:

Title of Thesis: FOSTERING CREATIVITY IN ENGINEERING STUDENTS USING PSYCHOLOGICAL THEORY

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Four experiments were conducted exploring the application of modern psychological theory to improving creative performance in engineering students, as measured by the divergent thinking test the Alternative Uses Task [AUT] and the graphical data analysis method linkography. Evidence was found for the presence of the serial order effect, but not for the efficacy of incubation or direct instruction in the psychology of creativity. A more practical test and instruction may be required. Making a meaningful improvement in the creativity of engineering students may require broad, systemic change in the way engineering is taught.

FOSTERING CREATIVITY IN ENGINEERING STUDENTS USING PSYCHOLOGICAL THEORY

by

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To Colleen, for her unwavering patience and support.

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> “Look around! We have so much to work with! So many different things – things that no one would dream of putting together! We cannot help but do something new! Something interesting! … We want to see the unexpected! The strange and terrible! A dream merely soothes – but our nightmares make us run!”
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> ― Agatha Heterodyne, *Girl Genius*[1]

1. Introduction:

According to Kazerounian and Foley: “The history of achievements reveals a process in which knowledge of the mathematical and natural sciences converged with the skills of critical judgment and creativity, an understanding of economics, the adoption of iterative processes that embrace failure, and the desire to create technological miracles. This amalgamation is now known as engineering [1].” There is both an art and a science to creating objects, structures, and processes that enhance peoples’ lives. The problem, not one unique to engineering, is that there is a lack of practical understanding of creativity, its potential to add value to our work, and how to foster it in the education of younger generations [2]. For engineers, creativity is especially important, as industry is looking for workers with the ability to recognize and validate problems, then use critical thinking to develop innovative, original solutions, and to communicate those effectively to their peers and the general public [3].

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[1] P. Foglio and K. Foglio. *Girl Genius,* vol. 13, July 15, 2013. [Online serial]. Available: http://www.girlgeniusonline.com/comic.php?date=20130715. [Accessed Nov. 15, 2018].

As a concept, creativity is something people tend to hold strong intuitive feelings about. Creativity is easily recognized and often attributed to individuals as an innate and ineffable quality. A given person is said to simply be either creative or not. Such people seem to effortlessly generate ideas and objects that are beautiful, emotive, innovative, and compelling. Creativity is also a key part of generating potential solutions for problems, which makes it a subject of great interest to designers and engineers. However, research on creativity has largely been seen as a topic for psychologists to puzzle over.

The capacity of humans to be creative renders us a number of advantages, both social and otherwise: Creativity leads to our survival by allowing us to develop solutions to emerging problems and to develop more refined and effective solutions to existing ones. Creative ideas are often highly lucrative, to their inventors as well as to society more broadly. For some, creativity has led to fame and notoriety. And lastly, whether we wish it or not, humans are inherently creative creatures, who see innovation as its own reward. What's more, all four of these aspects of creativity may be at play simultaneously [4].

In the field of cognitive psychology, such an ethereal definition of creativity is insufficient. A two-criterion definition of creativity, as a combination of originality and effectiveness, has been in widespread use by psychologists since at least the 1960s, and can now be seen as standard [5]. This definition is likewise common in the engineering literature [6]. The importance of originality [often also referred to as "novelty" or, awkwardly, "uncommonness"] is a self-evident in the layperson's definition of creativity and may even be synonymous with it. Effectiveness [or "usefulness", "fitness", "appropriateness", "utility", etc.] acts as a counterweight to originality, keeping creative ideas grounded, at least to a degree, in reality. In the cognitive research, originality is typically the criterion of interest as it is more easily quantified.

Of late, the subject of creativity has been undergoing something of a sea change in the field of cognition research. The conventional view holds that creativity can be divided into two separate processes relying upon different mental mechanisms and leading to different ends. Divergent thinking – the generation of multiple potential answers to an open question – was thought to be a bottom-up process, the result of automatic processes through which semantically distant concepts are activated and combined to form novel ideas. In contrast, convergent thinking – the generation of a best single solution to specific problem – relied upon top-down processes including conscious executive control on the part of the thinker. The distinction between divergent and convergent thinking was first made by J. P. Guilford in his "structure of intellect" model of human intelligence [7]. Though most aspects of this model failed to make a lasting impact on the field of psychology, the concepts of divergent thinking and convergent thinking have stood the test of time.

The growing knowledge of psychologists presents an opportunity for engineers, since at present, there is a disconnect within the field of engineering education. While it is generally accepted that creativity is a fundamental part of innovation in engineering [1]-[4],[6],[8]-[10], and that a greater emphasis on creativity should therefore be incorporated into engineering curricula, attempts to do so have achieved mixed results. Creativity is still sometimes perceived as sloppy, inaccurate, frivolous, and somehow beneath engineers' dignity. What's more, a bias toward the conventional and a fixation upon getting "correct" answers has led to a state where engineering students are disinclined to take risks [1].

Kazerounian and Foley found in a survey of engineering courses at the University of Connecticut in the mid-2000's that while the faculty believed they were encouraging their students to be innovative through the use of open-ended, ambiguous problems and team-based projects, students did not feel encouraged to take creative risks [1]. Work done by Daly et al. at the University of Michigan almost a decade later similarly uncovered a disconnect between the intended goals of instructors and the lessons learned by students [11]. Cropley cites a number of reasons why engineering education struggles to effectively teach creativity. Firstly, there is a lingering opinion in some quarters defining creativity as being the exclusive province of the arts and therefore as being an unsuitable subject for exploration [2]. In addition, engineering degrees tend to be narrowly specialized, with their available credit-hours focused on the acquisition of factual knowledge and technical skills. And, perhaps most crucially, many educators lack a sufficiently detailed understanding of creativity to effectively instill it in their pupils [12].

The purpose of this work is to explore some of the implications of creativity in engineering education, from a psychological perspective. Central to this goal is not just the assertion that creativity should be taught, but that it can be taught [4],[13],[14]. Standing in the way of this premise is the inertia of an education system which, when it comes to engineering, has often seen innovative ideas as happy accidents or tiny miracles if and when they arise. In the highly competitive field of engineering, emphasis has been placed on generating correct answers over wonder and discovery. Instructors are influenced by the methods with which they themselves were taught. And in a profession made up largely of white men, a lack of women and minorities and their differing experiences and worldviews has helped lead to an over-abundance of staid, tried-and-true designs [1].

As Cagan puts it, “Cognitive science offers the possibility of not only acknowledging that creative breakthroughs happen, but how they happen, when they happen, and, from that, how to help them happen [15].” To these ends, the following research questions are explored:

1. Does cognitive psychology theory predict and explain the behavior of engineering students during creative [divergent thinking] tasks?
2. Is the creativity of engineering students affected by the explicit incorporation of cognitive psychology into their curriculum?

The remainder of this thesis consists of the following: Section 2 provides a general overview of the psychological theory underlying creativity, particularly divergent thinking, the current state of engineering education when it comes to creativity, and an introduction to a graphical data-analysis tool called a linkograph. Section 3 consists of a literature review, in which experiments in divergent thinking, incubation, psychology of creativity in engineering education, and linkography are described. Section 4 describes four experiments concerning the serial order effect, the incubation effect, linkographic analysis, and the effect of teaching cognitive psychological theory to engineering students on their creativity. Section 5 discusses the implications of those experiments. Section 6 contains concluding remarks, section 7 a list of contributions of this work, and section 8 brief suggestions for future studies in this vein. Finally, the appendices contain a copy of the presentation slides used in experiment 4 to teach students the basics of the psychology of creativity, as well as information on conducting the experiments and categorizing their data.

2. Background:

This section describes the history and current state of creativity in the field of cognitive psychology, provides an overview of the teaching of creativity in engineering education, and details a graphical method for analyzing designers' thought patterns called a linkograph.

2.1 The Psychology of Creativity:

Cropley cites the Soviet launch of *Sputnik* on October 4, 1957 as the catalyst that caused psychologists in the United States to focus on creativity as a concept to be studied systematically as a matter of national importance [2]. In 1959, J.P. Guilford laid out four stages that encompass the problem-solving process. First, a problem must be recognized and defined, a convergent task requiring the isolation of root causes from peripheral ones. Next, potential solutions must be generated using divergent thinking, developing a broad array of possibilities for evaluation. The final two stages, both selecting the most promising solution for further attention, and drawing conclusions about how effective it might be, again largely require convergent thinking [2],[16]. Wallach and Kogan's influential 1965 book *Modes of Thinking in Young Children* established a dominant paradigm in creativity research holding that divergent thinking is an exclusive function of associative processes working non-consciously in the background of the mind, and convergent thinking is the result of executive processes actively employed by the creative thinker [17]. This view held for four decades.

Several psychological tests have been developed to study both divergent and convergent thinking. Two of the most common were developed in the 1960s and remain in use today: the Alternative Uses Task[2] [AUT], which assesses divergent thinking, and the Remote Associates Test [RAT], which assesses convergent thinking.

As laid out by Guilford [7],[18], the Alternative Uses Task is quite simple. The participant is asked to think about a specific, common object such as a newspaper, tire, or shoe, and then told to list six novel uses for the item. Novelty in this case is defined as being outside the participant's experience, either directly [within their personal experience] or indirectly [read about in books, seen in films, etc.]. The four common ways of scoring the AUT are for *fluency, originality, flexibility,* and *elaboration.* A subject's fluency is measured by counting their responses, with highly fluent individuals having more ideas than less fluent ones. Studying fluency has necessitated abandoning Guilford's initial six-item limit in favor of an arbitrary time limit in more recent studies. Originality is commonly determined either through scoring by a panel of independent judges or by measuring how frequently a given use appears across a study's sample. Flexibility is rated by the number of broad uses for an object. For example, a brick might be used to build a bridge, build a house, or be thrown as a projectile weapon. A brick used to construct a bridge or a house would both be examples of the category "building material," and would be scored as distinct from the category of "weapon." Finally, the elaboration used in a participant's answers might be judged based upon word count, although in recent research, participants are often limited to a single word or short phrase for each response.

The Remote Associates Test was developed by S. A. Mednick in 1968 to measure individuals' performance in convergent thinking [19]. Mednick believed that creative ideas

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[2] The Alternative Uses Task is sometimes referred to as the Unusual Uses Task or the Other Uses Task.

were the result of individual differences in associative hierarchies. The way every person's history and experiences shape the way ideas are stored in the mind is unique and variations in mental structures contribute to differences in convergent thinking from one mind to the next [20]. Specifically, Mednick hypothesized that the flatter an individual's associative network was, i.e. the less prone it was to form stronger associative links between certain concepts over others, the easier it would be for an individual to draw upon remote ideas and combine them in novel ways. The RAT itself is simple; the subject is presented with a series of words – the archetypical example being "mouse," "blue," and "cottage" – and is then tasked with finding a word to link them, such as "cheese." The novelty of the subject's answers can be measured by independent judges or comparison against an established bank of answers.

Recent work, notably by Beaty et al., has shown that when performing a task measuring divergent thinking ability, such as the Alternative Uses Task, both top-down and bottom-up processes contribute to individual performance, with subjects utilizing both conscious problem-solving techniques and the automatic linking of activated mental concepts to generate responses. Divergent thinking may only be one aspect of creativity, but it is well suited as a focus for engineering design research given that the generation of a multitude of diverse design concepts is one of the first, crucial phases of the product design process. And while the ability to generate a large number of novel solutions suggests design success, it does not guarantee that any of the ideas will be viable or practical, as the two-part definition of creativity requires. However, of the four available types of creativity tests, which also include attitude and interest inventories, personality inventories, and biographical inventories, the measurement of divergent thinking has dominated the field of creativity research for decades due to its relative ease of use [21].

One of the explicit tenets of cognition as a field is to describe how the human brain functions in a controlled setting, rather than attempting to apply research in practical, real-world situations. While the major findings of the Alternative Uses Task have been replicated by researchers in other fields [22],[23], their application of the latest cognition theory has yielded mixed results. This is not to suggest that the question of how to make use of cognitive theory is straight-forward, as it is decidedly not. The effects of psychological experiments are subtle and whether or not techniques increasing performance on divergent thinking tests are transferable to more complicated and realistic problems is unclear.

In considering the potential ways of enhancing divergent thinking performance in creators, there are a variety of psychological aspects to explore. One of the most promising is harnessing the potential of the incubation effect. Known to psychologists for at least a century, the incubation effect is a formalized expression of the common human experience of reaching a mental impasse while attempting to solve a problem and setting it metaphorically aside, only to have the solution readily appear as soon as the problem-solving task is resumed.

The causal mechanism behind the incubation effect remains a matter of contention. Mathematician and philosopher Henri Poincaré proposed in 1905 that there exists a "subliminal self" who works diligently on problems while they are outside of conscious attention. This proposed unconscious agent works by automatically testing all the possible combinations of mental elements, analogized by Poincaré as gaseous atoms being formed into molecules, generating a set of potential solutions that are “exceedingly numerous, useless and cumbersome.” The subliminal self then presents those few best potential solutions to the conscious mind for consideration [24]. Incubation was identified as one of four steps in problem solving by Graham Wallas in 1926, who defined it as an unconscious process which generates solutions if conscious attempts at defining a problem prove insufficient to the task [25].

More modern thinking on incubation suggests a number of potential explanations for the effect. These explanations vary not so much in the results, which appear at least partially positive in a majority of incubation studies [26], but rather in terms of which physical and mental mechanisms lead to increased problem-solving performance. Typical explanations suggest that taking a respite from conscious work on a problem yields one or more of the following benefits: a reduction in fixation, a chance to recover from mental fatigue, or the opportunity for nonconscious mechanisms to carry on the work [27]. Fixation is a condition where previous thoughts persist within a subject’s working memory beyond their usefulness, which may lead a thinker to continually retrace well-worn mental paths in search of a new idea. A cycle of fixation may be broken by having the mind focus upon another, unrelated task. Mental fatigue occurs when a certain set of neural circuits becomes overworked through continual use. Resting these areas of the brain may likewise result in a renewed level of performance.

2.2 Creativity in Engineering Education:

While there is significant support for the incorporation of and emphasis on creativity in academia, it is by no means universal. The divide tends to fall between educators focusing on design, who favor the teaching of creativity, and those focusing on process or systems, who are less enthusiastic. This may be the result of a misunderstanding about the nature of creativity, which in the popular imagination can seem both too nebulous for a highly technical domain and also as being an innate talent of individuals, as opposed to a teachable skill. This view has not been effectively countered by the literature on creativity in engineering education, which tends to consist of either a.) anecdotal accounts of creative processes in schools or b.) the personal views of educators based upon their own experiences [6].

Broadly speaking, the history of engineering education in the developed world has undergone three phases since the middle of the 20th century. During the 1950's and early 1960's, engineering education focused on hands-on learning, emphasizing the education of veterans after the Second World War. These engineers often already possessed a great deal of informal technical knowledge gleaned from either defense work at home or the use of increasingly technologically sophisticated equipment abroad. From the late 1960's until the early 1980's, the demands placed upon engineers by the Space Race, the Cold War, the energy crisis, and computing began to outstrip the intuition-based learning of the previous phase. Being an engineer now meant having a mastery of mathematics and science, and the curricula followed suit. Finally, since the late 1980's, the emphasis on technical learning has left engineers lacking in critical thinking, team dynamics, cultural awareness, communication, creativity, problem solving, and economic analysis. To counter this, engineering education has turned to teaching design [1].

Within any given designer, Treffinger et al. identified a number of "personal creativity characteristics," including cognitive abilities, personality traits, and personal experience. These characteristics vary between individuals and may involve aspects that interfere with each other. As such, no one person is going to be capable of possessing all personal creative characteristics, or even be able to make use of all they do possess at once. What's more, personal characteristics are just one of four interacting factors affecting creativity, along with creative strategies, environmental and social effects, and the created object itself [28].

When it comes to teaching creativity to prospective engineers, it becomes important to explicitly state what kind of creativity is needed. Liu and Schönwetter identified five levels of creativity, with a hierarchy in terms of how utilitarian its ideas are. *Expressive creativity* involves developing a unique idea without paying attention to its quality [i.e. its feasibility, durability, affordability, etc.] *Technical creativity* involves creating products skillfully, but without a sense of expression or innovation. *Inventive creativity* is the repurposing of old ideas in new ways. *Innovative creativity* is the ability to "penetrate foundational principles," or to "think outside the box." Finally, *emergent creativity* is the ability to incorporate the most abstract principles from a body of knowledge, such as relativity. As engineers, our goal should be innovative creativity. To this end, working in teams is extremely useful, as a diversity of experience and expertise in problem solving leads to openness, flexibility, non-conformity, risk taking, the tolerance of ambiguity, and intellectual bravery [9].

In order to spur students to generate creative designs, there are a number of common methods used in the concept generation process, including *brainstorming, synectics, morphological analysis,* and *brainwriting.* Each has various strengths and weaknesses when compared to the others, but all are focused on enhancing designers' divergent thinking abilities [6].

Used as intended, brainstorming is rather more rigorous than just having a group of people generate a list of ideas. The technique is based upon two fundamental principles: the deferment of judgment and the notion that quantity breeds quality. All ideas are important in divergent thinking, even the outlandish or unfeasible ones, because any idea can act as the trigger for further, useful concepts. For this reason, criticism is prohibited during the brainstorming process and participants are encouraged to "freewheel" with their ideas. In particular, working in a group with a variety of personal experience can lead to the combination of and improvement upon ideas that would be impossible to generate by a single individual. The single greatest potential impediment to brainstorming is the unwillingness of participants to fully commit to a judgment-free process, leading to pre-emptive self-judgment which may quash useful suggestions. Fear of appearing foolish may lead to useful ideas never being uttered aloud [6],[29]. Brainwriting, a related method in which ideas are shared in a written rather than vocal form, tends to result in reduced inhibition and self-judgment by participants [6].

Synectics, or design by analogy, involves the use of analogies and metaphors within a systematic framework. A trained facilitator uses operational mechanisms particular to the method bring about creative thinking and overcome creative blocks [6],[30]. A typical synectic process involves generating a list of people, objects, situations, and actions similar but unrelated to a given problem. Each of these concepts is then described in detail without referring to the original problem, before being translated into statements that do apply, whereupon they are discussed as potential solutions [6],[31].

In morphological analysis, problems are divided up into the smallest possible number of solution neutral functions possible, in an attempt to develop the broadest possible problem definition with the largest possible solution space to explore. Achieving this goal requires great care in preparing the functions, eliminating as many biases as possible, which usually take the form of pre-existing solutions to the problem. A variety of possible methods for achieving each of the functions are proposed, which can then be mixed to form a variety of potential solution concepts [6],[32].

As Sören Törnkvist notes, part of the current emphasis on scientific and mathematical fluency in engineering education is there to delineate a social stratification between engineers on the one hand and technicians and mechanics on the other. This notion is further reinforced by the prevalence of “weeding out” courses in undergraduate engineering curricula. While 90% of students who start in such programs might make capable engineers, only 40-50% of them will graduate with engineering degrees. Further, and somewhat controversially, Törnkvist identifies five ways in which engineering education can be changed to emphasize creative outcomes for students:

1. Educators must know and apply modern education theory in their classes.
2. Educators must adopt humanistic attitudes in their teaching by, among other things, adapting their lessons to appeal to a broad variety of learning styles.
3. Teaching should emphasize the use of [open-ended] problems.

4. Traditional engineering education should be complemented with qualitative subjects like sociology, the history of technology, and anthropology to put the technical work into a broader social context.
5. Engineering departments must accept that a single person cannot simultaneously engage fully in engineering research while also fostering future engineers [4].

As early as 1961, educators were being professionally advised on the nature of creativity in students. In that year, Mel Rhodes advised his fellow teachers in the *Phi Delta Kappan* that there were "4 P's" that defined a person's capacity for creativity. *Person,* the individual's traits including personality, intellect, temperament, habits, behaviors, and attitudes [among other qualities], determine whether or not someone is capable of creativity. *Process* includes a person's motivation, perception, thinking, and communication, which are teachable qualities, at least to a degree. *Press* is the relationship between humans and their surrounding environment and is a reminder that we exist within the larger world, not apart from it. Finally, there are *products,* the physical manifestations of ideas, each of which represents the creative impulse of other people, possibly across a significant time and/or distance [13].

When it comes to incorporating the habit of creativity into any plan of study, Sternberg identified three crucial factors to success. The most basic and self-evident factor, without which creativity is impossible, is that students must regularly be given the opportunity to try out new ideas. Furthermore, creativity requires positive encouragement and exhibiting the desired creativity must be rewarded somehow [28]. Kazerounian and Foley came to similar conclusions, combing the literature to collect and refine a series of rules they termed 'The Ten Maxims of Creativity in Education:"

1. *Keep an Open Mind:* If students can be taught to look at common situations in fresh or unusual ways, they can learn that the best answer to a problem is not always the obvious one.
2. *Ambiguity is Good:* Students can be taught that the uncomfortable period between having a question and reaching an answer is not only tolerable, but useful. The more time taken to gather information before reaching a decision, the more likely innovation is [1].
3. *Iterative Process that Includes Idea Incubation:* Following Wallas [25], time must be allowed for students to understand the problem, collect information, to allow for incubation, to formulate solutions, and to verify the chosen solution.
4. *Reward for Creativity:* Creativity is enhanced by positive reinforcement. If creativity is explicitly rewarded, students will be incentivized to innovate. If a set answer is required, they will have little reason to put the effort into being creative.
5. *Lead by Example:* Students can be inspired to be creative by learning from past historic and personal examples.
6. *Learning to Fail:* Mistakes can readily lead to a deeper understanding of complicated ideas, but the fear of harsh criticism or low grades for making mistakes leads to a learning environment that discourages intellectual exploration and discovery.
7. *Encourage Risk:* Similar to “learning to fail,” students who are recognized and rewarded for not playing it safe will be more likely to take on challenging projects and give themselves the opportunity to learn more.

8. *Search for Multiple Answers:* Even if students generate a working solution to a problem, the use of brainstorming and "what if" questions can stimulate creativity even if they are purely hypothetical.
9. *Internal Motivation:* Making a topic relatable and important beyond the scope of the classroom can build students' curiosity and motivation to understand it more deeply and fully.
10. *Ownership of Learning:* Giving the students some control over the direction of their education, be it by allowing them to choose project topics or to participate in curriculum development, will increase their personal investment [1].

Taken together, these maxims encourage engagement on the part of students and require instructors to give them the flexibility and space to do so. In the case of engineering education, they represent a systemic shift away from the highly structured and limiting approach that had taken hold by the end of the 20th century.

In terms of developing metrics to study the psychology of engineering students, J.J. Shah was one of the earliest cognitive design researchers in engineering; one of his earliest works on creativity in engineering design noted the need to explore the applicability of cognitive psychological theories to the problems of engineering design through controlled experiments using complex tasks, such as redesigning traffic lights to mitigate the effects of snow [34]. Collaborating with a cognitive psychologist, educational psychologist, and a psychometric consultant, Shah developed tests for students to assess their development of cognitive skills important to creativity in engineering design: divergent thinking [35], visual thinking [36], and abstract reasoning [37]. This work is ongoing, with an active request to engineering researchers to collect additional data.

2.3 Linkography:

A graphical data analysis technique known as "linkography" was developed by Gabriela Goldschmidt to study and quantify the productivity of architects designing in groups [38]. Despite being from a different, albeit similar, field, linkography provides a means for studying the way designers work in engineering as well.

A typical linkographic data set begins with an audio or audio/visual recording of designers undertaking a design task. This recording is then divided into "moves" by the researcher, relying largely upon common sense to parse the conversation into a series of discrete ideas. Goldschmidt identified a move as a single coherent proposition pertaining to the design activity, with the scale and resolution of the analysis being set by how conservative the researcher is in interpreting where one move ends and the next begins [38].

After being divided into *moves,* the connections between the moves are then developed, forming the eponymous *links* in a linkograph. Like moves, identifying links is largely left up to the common sense of the researcher. Links are found by working piecewise through the moves sequentially, asking whether or not each individual move related in any way to one of its predecessors. *Forelinks,* which lead to future moves, indicate an idea to be explored further, while *backlinks*, which connect to previous moves, reflect a refinement or conclusion of previous ideas [38].

A number of patterns and metrics can be drawn from a linkograph, which can be used to infer something about the designers being studied. Three patterns of linking are particularly common. A *chunk* is a group of consecutive moves, typically between one and two dozen, which generate links within wholly or almost wholly with each other but not with other moves. A chunk reflects the identification and exploration of a single idea. *Webs* are particularly dense areas of a linkograph representing a period of particularly intense design reasoning. In Goldschmidt's studies, webs consist of roughly 12 links in a span of 8 or so moves, and are relatively rare, occurring in fewer than half of linkographs. If four or more sequential moves all form backlinks to the move immediately preceding them, a *sawtooth* is formed, and may indicate the gradual refinement and evolution of an idea. The *link index* of a linkograph is calculated by dividing the number of links by the number of moves, with a value of 1.0 being the rough cutoff between linkographs displaying low versus high productivity. Particularly important moves are designated *critical moves* and are identified as those moves with more than a threshold number of backlinks or forelinks [or in exceptional cases both]. This threshold is identified by the researcher and set at a value to designate roughly 10-12% of the moves as critical [38],[39].

While linkographs were once drawn by hand and can now be made using specialized software [40], it is also possible to make and manipulate linkographs by adapting a spreadsheet program such as Microsoft Excel. An example of such a linkograph is shown in Figure 1. In such a linkograph, moves are displayed as a list, with a diagonal linkographic field placed next to it. Darkened spaces indicate a link between two moves, with forelinks being read along rows and backlinks being read along columns. In Figure 1, for example, move one has forelinks to moves two and five, while move five has backlinks to moves four and one. A sawtooth exists between moves thirty-one and thirty-four, somewhat nebulous chunks can be seen at the beginning, middle, and end of the sequence, and no webs are obvious.

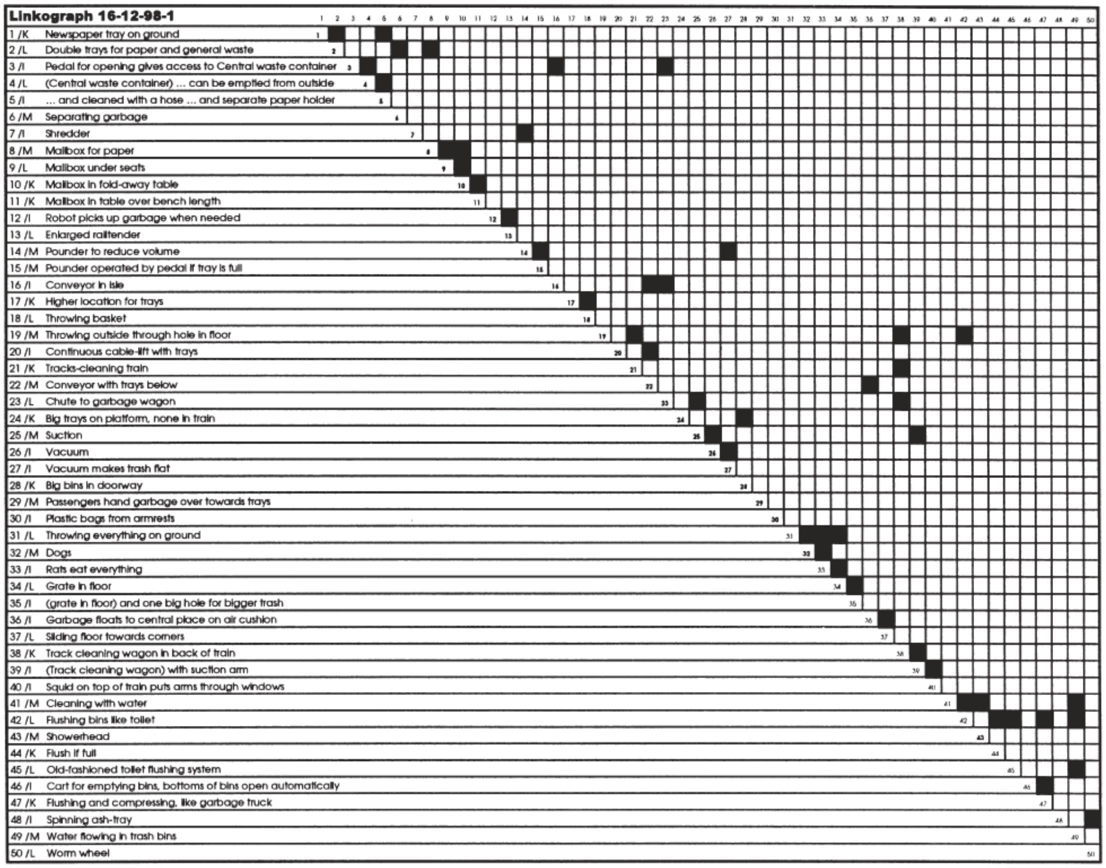

Figure 1. An example of a linkograph generated using spreadsheet software [41].

3. Literature Review:

Experiments in divergent thinking, incubation, creativity in engineering education, and linkographic analysis are described in this section.

3.1 Divergent Thinking:

Gilhooly et al. (2007) [42]:

Gilhooly et al. claim to have conducted the first detailed examination of the cognitive processes underlying subjects' performance on the Alternative Uses Task. Emphasis was placed upon determining why the subjects made the choices they did, by both having them narrate their thought process as they completed the test, and then by identifying which responses were old, i.e. the product of past experiences stored in their episodic long-term memories, and which were new, that is generated within the context of the study through the combination of elements within their semantic memories.

The first experiment in the study served two purposes. By comparing the originality and fluency of subjects on the AUT between one group 'thinking aloud' [N = 40] and the other acting as a silent control [N = 64], it was established that narrating their thought process did not impede the participants' performance in any meaningful way. Also, by analyzing the content of the speaking subjects' statements, patterns were found. 97.5% of the subjects began the test by accessing their episodic memories and giving examples from their past experiences. Only when this source was exhausted did they move on to one or more of three semantic strategies, which did not occur in a set order. In the property use strategy, the subjects might focus on the object's intrinsic properties, for instance recognizing that a brick’s weight might make it a useful doorstop. The disassembly strategy involves mentally deconstructing an object and then assessing each component’s intrinsic properties for useful ideas, such as removing the lace from a shoe and using it to tie back one’s hair. The broad use strategy is exhibited by using the item in a non-specific way, such as for transport or as an object d’art. In general, fluency in divergent thinking relies on memory use to quickly state a large number of ideas, whereas novelty relies upon the semantic strategies in order to generate unforeseen combinations.

In a second experiment, Gilhooly et al. investigate how subjects [N = 103] used inhibition and switching behaviors to generate responses on the AUT. Inhibition was used by subjects throughout the test, first by suppressing the dominant use of the target object to come up with alternatives, then by suppressing previously given and otherwise unsuitable responses to prevent repetition. Each participant’s decisions to switch from one strategy to another, or even within a single strategy was also considered. After taking the AUT, the participants were asked to circle those responses they considered ‘new’. They were then given a test of category fluency, by naming as many kinds of animal as possible, which predominately uses long term memory, and letter fluency, by naming as many words as they could beginning with “H,” a task which relies on executive control processes. Fluency with new uses positively correlated with letter fluency, while fluency with old uses positively correlated with category fluency. These findings were interpreted as showing that higher levels of executive control suggest a better ability to generate novel ideas, while the generation of old ideas is largely a matter of automatic retrieval.

Vartanian et al. (2009) [43]:

Vartanian et al. compared participants' [N = 73] performance on the Alternative Uses Task with their performance on Wason's 2-4-6 task, which is used as a measure of inductive reasoning. In the 2-4-6 task, the subject is presented with a sequence of numbers [e.g. 2-4-6] and asked to determine the rule(s) behind their progression by presenting a succession of hypotheses to the test-giver, who is allowed only to confirm or refute each hypothesis in turn. Participants were judged on whether or not they successfully discovered the correct rule[3], how many hypotheses they made within the ten-minute time frame, and whether their hypotheses were positive or negative. While it was found that those who generated more hypotheses on the 2-4-6 test were also more fluent on the AUT, the exact nature of any connection was undetermined.

Nusbaum and Silvia (2011) [44]:

Nusbaum and Silvia tested the effects of executive strategy use and fluid intelligence upon divergent thinking. Fluid intelligence is the aspect of general intelligence that deals with understanding and processing novel information and situations. After an initial experiment [N = 226] showing a positive correlation between performance on fluid intelligence tests and the AUT, a second experiment was conducted to determine whether strategies for divergent thinking could be taught. Participants [N = 188] were divided into two groups and each given the AUT and a fluid intelligence assessment. The control group

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[3] The rule to the 2-4-6 sequence is simply that the numbers increase from left to right. Most participants generate rules which are much more complicated than this to explain the sequence.

was given no special instructions, while the other was advised to use the disassembly strategy described by Gilhooly et al. [42][4].

Being given a strategy to use resulted in an exaggeration in the effect of fluid intelligence on divergent thinking when compared to the control. This indicated that strategies need not only be applied, but also must also be actively engaged with and maintained by executive processes in the face of interference. Individuals with higher fluid intelligence are better able to benefit from abstract strategies than those with lower fluid intelligence.

Beaty and Silvia (2012) [45]:

Beaty and Silvia investigated the serial order effect, an extremely robust finding in creativity research where the originality of answers on a test will tend to increase with time even as the rate of ideation decreases. The classic explanation for this phenomenon is that it results from the low-level, non-conscious activation of associative links over time, eventually resulting in increasingly remote semantic distances between the concepts combined into novel ideas [20],[46]. This traditional explanation is tested against a hypothesis based upon various executive processes unfolding over time, including strategy choice, interference management, and directed search and retrieval. Beaty and Silvia note, based upon the work of Gilhooly et al. [42], that people identify, exploit, and switch away from strategies over time. The number of times these switches occur is positively correlated

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[4] As the object given for the AUT was a brick, which is difficult to disassemble, it is curious that they chose this strategy to teach.

with both general intelligence and working memory span, as is the ability of subjects to inhibit interference caused by obvious uses, previously named uses, and sundry distractions on the Alternative Uses Task.

133 undergraduates were given the AUT on a computer, with each response individually time-stamped for use in a fine-grained temporal analysis. Subjects were also given a series of six tests of fluid intelligence, emphasizing visuospatial and non-verbal tasks, which Beaty and Silvia considered a better match for the AUT than verbal intelligence tests. If divergent thinking is an unconscious associative process, performance on the AUT should not be affected by a subject's fluid intelligence. If divergent thinking is an executive process, fluid intelligence should predict novelty on the AUT while also moderating the serial order effect, with more novel answers given throughout the test regardless of time.

These latter predictions were mostly confirmed in the experiment. While the serial order effect was seen to some degree across all fluid intelligence levels, it was less pronounced in those with higher fluid intelligence, i.e. they began the test with more novel answers and experienced a smaller relative increase in novelty over time. The continued presence of the serial order effect for participants with high fluid intelligence, albeit in a diminished state, was taken as "indirect and oblique" evidence that there is an interplay between associative and executive processes in divergent thinking tasks.

Benedek and Neubauer (2013) [47]:

Benedek and Neubauer sought to test two hypotheses based upon the work of Mednick [20], which had reportedly been taken for granted since their initial introduction. Firstly, that creative people activate associative links more slowly to begin with than uncreative people, due to the lack of strong associations in their semantic network, but they will generate responses at a steady rate and be more fluent in the long run. Secondly, that the associations made by creative people should be more novel than those made by non-creative people.

150 undergraduates were first given a number of tasks, including free word association, the Alternative Uses Task, and a questionnaire designed to measure creativity. From these creativity data, the top and bottom thirds of performers were divided into separate groups and given the Random Associates Test. Their responses were compared to those given by a large [$n \geq 13{,}000$] reference group. The associative hierarchies shown by the creative and uncreative groups were virtually indistinguishable, with each group becoming slower in its responses to the AUT over time, as well as more original, although the more highly creative group did produce more original answers throughout the test. Both groups showed the same dominant associations, which Benedek and Neubauer attributed to their similar ages, environment, and experiences as college undergraduates. The more creative group also showed a greater fluency in their responses at all points during the study, without the slow start predicted by Mednick.

Benedek and Neubauer showed Mednick was partially correct in that more creative people generate more original ideas, which seems an almost tautological statement. However, these differences are not borne out in the way creative people organize semantic information in their minds. The associative links made by all subjects in this study showed similar shapes, with the same dominant associations, indicating that creative individuals do not possess an unusual way of organizing their associative knowledge, but rather a more effective method of accessing it. The answer to exactly what this method is remains to be determined.

Beaty et al. (2014) [48]:

Beaty et al. seek a rapprochement between the associative and executive process camps studying divergent thinking. To this end, they conducted a study incorporating variables of interest to each theory, finding evidence for the presence of both bottom-up and top-down processes in divergent thinking. Associative performance was tested by means of a series of verbal fluency tasks, such as listing words in a free association chain. Responses were assessed by latent semantic analysis, which compared the responses versus "a large corpus of text" to determine semantic distance. Executive performance was tested through a variety of fluid intelligence tasks, specifically non-verbal ones, including a paper folding task, in which participants were asked to fold a piece of paper in a specific way, puncture it with a pencil, and then predict the paper's form once unfolded.

Two separate experiments were performed [N = 147 and N = 185], with each comparing novelty and fluency on an AUT versus performance on either the associative tests or the executive tests. Correlations were found linking divergent thinking fluency and novelty to both the ability to connect semantically distant ideas as well as the ability to executively inhibit undesirable information and to switch strategies.

Storm and Patel (2014) [49]:

Storm and Patel explored the connection between divergent thinking and forgetting in a series of experiments, concluding that the generation of new uses on an AUT caused subjects to forget previously studied uses more quickly than those who did not participate. In one experiment, a baseline group [N = 34] was given a list of uses for an object to study for 12 seconds, while an experimental group [N = 34] was given an identical list to study for 12 seconds before being asked to generate new uses for 60 seconds. The experimental group were specifically tasked to generate new uses that were either "unusual" or "mundane." All subjects were then asked to recall the list of uses initially studied. The baseline subjects, who had not been asked to generate new uses for the object, were better able to recall the listed uses than the experimental group. Within the experimental group, those asked to generate "mundane" uses outperformed those who generated "unusual" uses.

This general pattern repeated in further experiments, leading to the conclusion that the process of forgetting may be a mechanism through which the mind overcomes fixation, suppressing information which is unlikely to be useful without impeding access to information which is more likely to be.

Van de Kamp et al. (2015) [50]:

In order to improve the divergent thinking and thus creativity of art students, van de Kamp et al. provided art instructors with a lecture and lesson plan to give the students an explicit grounding in metacognitive theory. Particular interest was paid to the fluency, flexibility, and originality shown in the subjects' responses.

After a pre-test of divergent thinking ability was given at the beginning of the school year, in which 147 high school students were asked to name as many different materials as they could think of, the art students were divided into a treatment and a control group, with the treatment group being given a 50-minute class period of lecture and discussion on the fundamentals of cognitive theory while the control group received a lecture on more traditional art education subjects. The treatment consisted of a brief whole class discussion about the students' previous experiences with innovative design, followed by direct instruction in metacognition and the use of divergent thinking strategies, a whole class discussion comparing the students' old and new ideas about creativity, direct instruction involving examples of innovative artwork and how they relate to lecture topic, and finally practice, including an AUT.

A post-test similar to the pre-test was then administered later in the school year, with those students who received the lesson on meta-cognition placing higher on tests of fluency and flexibility in their idea generation, but not in their originality. To increase the originality of subjects, it was proposed that more material specifically related to originality be placed in the meta-cognition lecture, as in [51].

Van de Kamp et al. (2016) [51]:

Expanding upon their work in their previous study [50], van de Kamp et al. revised their treatment lecture on the metacognition of creativity to include more complex forms of association and the generation of ideas by combination and abstraction. A model was developed categorizing twelve different divergent thinking activities, placed on a matrix with axes for the abstractness of the ideas generated and the metaphorical distance between concepts. For example, at one extreme, the least remote, least abstract activities were identified as having “free association”, in which ideas flow smoothly and incrementally from one to the next, without analysis and relying in large part upon previous experience and analogy. At the other extreme, the most remote, most abstract activities are “transformative,” blending seemingly incompatible ideas by analyzing concepts on a structural, non-literal level and identifying any heretofore unseen similarities. All other divergent thinking exercises, obviously, fall somewhere between these two.

Having developed this divergent thinking model, it was taught to 219 high school art students in a lecture format similar to the one described in van de Kamp’s previous study [50]. Each of the twelve methods was explicitly discussed with the students along with examples of artworks for each, with the goal of inculcating the knowledge necessary for the students to observe, analyze, and evaluate their thought process while thinking divergently, that they might successfully choose appropriate strategies.

By comparing subjects’ performance on divergent thinking tests conducted before and after the metacognition lecture versus that of students who had participated in a more traditional brainstorming exercise. Subjects were evaluated in terms of their fluency, indicated by the number of responses given, flexibility, indicated by the number of different categories their responses drew from, and originality, which was determined statistically by measuring the frequency of responses in the total sample. On all three indicators, subjects who were given the metacognition lecture outperformed the brainstorming group.

3.2 Incubation:

Segal (2004) [52]:

Segal investigated the perpetual question of what, precisely, underlies the incubation effect, favoring the view that the non-conscious work proposed by Poincaré [24] and Wallas [25] does not exist. Instead, Segal proposed that taking a mental break from a problem allows the mind to be released from “false organizing assumptions,” an idea blending both of the traditional explanations of incubation, one in which autonomous processes work on a nonconscious level, and one in which the incubation period allows subjects to be influenced by external cues from their environment. Also noted is the approximately equal distribution of psychological studies on the incubation effect showing evidence for improvement versus a lack thereof.

The hybrid explanation, dubbed the “Attention-Withdrawal Hypothesis” by Segal, states that withdrawing one’s attention from a problem will only be useful if the thinker’s train of thought has been brought to an impasse. In contrast, if the problem in question requires steady, incremental progress to solve, withdrawing attention for a period of time will serve only to delay the solution. Segal asserts that the first step in solving a problem is to set up an “organizing assumption,” which sets up the specifics of the problem in terms of what is known and what the goals are. In this way, the organizing assumption defines the potential problem space within which any viable solutions might fall. A false, or faulty, organizing assumption will result in a problem space which does not include the potential solutions. The act of withdrawing one’s attention from a problem with a false organizing assumption and then returning to it allows the mind to form a new organizing assumption with a new potential problem space, which may allow for a successful outcome.

147 subjects were given a deceptively simple, purposely misleading geometry problem to solve. Those who determined they had reached an impasse were divided into five treatment groups, one which received no break, two which received a short break of four minutes, and two who received a long break of twelve minutes. In addition, those groups which received a break were given either a demanding or a non-demanding task to work on in the interim. All four treatment groups were more likely to solve the problem that was the non-treatment group, with those working on the demanding task faring better than those with a non-demanding task. Those groups taking a short break also received a slightly greater benefit than did the long break groups.

Snyder et al. (2004) [53]:

Snyder et al. attempted to find evidence of nonconscious work by studying whether or not people continue to generate solutions to a problem even after they have been told that a task is ended. 125 subjects were asked to list as many uses as they could in five minutes for a sheet of paper, at which point the subjects were told that the task was completed. After spending five further minutes on a different cognitively engaging task, the subjects were asked to continue listing uses for a sheet of paper for a final five minutes. While the subjects tended to find more uses for the paper in the first five minutes than the second, and often they had run out of ideas before the first portion of the test ended, more novel ideas were found to be forthcoming in the second portion of the test, suggesting the presence of unconscious work.

Ellwood et al. (2009) [26]:

Ellwood et al. note that most studies of the incubation effect have been binary, with subjects [N = 90] judged solely upon whether or not they successfully solve a given problem. This approach is problematic as *any* progress made during the incubation period can be seen as an incubation effect, even if it does not yield total success. Evidence of this incremental incubation effect can be more readily seen in tests of divergent thinking, which involve an effectively limitless pool of potential answers, rather than convergent thinking, in which the potential set of solutions is finite and often only contains one answer.

Three potential causes for the incubation effect were identified. Firstly, incubation may allow for the mind to work on the problem in a nonconscious fashion. The incubation period may also allow for either the decay of fixating ideas upon which the mind is fixated, or for the recovery of those neural pathways which are heavily used in solving the problem at hand.

Subjects' performance was first tested on a wide variety of traits, including fluid intelligence, crystallized intelligence, long-term memory capacity, working memory capacity, and a comprehensive personality inventory. Each subject was then given a variant of Cattell's Things Categories Test [TCT], in which they were tasked with coming up with as many possible uses for a piece of paper as they could.[5] One group was allowed to work for four minutes without interruption. Two other groups were told to cease working after two minutes, before being given a task to complete during an incubation period. This task consisted of either an activity similar to the TCT, in which they listed synonyms to a

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[5] Cattell's Things Categories Test appears to be extremely similar to Guilford's Alternative Uses Task.

set of four words for one minute each, or wholly dissimilar to the TCT, in which they were answered questions from the Myers-Briggs Type Indicator test. The latter two groups were then asked to resume the TCT for another two minutes. It is important to note that the authors gave the incubation subjects the impression that they were done with the TCT after the first two minutes expired, thereby ensuring that any work they might do on the problem during the incubation period was not conscious.

In the end, those who answered the Myers-Briggs questions, which represented a total break from the Things Categories Test, showed a significantly greater number of new uses for a sheet paper than did the group that worked continuously. Those who listed synonyms during their incubation period had a performance between the other two groups', albeit not a statistically different one. As the type of activity conducted during the incubation period had an effect upon subjects' performance, the incubation effect cannot solely be the result of decaying fixation. Because the incubation task was cognitively demanding, the incubation effect cannot be the effect of recovery from fatigue across the whole brain. That being said, Ellwood et al. still saw the mechanism behind incubation as being unclear. The incubation effect could be the result of either nonconscious work or of task-specific fatigue recovery, which would account for why subjects performed better after working on the dissimilar incubation task than the similar. Unfortunately, using the method of this experiment, the evidence for either of these two explanations would appear identical.

Gilhooly et al. (2012) [54]:

Gilhooly et al. examined the influence of incubation on divergent thinking. 184 subjects were divided into three treatment groups, with an incubation task after they heard the test's instructions, with an incubation task in the middle of the test, or without an incubation period as a control. Within each treatment group, participants were given either a verbal [anagram] or spatial [mental rotation] task to complete. The control group was given both the spatial and the verbal tasks, but only once the AUT was complete.

Three possible mechanisms were hypothesized as potential reasons for any effects of incubation. First, it is possible that the mind intermittently devotes a small portion of its conscious attention to the original problem in the midst of the incubation task. This effect can be tested for by comparing the performance on the incubation task of a group with a problem to solve versus a control group without a problem. Second, the "fresh look" hypothesis proposes that during the incubation task, the mind automatically and passively removes inactive information from its working memory over time, including strategies which may have failed in solving the problem previously but are still occupying working memory resources, causing interference. The fresh look hypothesis can be tested by comparing the performance of subjects who receive an immediate incubation break [before any interfering strategies can build up] versus those who receive it in the middle of a problem-solving task. Third, the incubation effect may simply be the result of mental activation spreading through the subject's associative semantic network unconsciously. Gilhooly et al. note that these hypotheses are not mutually exclusive, but they can all be tested for using their experiment.

The experiment showed that having an incubation period, whether immediate or delayed, increased both the novelty and the fluency of participants on the AUT versus the non-incubation control. The immediate incubation period group showed significantly more improvement than the delayed. The type of incubation task, verbal or spatial, had no effect. What's more, the performance of the incubation groups on both incubation tasks was higher than the control, albeit not significantly. This finding does not support the intermittent conscious work hypothesis. The better performance by the immediate incubation group over the delayed was interpreted as favoring the unconscious work hypothesis over the fresh look hypothesis. While the immediate incubation group's minds simply had to passively allow associative links to activate, the delayed group also had to expend some mental resources clearing their working memories, resulting in decreased performance due to fewer available mental resources. While Gilhooly's previous work [42] emphasized executive processes in divergent thinking, this study highlights the role of the mind's associative mechanisms.

3.3 Psychology of Creativity in Engineering Education:

Ghosh (1993) [55]:

Ghosh hypothesized that by giving challenging, open-ended questions on examinations in six semester-long computer science courses at Brown University, students would be forced to think creatively and would gain an appreciation for developing creative solutions. In this case, "open-ended questions" are those that have more than one satisfactory solution, are better the more effort is put in them, force students to reorient their thought processes and think in unconventional ways, and which require the critical re-examination of fundamental knowledge.

Ghosh characterized between 1.5 and 5% of the students as “outstandingly creative” based upon their performance on the exams. 45% of the students were rated either “very good” or “good.” The bottom 40% were described as disinterested, incapable, or unwilling, and viewed the questions as “improper, difficult, and irrelevant.” High achieving students said they enjoyed the questions, despite their challenging nature.

Conwell et al. (1993) [56]:

Conwell et al. describe a case study, specifically the experiences of one team at Louisiana State University in a two-semester capstone mechanical engineering course. In this class, students had to design, build, and test a functioning prototype according to a pre-set, open-ended problem. Specifically, the students were required “to extend the reach of someone in a wheelchair,” including assistance in accessing both low and high areas. The goal was to integrate critical thinking skills with creative thinking skills, i.e. to combine convergent and divergent thinking, respectively.

To design such a reach-extender, the team first considered a number of design problems through various means, including roleplaying out the situation of someone in a wheel chair to get an experiential understanding of the issues in play. The open-ended problem statement was refined by asking salient questions, e.g. “What is the scope of this project? What variables are fixed? What are the available resources? etc.” Collective and individual brainstorming were used, emphasizing the use of “leap-frogging” [adapting and adding to others’ ideas in order to form new ones.]

In the end, verticality was identified as the major issue to be contended with, and two concepts were advanced for consideration by the team, a “periscoping gripper” and an “adjustable height wheelchair.” By listing out the advantages and disadvantages of each, paying particular attention to the forces and stresses involved, the ease of manufacture, and the reliability and safety of the device.

Johnson (1999) [57]:

Chronicling the restructuring of a junior/senior course on hydraulic engineering at Pennsylvania State University, Johnson describes the benefits and shortcomings of replacing a traditional, lecture-based approach to the subject with problem-based learning and cooperative learning techniques. The goal was to use active learning and teamwork to increase students’ critical thinking, self-direction, comprehension and skill development, and self-motivation. In designing problems to foster these outcomes, it was important to make the topics relevant and interesting, to design them to guide students to discover the desired information, and to be complex, but not frustrating, with multiple potential answers. To these ends, the course was developed with the input of former students.

The class of students was divided up into seven teams of four and one of three, with team members chosen on the basis of balancing students’ GPAs, their grade in the pre-requisite fluids course, and any previous experience with hydraulics. To reinforce the team-centered nature of the course, grading was evenly split between individual grades – quizzes

(20%) and exams (30%) – and group projects and presentations (50%). While initially six two-week long projects were planned, as a result of feedback from students at a midsemester assessment, this number was reduced to four and a number of non-graded homework sets were added.

In the end, Johnson concluded that the problem-based learning approach was effective at teaching the material, but time-consuming to incorporate into the curriculum. This evaluation was based upon high grades and high satisfaction ratings on students' course evaluations. No direct comparisons were drawn with respect to previous versions of the course.

Cropley and Cropley (2000) [58]:

85 engineering undergraduates were divided into three treatment conditions and assessed on their originality in completing an open-ended design task. 64 students were given a trio of lectures on creativity at the beginning of a course on innovation. These lectures focused on the non-cognitive of creating novelty, including "the image of a successful engineer," intellectual courage, and a tolerance for unusual ideas. Of these 64 students, 37 took the Test for Creative Thinking – Drawing Production [TCT-DP] [59] and received individual counselling to improve their creative performance based upon that test. The remaining 21 students acted as a control group.

Six weeks after the treatments were given, the students were divided up into small teams and instructed to "build a wheeled vehicle powered by the energy stored in a mousetrap." At a competition, these vehicles were then judged blind by their peers in terms of one objective criterion – the distance travelled – and three subjective criteria – novelty, elegance, and "germinality" [a combination of utility and the ability to open up new perspectives].

While all of the teams produced vehicles fulfilling the minimum requirements set out by the test, most generated fairly conventional designs, using four wheels and powered by spring tension. Some of the more creative solutions included using a mousetrap to launch a [wheeled] airplane on a catapult, attaching the mousetrap to a wheeled cart by a length of string and then throwing the mousetrap, and burning the mousetrap as a source of fuel to generate steam power.

The results of the scoring showed that while scoring highly on the TCT-DP was indicative of the ability to generate creative ideas, this abstract performance did not necessarily lead to an innovative performance on a practical test. Even so, the students who had received individual counselling generated the most creative designs, while those who just attended the lectures were less elegant and novel.

Charyton and Snelbecker (2007) [60]:

Charyton and Snelbacker compared the performance of 100 music students with that of 105 engineering students on a variety of creativity metrics, including the Creative Personality Scale of Adjective Check List [61], the Creative Temperament Scale [62], the Cognitive Risk Tolerance Survey [63], the Harmonic Improvisation Readiness Record [64], and the Purdue Creativity Test [65]. From these tests, scores were selected to reflect the subjects' general, scientific, and artistic creativities.

In general creativity, the music students showed a slight advantage versus engineering students in terms of their creative attributes, creative temperament, and cognitive risk tolerance. As might be expected, the music students also possessed a slightly higher ability at musical creativity. Lastly, and surprisingly, in terms of scientific creativity, there was no statistical difference between the two groups. Even so, both the music students and the engineers displayed higher creativity on average than the general population.

These results led Charyton and Snelbecker to question whether or not existing metrics were capable of adequately measure the creativity of engineering students.

Kazerounian and Foley (2007) [1]:

To explore how well their Ten Maxims of Creativity in Education[6] correlated with the current state of higher education, Kazerounian and Foley conducted surveys of 75 instructors and more than 400 students in three broad academic disciplines: the humanities [anthropology, education, and language], the pure sciences [math, physics, biology, chemistry, and computer science], and engineering [mechanical, biomedical, electrical, computer, civil, environmental, material and chemical engineering]. Instructors were asked which of the maxims they tried to emphasize in their curricula, while students were asked which of the maxims they felt were true of their courses. Particular attention was paid to instances where instructors said a maxim were in use, but students did not perceive it. These instances were termed "disconnects."

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[6] See section 2.2.

Of the three groups, the engineering students were the most likely to feel that one of Kazerounian and Foley's creative maxims was absent from their coursework, perceiving a lack of nine out of ten [with Internal Motivation being the only one present.] By contrast, science students believed that six of the maxims were lacking and the humanities students only two. While all the student groups claimed to value creativity themselves, only the humanities students believed that their instructors agreed, while the engineers believed that their instructors did not value creativity, while the science students' results were inconclusive. In contrast, all groups of instructors said they valued creativity in their students, but only the humanities instructors said that it was evident.

For each of the ten maxims, Kazerounian and Foley presented the following conclusions regarding the state of engineering education:

1. *Keep an Open Mind:* Engineering assignments tend to have known solutions and expected methods for reaching those solutions, which limits the need for creative thought.
2. *Ambiguity is Good:* Students think that mulling over problems is a waste of time. Efficiency and speed are seen to be emphasized by instructors over introspection.
3. *Iterative Process that Includes Idea Incubation:* The technique of putting a problem on the "back burner" was uniquely absent from the engineering students as opposed to the humanities and science students, even though engineering instructors said they preferred to give assignments well in advance of their due dates.
4. *Reward for Creativity:* While engineering instructors say that they reward creativity, they do not do so explicitly. Without a reward for taking an

unconventional stance on a problem, i.e. a higher grade, students lack the incentive to take risks.

5. *Lead by Example:* Engineering instructors claim to use examples of innovators in their field in their lesson plans. Engineering students say they do not. This disconnect may stem from a lack of emphasis on these stories.
6. *Learning to Fail:* All the student groups felt that failure was punished in their courses by means of poor grades. Students tended to prioritize receiving high grades over any personal satisfaction they might derive from more fully exploring the material.
7. *Encourage Risk:* For previously stated reasons, students are reticent to take risks on graded assignments.
8. *Search for Multiple Answers:* Both engineering students and instructors agree that this maxim is lacking in engineering education. A lack of open-ended questions is cited as the cause.
9. *Internal Motivation:* Engineering instructors see students' unwillingness to challenge ideas taught in class, as well as the multitude of identical assignments given as reasons why students lack engagement in the material. Uniquely, internal motivation is the one maxim students do not see this maxim as lacking in their education.
10. *Ownership of Learning:* Engineering students feel that their course plans do not provide sufficient room to accommodate personalization and electives they want to tailor their educations to individual needs and desires.

Shah et al. (2012) [35]:

Shah el al. hope to create a comprehensive set of applied tests to gauge an individual's design skills. These evaluations are intended to evaluate designers – primarily students – on a variety of skills associated with engineering design, in order to identify strengths and weaknesses and to address these with specific educational tools.

Shah et al.'s proposed test for divergent thinking is intended to be non-technical, suitable for undergraduate students at or above the sophomore level, and brief enough to be conducted within a single 50-minute class period. Eight subskills were identified as composing divergent thinking, with four being directly measured from the data and four being indirectly measured by comparing the answers of participants against each other. The four direct subskills are *fluency,* or the ability to consistently generate many solutions, *flexibility,* or the ability to fully examine the design space, *originality,* or the ability to generate unexpected results, and *quality,* or the ability to generate feasible solutions. The four indirect subskills are *afixability,* or the ability to not fixate upon previous solutions, *abstractability,* or the ability to find relationships between ideas, *decomposability,* or the ability to break down complex problems, and *detailability,* or the ability to think about a problem at a granular level. These subskills are measured through a series of eight tasks, with a single task being used to evaluate one or more of the subskills.

Kudrowitz and Dippo (2013) [23]:

Kudrowitz and Dippo applied the Alternative Uses Task – usually a tool used by psychologists in creativity research – directly to the field of design education with the goal investigating the relationship between fluency and novelty. Important developments included the implementation of a method of measuring the novelty of responses based upon the proportion of similar responses across the sample, as well as a method for categorizing responses in a hierarchical manner. 293 AUTs were administered using a paperclip as an example object. Approximately half of the subjects were design/engineering undergraduates and half professional designers and engineers.

The subjects' raw responses were divided into "keywords," which served as the most granular form of the answer during analysis. Multiple semantically equivalent responses, even when worded differently by the subjects, would be treated as identical for the purposes of determining novelty. 2999 individual responses were thus transformed into 214 keywords. These keywords were further refined into a series of 80 "generalized functions," which grouped similar, but not identical ideas together. Finally, the generalized functions were divided eight "treatments" based upon how the paperclip would have to be modified to achieve the desired function.

Kudrowitz and Dippo showed that those who gave fewer responses on the AUT tended to give more common responses than did those who provided a large number, with an average of nine responses being needed before crossing an arbitrary threshold for creativity of 10%, i.e. a response that was given by no more than 10% of subjects. Higher flexibility was also shown to correlate with creativity. By examining the number of treatments used by respondents, it was shown that manipulating the paperclip in a greater number of ways led to more original responses.

Kudrowitz and Wallace (2013) [66]:

Kudrowitz and Wallace presented a study examining a method for quickly winnowing down a large number of product ideas at the beginning of a project, i.e. assess the creativity of subjects' divergent thinking, by means of an on-line service called Mechanical Turk. These ideas were studied in terms of novelty, utility, and feasibility, in a "blue-sky" setting, without constraints or expected outcomes.

A mixed pool of designers, improvisational comedians, engineering students, and others were asked to generate sketches and brief explanations for ways to improve umbrellas, toasters, and toothbrushes. These sketches were then scanned and uploaded to Amazon's Mechanical Turk program, which allows data to be evaluated through crowd-sourcing in return for a small monetary payment. Each sketch was graded on a three-point Likert scale for creativity, clarity, novelty, utility, and "product-worthiness" [a combination of feasibility and marketability.]

While it was found that the quantity of ideas tended to correlate with their creativity [$R^2 = 0.82$], and that large amounts of data could be rapidly processed through the use of untrained, anonymous evaluators, the utility of the ideas generated correlated with neither their creativity nor their quantity.

Daly, Mosyjowski, and Seifert (2014) [11]:

The goal of this study was to assess the current state of the curriculum at a large, midwestern university in terms of its incorporation of creativity as a subject and a goal by the engineering school. The authors identified seven courses which should emphasize creative thought. Five of these courses explicitly included the word “design” in their title, while the other two were cross-disciplinary. Two were introductory [first or second year], three were advanced [third or fourth year], one was a course combined for graduate and undergraduate students, and the final course was a graduate-level introduction to design. Each course emphasized the use of open-ended design problems and a team-based approach. Information was obtained through a combination of class surveys, analysis of lecture materials, and semi-structured interviews with instructors and students.

Courses were assessed on the creativity criteria laid out by Treffinger et al.: generating ideas [divergent thinking], digging deeper into ideas [convergent thinking], openness and courage to explore ideas [risk-taking], and listening to one’s inner voice [metacognition] [28]. For the purposes of fostering creativity in engineering students, improving students’ performance in any or all of these categories was explicitly stated as a goal in one or more of the classes surveyed. Through the data gathered from instructors and students, Daly et al. compared the instructors’ stated goals, the content of the course material, and the students’ learning outcomes were compared.

While improving at least one aspect of the generation of ideas was expressed by each instructor, only three of the courses showed an increase in the students’ abilities. Each of the courses also expressed the intent to improve student’s openness and courage to explore ideas, but only one succeeded. Digging deeper into ideas and listening to one’s inner voice, on the other hand, met with significantly more success, with almost every course meeting these criteria, even when they were not expressed as desired results. This disconnect between the instructors’ teaching goals and the students’ learning outcomes was attributed to the lack of assessment [i.e. grading] on the students’ abilities to generate ideas or to take risks. Students' limited time to devote to coursework and study, as well as the [perceived or real] emphasis on successful projects in grading led to them focusing their attention thusly.

In short, giving students the opportunity to be creative in their coursework will not necessarily lead to this end.

3.4 Linkography:

Goldschmidt (1995) [67]:

While she originally developed linkography to study design done by teams, in this study the process was modified to examine the differences in design work conducted by individual designers versus teams. Specifically of interest is whether the lack of a need for compromise and conformity in an individual designer leads to more diverse and creative concepts than a group of designers with a wider variety of skills and experiences. The individual and the team of three were given the same design task, to create a rack system for attaching a backpack to a bicycle. Both were recorded, with the individual being asked to "think aloud" through the process, narrating the steps taken and his internal thoughts regarding his actions and choices.

It was found that the individual and the team went through broadly the same process in generating a design. In the teams, members were able to perform different roles, acting as checks on one another and ensuring an effective design process, while the individual designer took on multiple roles in order to check his work and ensure against missteps, and to remain conscious of both the big picture and minutiae throughout the process. Both design concepts were considered to be of equivalent quality.

Van der Lugt (2000) [40]:

Van der Lugt investigated the effect of including visual methods in creative problem-solving by using linkography. Four groups of four junior and senior design students each were asked to develop methods for disposing of litter in a railway carriage over the course of ninety minutes. These design sessions were video recorded for later coding and linkography. Links between moves were said to be present in any of the following criteria were met:

1. A new idea displays an obvious similarity with a previous idea.
2. A subject explicitly refers to a previous idea verbally.
3. Similarities in associations [nearly identical ideas with one change between them].
4. Similarities in sketches.
5. Looks and gestures toward previous ideas.

Link density, or the number of links generated divided by the number of moves, served as the primary measure used to analyze the data in this study. This number was further refined into a number of indices based upon the types of links. Links were divided into three categories: supplementary links, which represent small or auxiliary changes, modification links, which involve structural changes to an existing line or thought, and tangential links, which represent an indirect connection to previous ideas. Each of these categories was divided into an index by dividing the number of links of that type by the total number of links. In addition, van der Lugt calculated a self-link index for each subject by dividing the number of links made to each individual’s own ideas divided by the total number of links.

From these measures, van der Lugt determined that more sentential methods of brainstorming were more effective in generating solutions early in the design process, as shown by higher idea quantities and link densities.

Vidal et al. (2004) [68]:

Vidal et al. used linkography as a means of determining the methodology used by design students to brainstorm solutions to design problems. Three different versions of brainstorming tasks were used, termed the visual [or drawing], the sentential [or written], and the objectual [or physical modelling] methods. 60 subjects were randomly placed into groups of five and tasked with designing a “space-saving” drafting table, which provided a topic with which they were intimately familiar. As these groups used the various methods to develop solutions, they were recorded for later analysis by linkography.

In general, Vidal et al. saw a dense linkograph as being indicative of success. Density, in this case, is measured in terms of link density, i.e. the number of links in the linkograph divided by the number of moves in the linkograph. Determining whether or not a link is present between two moves was accomplished by slightly modifying the criteria established by van der Lugt [40]: similarity of content, references to previous ideas, similarity by association, and ideas that arise in the midst of another idea.

Statistical analysis showed that the total number of ideas generated by the subjects did not vary by method.

Kan et al. (2007) [69]:

Kan's team aimed to develop a quantitative tool to use in interpreting linkographs using Claude Shannon's entropy of information theory. A fully saturated linkograph, one in which every potential link is present, indicates no diversification of ideas, and thus conveys no information. In this way, it is effectively no different than a linkograph in which there are no links present. If these outcomes both yield no information, Kan argues, there must be some level in between these two extremes at which a maximum amount of information is present. Using Shannon's information theory, which relates the information in a message with its probability, it was determined that the optimal linkograph will have 75% of its potential links filled.

Goldschmidt (2016) [70]:

Goldschmidt used linkography to interpret the nature of the cognition going on within problem-solving groups. Specifically, the direction of links tends to indicate whether divergent or convergent thinking was used, with forelinks using associative or automatic reasoning [divergent thinking] and backlinks indicating rational and conscious analysis [convergent thinking.] Using ideation sessions recorded at the Massachusetts Institute of Technology and Delft University of Technology, linkographs were prepared. Critical moves were defined as those with 4, 5, and 6 forelinks or backlinks. On a few rare occasions, a critical move might have links in both directions.

Goldschmidt proposed that creative design would show a balance of forward and backward critical moves, and that critical moves would tend to have links in both directions, even if they fell under the critical threshold. 59% of the critical moves were forward and 41% were backward. In these moves, approximately 80% of the links are in the dominant direction [e.g. forelinks in a forward critical move] and 20% were opposite [e.g. backlinks in a forward critical move.] The slight preference for divergent thinking over convergent thinking was deemed to make sense in ideation sessions. The presence of opposing links in critical moves shows that convergent and divergent thinking happens simultaneously or nearly simultaneously in the ideation process, while the pattern of switching between forward and backward critical moves indicates that the process of ideation has a cyclical nature, alternately generating and then refining concepts as ideation happens.

4. Experiments:

4.1 Experiment 1: The Serial Order Effect

4.1.1 Hypothesis:

By analyzing AUT data from previous semesters, patterns consistent with current cognitive psychology literature, most notably the serial order effect, should be evident.

4.1.2 Method:

An Alternative Uses Task was administered to 62 engineering students at the University of Maryland, 37 enrolled in a senior-level design methods course and 25 enrolled in a graduate-level design methods course, in exchange for class credit. The participants were given ten minutes to list as many possible uses as they could for a “tin can,” which was judged to be an object of similar complexity to those outlined by Guilford [7]. In lieu of the original six item limit, a ten-minute time-frame was chosen in an effort to fully exhaust the participants’ potential ideas, as well as to test the relative originality of those answers given at the beginning of the test versus those given at the end. A detailed procedure for administering this experiment is available in Appendix A.

4.1.3 Results:

The 62 participants provided a total of 1,183 potential alternative uses for tin cans, yielding an average of 19.1 responses each with a standard deviation of 7.81 and a median value of 18.5. The fewest responses given was 5 and the most was 37.

Responses were analyzed using a process based upon the work of Kudrowitz and Dippo [23], particularly in the sorting of the individual responses into keywords and generalized functions. The responses were each categorized into one of 206 keywords, with 23 [or 1.9%] of the responses deemed either illegible or otherwise uncategorizable either due to a lack of seriousness [e.g. “food for billy goats”] or vagueness [e.g. “cut off both top and bottom of cans and cut the middle.”] A list of example keywords, those developed for tin cans starting with the letter B, is shown in Figure 2. A list of all keywords is available in Appendix B.

Keyword:	Meaning:
ball	use of cans to take the place of a ball in a sport
bank	use of cans to hold money, especially coins
basket	use of cans to weave a container
bathtub	use of cans to hold water for bathing or swimming
beerpong	use of cans to play 'beer pong'
bell	use can to ring like a bell
bikenoise	use of cans to make noise while riding a bicycle
birdfeeder	use of cans to hold birdseed
birdhouse	use of cans to give birds a place to nest
blade	use of cans as a non-weapon cutting tool
blender	using cans to make a blender
blinder	use of a can to restrict vision
boat	use of cans to act as floating transportation
bomb	use of cans to hold explosives
bookend	use of cans to hold up books on a shelf
bookmark	use of cans to mark a page
bowl	use of cans as bowls
bowlingpin	use of cans as bowling pins
bracelet	use of cans to adorn the wrist
buoy	use of cans to mark a location in the water

Figure 2. Sample keywords used to analyze tin can AUTs.

The list of potential keywords was developed in tandem with the analysis of the data, either as the verbatim responses were entered into a spreadsheet or during a later review. In formulating these keywords, emphasis was placed upon retaining as much specificity as possible while still accounting for differences in individual participants' phrasing, knowledge of specific English vocabulary, and so on. For example, the responses "piggy bank", "to hold spare change," and "used to collect quarters and coins so that you may be able to use later," despite certain minor semantic differences, were all denoted with the keyword "bank" for the purposes of analysis. Further, the keyword "bank" is considered distinct from the keyword "container", to maintain the most important element of the individual's intent. In contrast, the keyword "container" is reserved for only the most generic responses such as "storage" and "bucket," which do not hold a specific item. Given the occasional and inevitable difficulties in interpreting another's intent from text, a small number of responses had to judged closely to determine whether or not a keyword could be applied.

The most common keywords, those which occur in at least 20% of participants' responses, are displayed in Figure 3. As there were several instances of a respondent giving more than one response that fit a certain keyword, a keyword's commonness is determined in terms of number of respondents rather than the total number of responses. At the other end of the distribution, sixty keywords all share the distinction of having a single instance each.

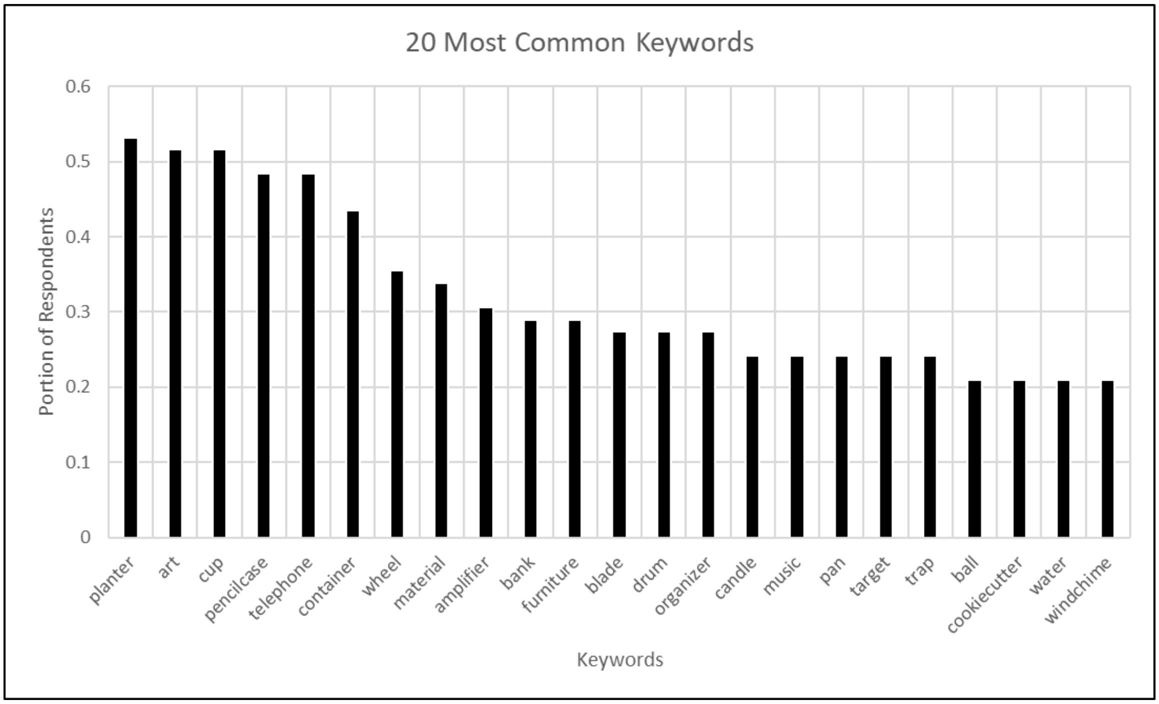

Figure 3. The most common keyword responses for alternative tin can uses.

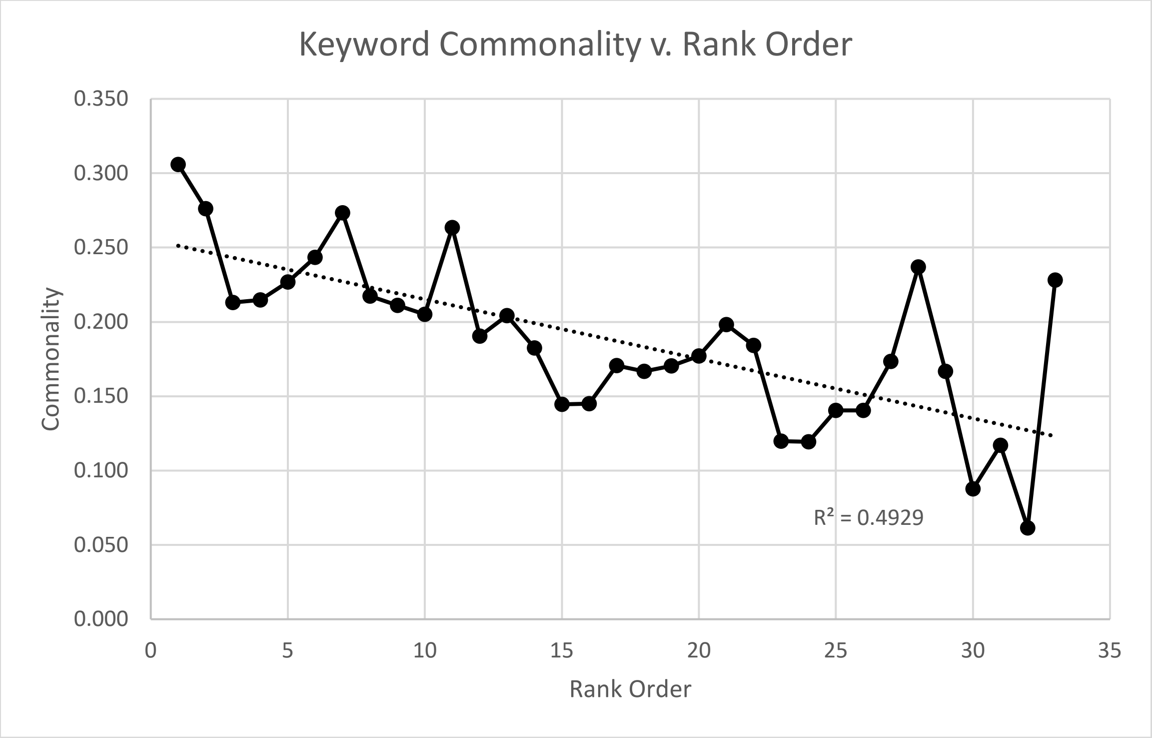

Figure 4. The average tin can keyword commonality compared with rank order.

It was found that those answers given toward the beginning of the exercise tended to be less original than those given toward the end, as shown in Figure 4. For this purpose, commonality can be seen as the inverse of originality. Put another way, commonality is the portion of all respondents who provided a given response at some point in the exercise. As the AUT proceeds, this value decreases in an approximately linear fashion ($R^2 = 0.4929$). Due to exaggerating effects of outliers, especially at the higher rank orders where far fewer respondents gave answers, Figure 4 is based upon the middle 92% of respondents, i.e. those who gave more than 5 and fewer than 34 total responses.

These data suggest that there is an inverse correlation between the commonality of answers given on the AUT and the order in which they are given. This supports the serial order effect, which holds that people will initially use ready examples from their past experience before generating more original answers by combining semantically distant concepts.

4.2 Experiment 2: Incubation

4.2.1 Hypothesis:

By conducting a second AUT on a different object [a paperclip] and incorporating an incubation task into the procedure, the originality of the subjects' responses should increase.

4.2.2 Method:

The Alternative Uses Task was administered to 54 engineering students at the University of Maryland enrolled in a graduate-level design methods course, in exchange for class credit. As 25 of these students had previously participated in an AUT using a tin can as the sample object[7], a new object was chosen to prevent any issues due to repetition. The participants were given ten minutes to list as many possible uses as they could for a paperclip. In addition, roughly half of the students [N = 26] were given an incubation task; immediately after receiving the instructions for the AUT. These students were asked to spend four minutes sketching a still-life consisting of a school bag and notebooks, before being given ten minutes to list unusual uses for paperclips. The remainder of the students [N = 28] conducted the AUT as described in Experiment 1 to act as a control group. Five of the students in the class participated asynchronously, i.e. via recorded video over the internet, and were thus assigned to be part of the control group, as they did not have access to the drawing task. A detailed procedure for administering this experiment is available in Appendix A.

4.2.3 Results:

Together, the 28 control group participants generated a total of 405 unique responses to the AUT, while the 26 incubation group participants generated 419, yielding a total of 824 responses. All responses were evaluated using the same process detailed for Experiment 1 and were categorized using 140 keywords. A list of all keywords used is available in Appendix B. 35 of the responses were judged unsuitable for categorization, or roughly 4.2% of the total. In all, respondents gave an average of 15.2 responses each, with a standard deviation of 7.32 and a median value of 14. The 28 participants in the control group gave an average of 14.4 responses each, with a standard deviation of 7.45. The 26

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[7] i.e. Experiment 1.

participants in the incubation group gave an average of 16.0 answers each, with a standard deviation of 7.24. The number of responses in the control group ranged from 3 to 42 and in the incubation group from 6 to 31.

The ten most common keywords used to categorize the paperclip data are given in Figure 5. Of the 140 keywords developed for the paperclips, 56 occurred only once in the response data. As in Figure 3, the frequency of the keywords appears to decline in an approximately linear fashion, albeit gradually. Figure 6 shows the number of times the most common keywords were found in both the control and incubation responses. There appears to be no discernable pattern in these data, with the number of appearances of a common keyword being approximately even throughout.

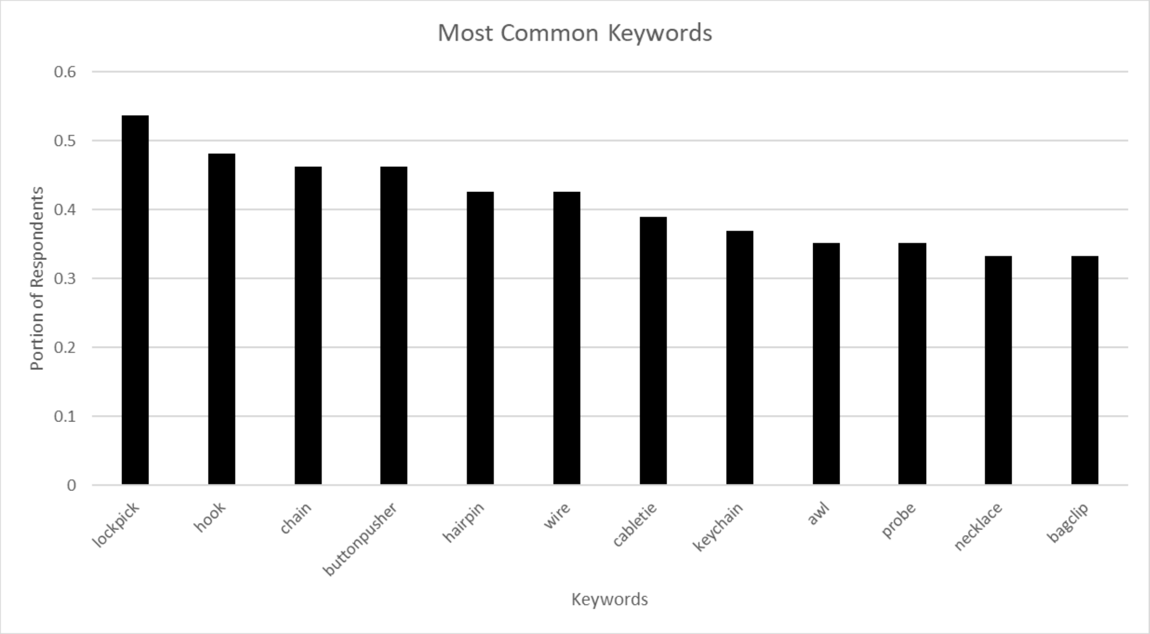


Figure 5. The most common paperclip keywords.

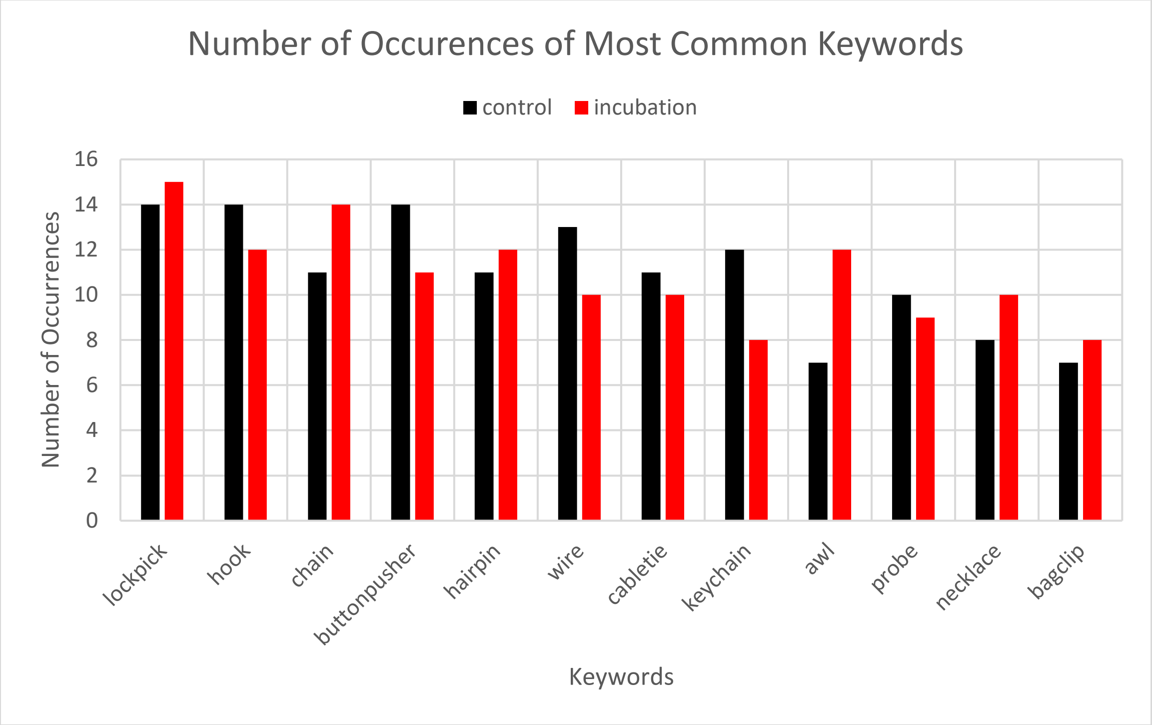


Figure 6. The number of occurrences of the most common paperclip keywords divided between control and incubation

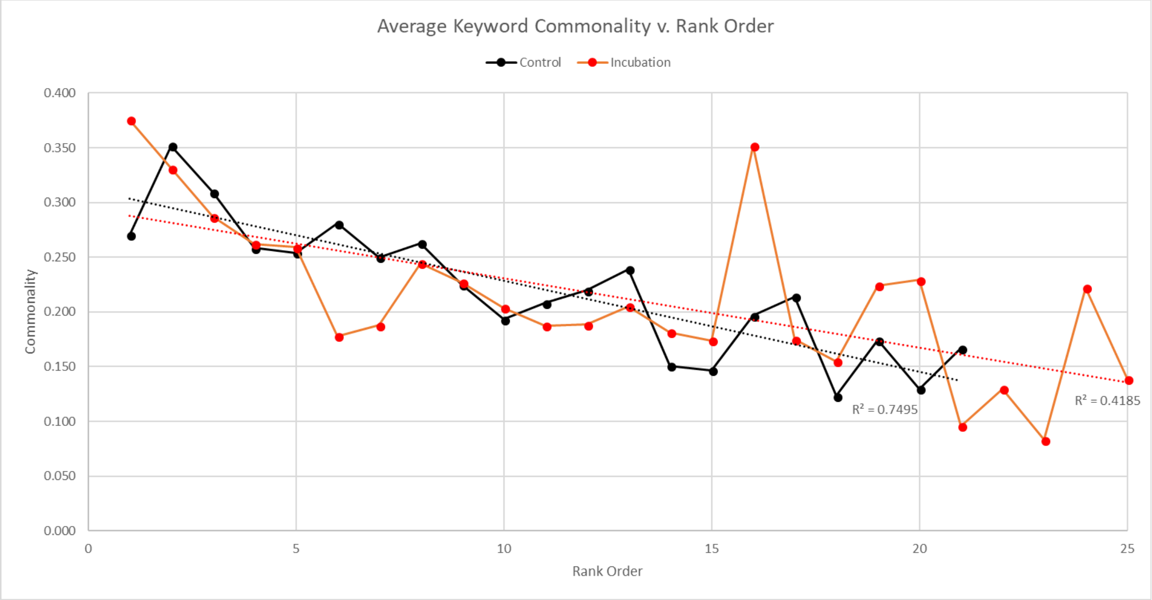


Figure 7. The average commonality of paperclip keywords compared to rank order.

The average commonality for all keywords given at each rank is shown in Figure 7. In both the control and incubation groups, there appears a moderate linear relationship between commonality and rank order, with R^2 values of 0.7495 and 0.4185, respectively. The average commonality for all responses in the control group was 0.257, with a standard deviation of 0.066, while the average commonality for the incubation group was 0.249, with a standard deviation of 0.061. A single-factor ANOVA showed these two groups were not significantly different if $\alpha = 0.05$, with a probability of 0.642 that the samples were of the same population. The data were also analyzed to look for differences in the highest and lowest commonalities generated by participants in the control and incubation groups. With $\alpha = 0.05$, single-factor ANOVAs showed that neither measurement was significantly different, with the highest commonality having a probability of 0.562 and the lowest commonality having a probability of 0.946 that the samples are identical. Finally, the number of responses given in the control and incubations groups was found not to differ significantly, with a single-factor ANOVA [$\alpha = 0.05$] showing a probability of 0.425 that the samples were similar.

While some evidence was found supporting the serial order effect, contrary to expectations, none was found for the incubation effect, with both the control and incubation groups generating very similar sets of responses in terms of both fluency and originality. Potential reasons for this include the present study's small sample size, the choice to give an incubation period before the participants had a chance to reach a mental impasse, using a design problem that was insufficiently difficult to reliably cause fixation, or by giving a task during the incubation task which may be insufficiently distracting or different from the AUT to provide a cognitive benefit.

4.3 Experiment 3: Linkographic Analysis

4.3.1 Hypothesis:

By organizing the AUTs from experiments 1 and 2 into linkographs, a measure of the subjects’ flexibility can be made, and flexibility will correlate with originality and the number of semantic connections made.

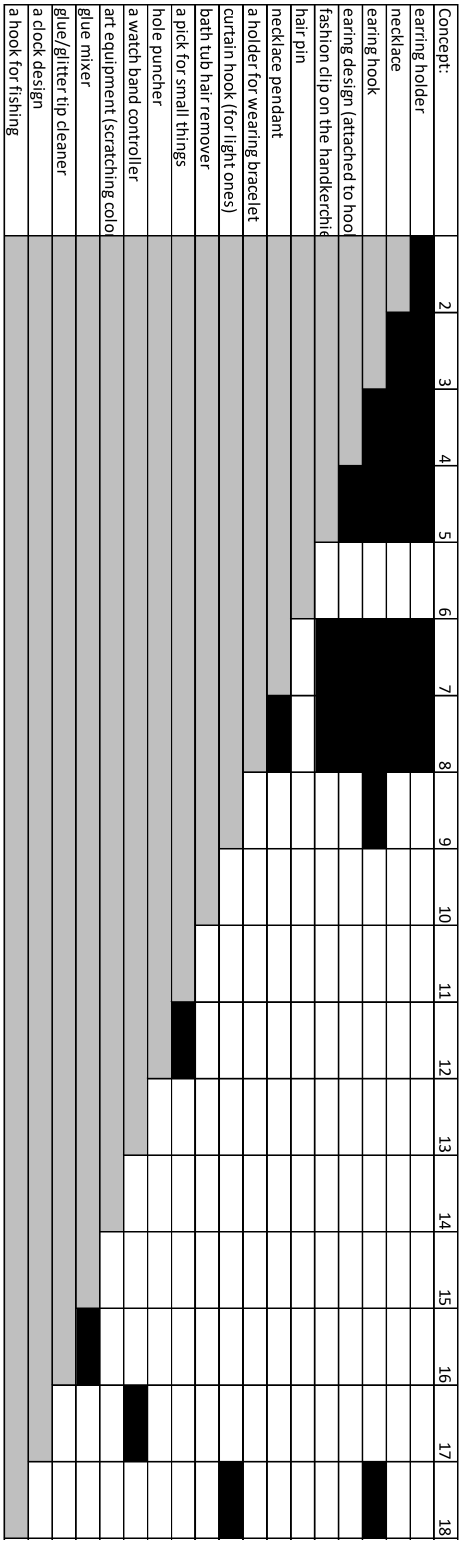
4.3.2 Method:

In order to glean some insight into the subjects’ cognitive process during the Alternative Uses Task, and in an effort to replicate some of the findings in Goldschmidt [70], linkographs were generated from the data obtained in experiments 1 and 2. As the small numbers of responses on some AUTs and the related problems of forming meaningful conclusions from small linkographs, only half of the subjects, those who gave at least the mean number of alternative uses were used in this experiment. This resulted in 30 linkographs on paperclips, with a minimum of 14 responses each, and 29 linkographs on tin cans, with a minimum of 19 responses each. Due to the lack of any statistical difference found between the incubation and control groups in the paperclip data, they were treated as members of the same population for the purposes of this experiment.

4.3.4 Results:

Traditionally, linkography has relied upon audio recordings of individuals or groups taking a ‘thinking aloud’ approach to a design task [38]. By its nature, the AUT provides written data consisting solely of finished proposals, without any interim steps. Ideally, a set of AUT responses consists of a constant stream of design ideas but given the fact that some respondents provided as few as five answers in a ten-minute period, this seems a remote possibility in practice. As such, it was necessary to take a conservative stance in assigning links between design moves, limiting them to cases where a clear, common sense relationship was evident. Combined with a relatively low number of data points when compared with other linkographic studies, this conservative approach may account for the paucity of high link critical moves in this experiment.

Each linkograph was generated by comparing the answers given in a piecewise fashion with those that came before. If a reasonable connection could be drawn between any two uses listed, a mark was placed in the corresponding box between them. Finished linkographs could then be interpreted individually, looking for patterns in how each subject approached the AUT. Further, by counting the critical moves forward and backward from all the subjects, it is possible to determine whether the sample as a whole favored divergent thinking, represented by forelinks, or convergent thinking, represented as backlinks [70]. Because each linkograph contained a different number of moves, a threshold had to be set for each to determine which moves if any were critical ones. This threshold was set individually for each linkograph as the number of links [forelinks for a CM> and backlinks for a <CM] that would encompass between 8% and 20% of the moves. Critical moves represent the most influential ideas in a linkograph, those with the largest number of connections to other ideas. In particularly sparse linkographs, it is possible that no critical moves exist.



Concept:	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
earring holder	■	■	■	■		■	■										
necklace	▨	■	■	■		■	■										
earing hook	▨	▨	■	■		■	■	■									■
earing design (attached to hoo	▨	▨	▨	■		■	■										
fashion clip on the handkerchie	▨	▨	▨	▨		■	■										
hair pin	▨	▨	▨	▨	▨												
necklace pendant	▨	▨	▨	▨	▨	▨	■										
a holder for wearing bracelet	▨	▨	▨	▨	▨	▨	▨										
curtain hook (for light ones)	▨	▨	▨	▨	▨	▨	▨	▨									■
bath tub hair remover	▨	▨	▨	▨	▨	▨	▨	▨	▨								
a pick for small things	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■						
hole puncher	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
a watch band controller	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				■	
art equipment (scratching colo	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				
glue mixer	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■		
glue/glitter tip cleaner	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
a clock design	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
a hook for fishing	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure 8. A portion of an example linkograph generated from a paperclip AUT.

A portion of an example of an AUT linkograph for paperclips is shown in Figure 8. Several patterns are evident in this piece. At the beginning of the test, the subject has formed a dense web made up of semantically related uses. Of the first eight uses given, seven – *1. earring holder, 2. necklace, 3. earring hook, 4. earring design, 5. fashion clip, 6. necklace pendant,* and *8. bracelet holder* – are all related to adornment. The seventh answer, *hair pin,* is also arguably related to adornment, although links were not assigned because a hair clip is often not a visible piece of jewelry. Together, these answers represent a very clear "chunk" in the data, an area in which several closely related ideas are produced in rapid succession. After this initial chunk, the linkograph settles down for a time, with only a few sequential links, like *15. glue mixer* and *16. glue/glitter tip cleaner*. At the end of the example, the subject makes their first large leap, with *18. fish hook* being semantically linked back by nine moves to *9. curtain hook* and by fifteen moves to *3. earring hook.* Whether or not any of these patterns are the result of conscious choices or changing strategies on the part of this individual is entirely speculative, as experiment 3 re-examines the data previously generated in experiments 1 and 2.

Three metrics were calculated from the linkographs: link index – the number of links divided by the number of moves – and the saturation, or how many of the potential links were actually made. These two values represent the density or richness of a given linkograph. In addition, a metric called "span" was developed. A linkograph's span is simply the number of moves between a given answer and its most distant link. To allow for the comparison of linkographs of varying size, the average span for each was normalized against the number of moves. A normalized span of 1 indicates that a link was made between the first and last answer on a linkograph, whereas a normalized span of 0 indicates a lack of any links whatsoever. Span represents how flexible a participant's thought process was during the AUT, in terms of how willing they were to engage with previous answers. The closer a linkograph's span is to 1, the greater the semantic distance over which a link was made. A span close to 0 indicates a very linear thought process, moving from one idea to the next without much reflection on previous thoughts. By comparing these metrics, possible correlations between a subject's linkograph and their creativity [as determined in Experiments 1 and 2] were examined.

There was little if any correlation between the commonality of a subject's responses and their linkograph's link index or span, as shown in Figure 9 through Figure 12. The R^2 value for a plots of link index versus average commonality in paperclips and tin cans are 0.0002 and 0.0209, respectively. Correlations between the normalized span and average commonality are similarly low, with R^2 values of 0.0373 for paperclips and 0.0597 for tin cans. The average saturations were calculated to be 3.83% for the tin can linkographs and 4.53% for the paperclip linkographs, with standard deviations of 1.84% and 1.91%, respectively. Both of these values are obviously well below the 75% goal set out by Kan et al. as an ideal linkograph [69].

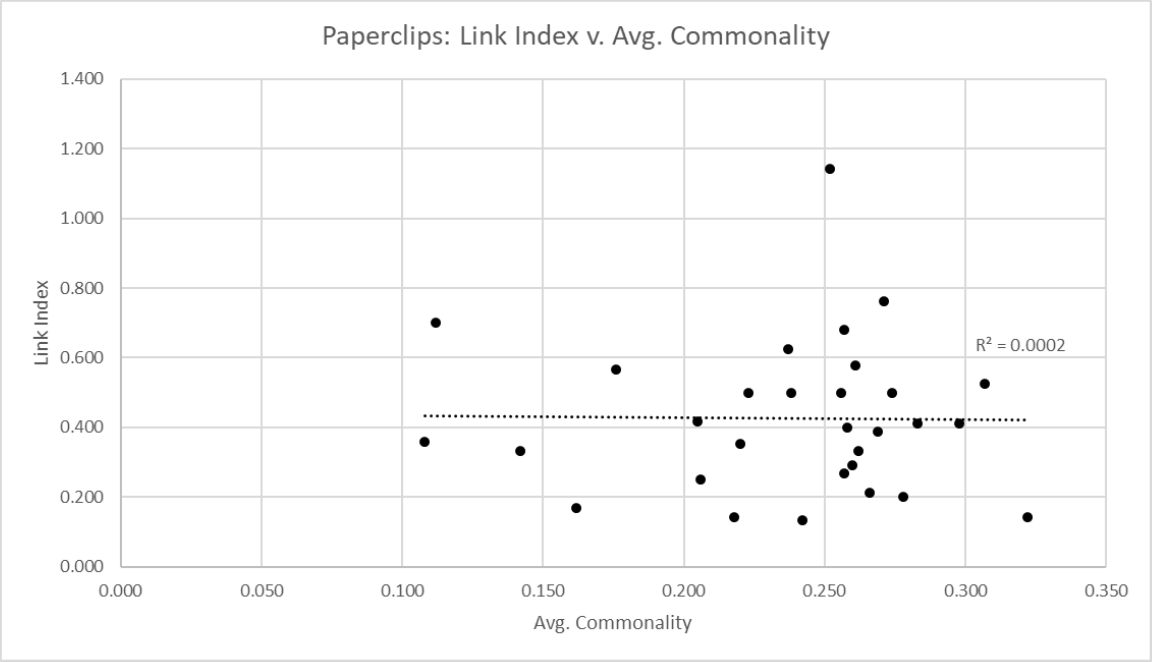


Figure 9. A scatterplot comparing individual subjects' link index and average commonality in a paperclip AUT.

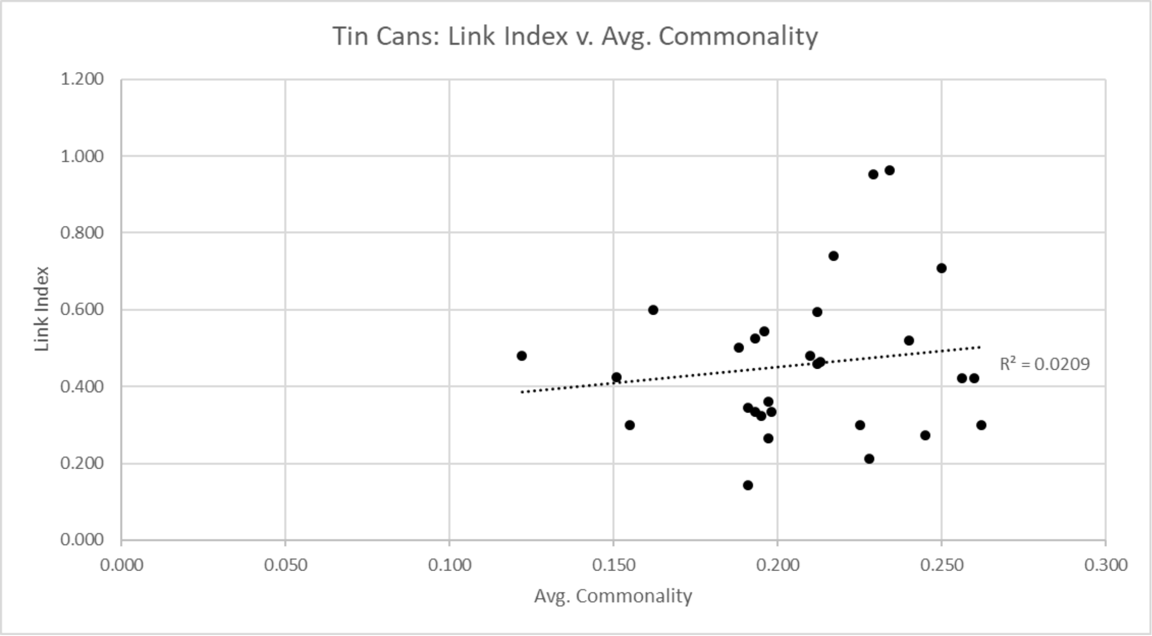


Figure 10. A scatterplot comparing individual subjects' link index and average commonality in a tin can AUT.

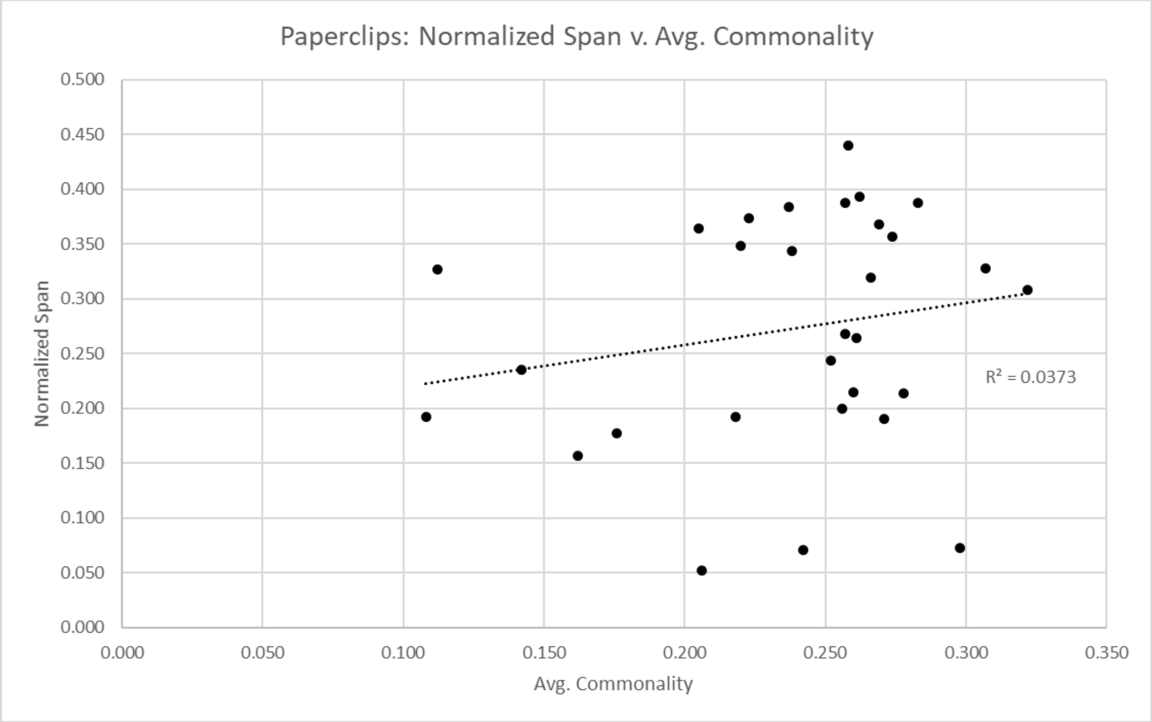


Figure 11. A scatterplot comparing individual subjects' normalized span and average commonality in a paperclip AUT.

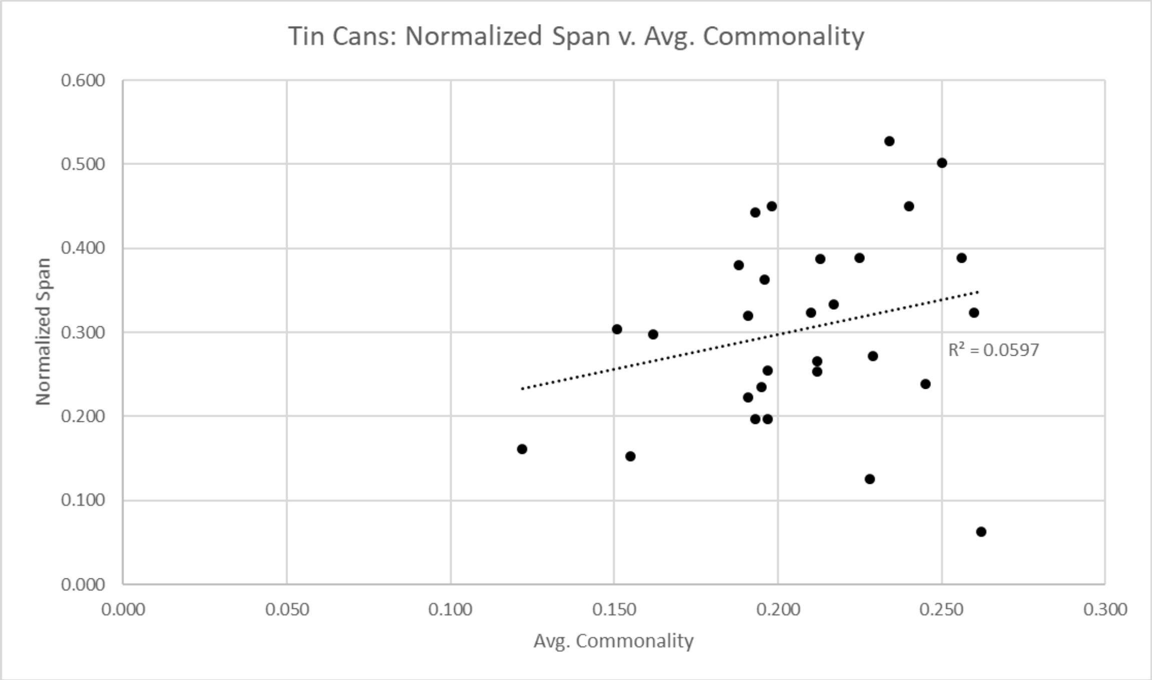


Figure 12. A scatterplot comparing individual subjects' normalized span and average commonality in a tin can AUT.

4.4 Experiment 4: Teaching the Psychology of Creativity

4.4.1 Hypothesis:

In an attempt to replicate the results of a recent psychological experiment [51], providing students with a lecture on the fundamentals of the psychology of creativity should result in an increase in fluency and originality, as measured by the AUT.

4.4.2 Method:

Experiment 4 was patterned after recent work done in the Netherlands by Marie-Thérèse van der Kamp et al. [50][51], in which art students showed improvement on the Alternative Uses Task when provided with a combined lecture and discussion session introducing modern psychological theories underlying creativity. This approximately 60-minute session included several real-world examples of consumer products and artwork deemed creative by the authors, discussions regarding ideation strategies, and practice AUTs. The presentation given to subjects in experiment 4 included many of the same elements, with additional material on Baddeley's revised model of working memory [71], divergent and convergent thinking, and the serial order effect. Some of the material most heavily related to fine art was removed and replaced with examples from engineering design because of concerns that the engineering students would not find it readily applicable to their studies. Copies of the slides used in the treatment presentation [as well as a brief concluding presentation outlining the results given at the end of the semester] are shown Appendix C.

A total of 52 engineering students from the University of Maryland participated in this experiment, 28 enrolled in a graduate-level design method course and 24 in an undergraduate design method course. Eight of the graduate students exercised the option to participate remotely and at their own leisure via an asynchronous video feed. The undergraduate classroom was not similarly equipped, and all subjects participated in real-time.

The experiment consisted of three phases: first an AUT pretest on a tin can was given to establish a baseline for their creativity. Two weeks later, they participated in the modified treatment lecture and discussion, moderated by the author. After a further two weeks, an AUT posttest on a paperclip was given. While paperclips and tin cans are generally seen as similar for the purposes of the AUT, they are not identical and subjects' performances on the pre- and post-tests are not directly comparable. For this reason, the pretest results were compared with those from Experiment 1 and the posttest results with Experiment 2, neither of which involved a presentation component and thus acted as a control. It was hoped that the pretest would show a similar performance to previous results while the posttest would display increases in fluency and originality. Both the pretest and post-test were given using the procedure given in Appendix A, without incubation.

4.4.3 Results:

The 52 participants generated a total of 1187 unique responses to the tin can AUT [pretest] and 859 on the paperclip AUT [posttest.] These responses were coded using the same process detailed for Experiments 1 and 2, utilizing the same lists of keywords with additions being made as the occasional new unique responses were found. These expanded keyword lists totaled 264 potential options for tin cans and 211 for paperclips, though it should be noted that not all the keywords from Experiments 1 and 2 were necessary to evaluate Experiment 4. 31 of the pretest responses and 33 or the posttest responses were considered unsuitable for categorization, due to illegibility or lack of clear intent. These account for roughly 2.6% and 3.8% of their respective data. On the pretest, respondents gave an average of 19.5 responses each, with a standard deviation of 9.66 and a median value of 18. The posttest yielded an average of 16.5 responses each, with a standard deviation of 9.16 and a median of 13.5. The fewest responses given on the pretest was 4 and on the posttest 3, while the largest number on each 47.

As in Experiments 1 and 2, the serial order effect is plainly visible in both the pre- and posttest data. As shown in Figure 13, the average commonality for a given rank decreased as the AUT proceeded, with both the pretest [tin can] and posttest [paperclip] showing a similar pattern. Regression lines applied to the pre- and posttest yielded R^2 values of 0.5165 and 0.6005, respectively.

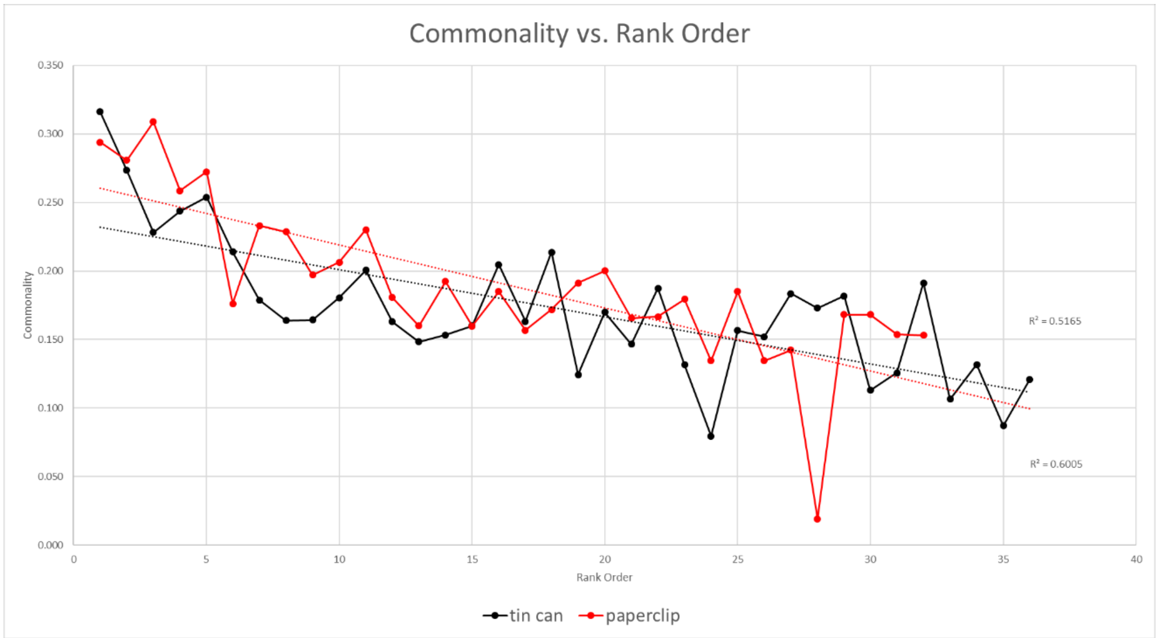


Figure 13. The average commonality of pre- and posttest keywords compared to rank order.

Single-factor ANOVAs comparing Experiment 4's pretest commonality and fluency data with that collected for tin cans in Experiment 1 found that, with an α of 0.05, the two samples were not significantly different, with a probability of 0.990 in terms of commonality and 0.809 in terms of fluency. This strong similarity between the samples suggests that any differences seen between the data in Experiment 4's posttest and Experiment 2's paperclip data would be a result of the treatment applied. Single-factor ANOVAs (α=0.05) comparing Experiment 4's posttest and Experiment 2 yielded a probability of 0.737 that the two groups were not significantly different in terms of commonality and a probability of 0.415 that they were not significantly different in terms of fluency. While these values are both lower in the posttest condition than the pretest, they are not significantly so, and it cannot be concluded that the presentation on psychology and creativity significantly impacted the subjects' performance.

An hour's instruction on the psychology of creativity had a slight, statistically insignificant effect on engineering students in terms of originality and fluency. While their pre-test scores were almost identical to the tin can AUT data from experiment 1, post-test performance differed significantly, especially in terms of fluency.

5. Discussion:

While these experiments align with the expectations set by the cognitive psychology literature in some respects, others have proven more difficult to understand. Part of this is likely due to the fact that the literature itself does not always agree. Otherwise, there may be issues with the experimental design, differences between the way engineers and non-engineers respond to these tests, or problems with the tests' execution.

In experiments 1, 2, and 4, evidence was found for the serial order effect. Participants were more likely to come up with the most common responses early in the test rather than later, which seems, if anything, intuitively obvious. In looking for answers in the Alternative Uses Task, it is likely that respondents will first rely upon unusual uses which they have already experienced, either in their real lives or indirectly through popular culture, then by proceeding on to other items which bear a resemblance to the AUT's subject. As these readily available solutions were exhausted, the participants were compelled to give increasingly diverse responses.

That being said, the serial order effect found in these experiments was much weaker than that found by Kudrowitz and Dippo [23], who found a strong, exponentially decreasing relationship between average commonality and the order of responses, as opposed to the more linear response seen in these data. While this may simply be due to the differences in scale between our samples, which vary by an order of magnitude, this remains undetermined.

Experiment 2 was designed specifically to keep in step with recent psychological experiments investigating the phenomenon. Gilhooly showed that the incubation period was most effective at the beginning of a task rather than in the middle, since the subjects' minds were free to associate with no mental resources would be diverted to clear the working memory of previous work on the problem [54]. Ellwood's work indicated that the use of a wholly dissimilar task as an incubation activity was most effective [26], while Gilhooly showed that there was no meaningful difference between the effect of a verbal versus a spatial incubation task [54]. The experiment's sketching task was chosen partly because of its use of a completely different set of abilities as opposed to the AUT's at least partially verbal nature and partly as a matter of expedience, as setting up a still-life is a simple task. A four- or five-minute incubation period was deemed sufficient time for mental blocks to clear in several studies [26],[52]-[54]. The remaining proposed cause for the lack of the incubation effect seems the most likely, that the AUT was not sufficiently mentally taxing to result in a great enough creative block to affect the majority of subjects, even though it is similar to tasks studied by Ellwood [26] and Gilhooly [54].

It seems worth mentioning that there was a moderate difference between the control and the incubation samples in experiment 2, and as Ellwood points out, the effect of incubation is continuous, not binary [26]. Further, Segal notes that incubation is a notoriously difficult effect to show statistically, with only about 50% of studies managing to do so [52].

Experiment 3 took advantage of the existing data from experiments 1 and 2, and it used those data to graphically explore the patterns of the subjects' thought processes. That there was virtually no correlation found between the density of the developed linkographs or the distance of the mental leaps taken Linkography was developed as a method for studying a very specific sort of data, that verbally generated by a team working to solve a specific, complex problem. While there have been some instances of linkographs being successfully used in other situations, such as a designer working alone, the data was still verbal and required that the subject “think aloud,” providing insight into their thought process [67].

In contrast, the Alternative Uses Task does not readily display a thought process to be interpreted by a linkograph. All the answers given on an AUT exist in a vacuum. Subjects never explicitly state when they are revisiting a previous idea for inspiration or refinement. While it often seems reasonable to infer connections between answers, it also seems reasonable to assume that there are many links between them that are hidden from observation due to the nature of the test. What’s more, linkographs are generally used to study design tasks, which require a constant cycle of divergent and convergent thinking [70]. The task posed by the AUT, on the other hand, is solely the province of divergent thinking. With a sufficiently thought-provoking object to generate alternative uses for, it would be possible to produce dozens of varied tasks one after another without ever consciously looking back and reflecting on previous responses. Any interpreted connections drawn by on-lookers would be entirely circumstantial.

The potential differences between experiment 4 and the experiment performed by van de Kamp upon which it was based are small, but numerous [51]. The original, art-based examples were replaced by ones judged to be similar, but appropriate for a course on engineering design. New material also included an overview of Baddeley’s model of working memory and an explanation of the Alternative Uses Task. Van de Kamp’s participants were led through their creativity discussion by their usual, professional instructors who had been trained on the material by psychologists, whereas the participants in experiment 4 were led by the author, who lacks formal training in education or psychology and is also a stranger to many of them.[8] It is possible that this lack of teaching experience led to less significant results than in van de Kamp's experiment due to an unintentional oversight brought about by this lack of knowledge and experience.

Throughout these four experiments, there have been differences between the participants – engineering students – and the typical participant in an AUT. Charyton and Snelbecker showed that engineering students and music students had significantly different abilities when it came to creativity, or at least to the creativity metrics used in their study, with music students having slight advantages in their creative attributes, creative temperament, and tolerance for cognitive risk [60]. Comparing engineering students' performance with those of van de Kamp's art students might show a similar disparity after a single hour of instruction on the psychology of creativity [51].

Cropley and Cropley were able to improve engineering students' originality, albeit with three hour-long lectures, as well as individualized counselling for a portion of the sample. The other key difference was in how the students' creativity was measured. Cropley and Cropley applied both an abstract test, the Test for Creative Thinking – Drawing Production {TCT-DP], as well as with an open-ended, team-based design project. It was shown that high performance on the TCT-DP did not necessarily translate into high originality in practice [58]. It is possible that the AUT is simply an insufficient means to fully judge the creativity of engineers. It is also possible that an hour of discussion and lecture on such a broad topic as the psychology of creativity was simply insufficient time

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[8] Although many if not most of the undergraduate participants should at least recognize the author as the teaching assistant for a mandatory junior-level design class at the University of Maryland.

for students to internalize such a large amount of data from a field of study which might seem unusual if not arcane.

Then again, the students in these experiments may be the issue. Over the space of ten minutes, while some produced dozens of uses for paperclips or tin cans, some participants only came up with a handful[9]. Several possible explanations present themselves. It is possible, however unlikely it may feel, that these participants are outliers who expended their mental resources for this task after only a few responses. Fixation or some other creative block might have set in early in the process. Many students were non-native English speakers, who may have had trouble understanding the test or expressing their ideas in a written form. Rather than writing down every alternative use they thought of, participants may have engaged in self-judgment, choosing to omit one or more answers as being unfeasible or otherwise foolish. Much like in brainstorming, such judgments are an example of convergent thinking and run counter to one of the goals of divergent thinking, generating as many responses as possible. The most cynical explanation is that some students were not interested in engaging with the exercise and chose to put forth the minimum possible effort.

Success in any form of education requires mental and emotional investment on the part of both the educators and the students. The subjects in these experiments have all experienced at least two or three years of engineering education at the collegiate level, which may already be enough to have instilled certain behaviors and biases on their part. Of Kazerounian and Foley's Ten Maxims of Creativity in Education, the most salient seem

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[9] The largest number of responses on any of the AUTs was 47 in ten minutes. The smallest was 3.

to be maxims two, four, six, and seven: Ambiguity is Good, Reward for Creativity, Learning to Fail, and Encourage Risk. In their survey of engineering students, Kazerounian and Foley found that the students tended to be uncomfortable with mulling over problems for an extended period of time, preferring to reach firm conclusions quickly [1]. Participants did not receive any benefit for producing a large volume of novel answers as opposed to a small number of conventional ones. For some subset of participants, the desire to provide data for the nebulous aim of creativity research may not have been sufficiently motivating. Students may also have internalized the lesson that providing risky or unfeasible ideas is discouraged in engineering education. Even in a situation like the AUT, in which there is no penalty for supplying bizarre or unworkable ideas, the subjects may be reticent to put them to paper.

In the end, these four experiments have left us with a few significant findings and many more tantalizing glimpses at potential means to improve the creativity of engineering students. From the literature, it seems clear that the topic of creativity needs to become a more regular and sustained topic of importance throughout the curriculum if it is to be a meaningful, expected outcome of an engineering education. From these experiments, it is abundantly clear that a single hour's instruction explicitly on the psychology of creativity is insufficient to meet that goal.

When considering how future changes might be made to better foster creativity in engineering students, there are many options. If Kazerounian and Foley [1] and Daly et al. [11] are right, the nature of modern engineering education leads to an environment that disincentivizes creativity, an earlier intervention could be more effective than one tried with seniors and graduate students. This may even require changes to students in high school or earlier. Adding a personal element, in which creativity strategies are practiced alone or in small teams under the supervision of an instructor appears to be more effective than exposing students to information about creativity and hoping it takes hold [58]. The move in general toward open-ended design projects seems the correct one, however emphasis in grading must be shifted away from conventional success to a reward for risk taking and an acceptance of failure as both a learning experience and a necessary consequence of innovation.

6. Conclusions:

Concerning the two research questions: “Does cognitive psychology theory predict and explain the behavior of engineering students during divergent thinking tasks?” and “Is the creativity of engineering students affected by the explicit incorporation of cognitive psychology into their curriculum?” the results seem decidedly mixed.

The presence of the serial order effect has been shown through this study, with engineering students conforming to the pattern generating conventional, obvious ideas on problems before moving on to original or unusual ones. Any effect, positive or negative, of incubation on creativity remains elusive. Linkographic analysis showed no correlation between the density of a participant’s linkograph or the semantic distance of their leaps and their creativity and fluency. An hour’s instruction and discussion on the psychology of creativity yielded only slight, statistically insignificant results.

It seems clear that developing meaningful change in the way creativity is taught in colleges and universities will require something more than a modicum of instruction in psychological theory. The literature tells a tale of instructors and students both seeing the value of creativity without having a full understanding of each sees the problem. The shift toward open-ended team projects in some courses is promising, but this could become the norm in many more courses. Mostly, however, for the culture of engineering education to become one that fosters creativity in students, it will have to normalize creative expression. If the taking of risks is rewarded and failure is accepted, students should follow.

Continuing this work answers a call from a distinguished set of engineering design researchers for more research using cognitive science approaches regardless of the challenges common to such research, including small sample sizes, the complexity of authentic design tasks, industry’s emphasis on employing teams rather than individuals for design, and participants’ individual differences of experience [72].

7. Contributions:

- This work has furthered the cause of incorporating creativity theory from cognitive psychology into the sphere of engineering education.
- The serial order effect manifests itself in the work of engineering students during divergent thinking.
- Incubation did not significantly impact engineering students’ originality or fluency in the Alternate Uses Task.
- A single hour’s instruction in cognitive psychology was insufficient to increase engineering students’ creativity.

8. Future Work:

Studying the effect of psychological theories on engineering students may require changes to some of the fundamental assumptions made in this study. The Alternative Uses Task measures solely divergent thinking, and it does so in a context without a goal to focus upon. As such, the AUT does not mimic in any meaningful way the way in which engineers express their creativity either in school or out. Experiments 2 and 4 in particular, might be better served with a small, practical, project-based test like that used by Cropley and Cropley [58] as a measure of originality, which they found did not necessarily correlate with performance on an abstract creativity test. Such a task would involve not just divergent thinking, but convergent thinking as well, and thus more closely replicate the goal-oriented nature of most engineering work. Alternatively, another task, such as having the subjects list as many ways as possible in a given time to solve a problem, might be investigated.

Should experiment 4 be revisited, an expanded treatment, incorporating not just instruction on strategy use but also individual practice and instruction using creativity strategies may yield more substantial results.

Concerning the reliability and replicability of this work, now that the preliminary effort of developing keywords has been done by a single judge, it should be expanded and refined so that anyone can use the same method and yield a near-identical result. In categorizing the data generated by the AUT, the goal was to find an ideal middle ground between maintaining the subjects' unique answers and classifying them so broadly that they lost all nuance. It may be possible to develop the keywords into a hierarchy, wherein a given AUT answer might be given multiple keywords of varying specificity. As an example, the tin can AUT answer of "boil water to make tea" might be assigned keywords including “kettle” [specific], “water container” [general], “cookware” [also general], and “food” [very general] among others. While there may be disagreement at the most specific levels of the hierarchy, these should vanish as the keywords grow more general and the rater’s judgment requires less subjectivity. Where comparing the use of specific keywords gave some insight into the originality of subjects, examining the broad categories might result in information about their flexibility. While it may prove too cumbersome in practice, in may also be possible to have subjects reliably apply keywords to their own responses, which would also mitigate subjectivity.

Appendix A: Alternative Uses Task Instructions

Alternative Uses Task procedure:

1. Pass out the record sheets.
2. Collect the subjects' basic demographic data at the top of each sheet. Record gender, class level, etc.
3. Read the following instructions as written on the record sheet to the group. These should also be printed at the top of the record sheet:

"Please consider the standard, every day tin can. Besides its obvious use – holding and protecting foodstuffs – there are any number of uses for tin cans. In the space provided, list as many possible uses for one or more cans. Do not limit yourself to any uses you have previously encountered. This task will last ten minutes."

4. Have both groups take the AUT for 10 minutes.
5. Collect the data and enter it verbatim into a spreadsheet.
6. Assign each response a keyword. See Appendix B for a list of all the keywords used in this thesis. New keywords may need to be developed as new uses are encountered. Some responses may be uncategorizable due to vagueness, silliness, or other issues.
7. To calculate each keyword's commonality, count the number of times each keyword is used within the entire sample and divide by the total number of responses.
8. Analyze the data according to the method laid out in section 4.1

Alternative Uses Task with Incubation procedure:

1. Divide the class randomly in to approximately equal groups – one control and one treatment.
2. Conduct the experiment with the control and the treatment groups in separate locations or times.
3. Pass out the record sheets. For the treatment group, pass out materials for the sketching task as well.
4. Collect the subjects' basic demographic data at the top of each sheet. Record gender, class level, etc.
5. Read the following instructions as written on the record sheet to the group. These should also be printed at the top of the record sheet:

"Please consider the standard, every day paperclip. Besides its obvious use – holding sheets of paper together temporarily – there are any number of uses for paperclips. In the space provided, list as many possible uses for one or more paperclips. Do not limit yourself to any uses you have previously encountered. This task will last ten minutes."

6. For the treatment group, have them conduct the sketching task for four minutes. Omit this step for the control group.
7. Have both groups take the AUT for 10 minutes.
8. Collect the data and enter it verbatim into a spreadsheet.
9. Assign each response a keyword. See Appendix B for a list of all the keywords used in this thesis. New keywords may need to be developed as new uses are

encountered. Some responses may be uncategorizable due to vagueness, silliness, or other issues.

10. To calculate each keyword's commonality, count the number of times each keyword is used within the entire sample and divide by the total number of responses.
11. Analyze the data as you see fit, or according to the procedure laid out in section 4.2

Appendix B: List of AUT Keywords

Tin Can Keywords:

Keyword:	Meaning:
abrasive	use of cans to polish, sand, or clean through abrasion
airduct	use of cans to channel air flows
airplane	to use a can as an aircraft
alarm	use of cans to generate noise in order to alert a listener
amplifier	use of cans to make noises louder
anchor	use of cans to weigh down a boat, ship, or other floating object
antenna	use of cans to receive radio signals
aquarium	use of cans to house fish or other small pets
armlet	use of cans to adorn the upper arm
armor	use of cans to protect the body
art	use of cans for non-specific aesthetic reasons
ashtray	use of cans to hold tobacco ash
ball	use of cans to take the place of a ball in a sport
bank	use of cans to hold money, especially coins
basket	use of cans to weave a container
bathtub	use of cans to hold water for bathing or swimming
beerpong	use of cans to play 'beer pong'
bell	use can to ring like a bell
bikenoise	use of cans to make noise while riding a bicycle
birdfeeder	use of cans to feed birds
birdhouse	use of cans to give birds a place to nest
blade	use of cans to cut
blender	using cans to make a blender
blinder	to use a can for restricting vision
boat	use of cans to act as floating transportation
bomb	use of cans to hold explosives
bookend	use of cans to hold up books on a shelf
bookmark	use of cans to mark a page
bowl	use of cans as bowls
bowlingpin	use of cans as bowling pins
bracelet	use of cans to adorn the wrist
buoy	use of cans to mark a location in the water
camera	use of cans to capture images
candle	filling cans with wax and a wick for use in lighting
capo	using cans to hold down the strings of a musical instrument
carousel	use of cans as a rotating amusement ride
chain	use of cans to form a chain

cheddar	used to press cheese
chimney	use of cans to direct smoke
chlorine	use of can to hold chlorine
chock	use of a can to stop a wheel
clock	use of cans to form a clock
clothing	use of cans as fashion
coaster	use of cans to protect surfaces from beverages
coffee	use a can to make coffee
collectable	use of cans as inherently interesting/valuable objects
comb	use of cans to straighten hair
commodity	use of cans as an investment
container	use of cans to hold other objects (miscellaneous or unspecified)
cookiecutter	use of cans to shape cookie dough
cooler	use of can to hold ice
costume	use of cans to disguise a person
counterfeit	use cans to make a phony item
cover	use of cans to cover another object
crab	use of can as a crab shell
cup	use of cans as cups
cupholder	use a can to hold a cup
curler	use of cans to curl hair
dice	use of can to hold dice
disguise	use of cans to disguise anything other than a person
doghouse	use of cans to shelter dogs
doorbell	use of cans to announce a visitor
doorstop	use of cans to hold a door in place
dreamcatcher	use of cans to build a 'dreamcatcher'
drill	use of cans to make holes
driveshaft	to use cans to transmit motion
drug	use of cans as drug paraphernalia
drum	use of cans as a percussive instrument
dumbwaiter	use of cans to carry food up and down a shaft
earmuff	use cans to cover ears
earring	use of cans to adorn the ear
electrical	use of cans' inherent electrical properties like conductivity
engine	use to make part of an engine
envelope	use of cans to hold mail
exercise	use of can to help exercise
extinguisher	use a can to smother a flame
eyeglasses	use of cans to form eyeglass frames
fan	use of cans to move air
Faradaycage	use of can to block EM waves
fingernails	use of cans to form artificial nails

fireholder	use of cans to hold fire (mobile)
firepit	use of cans to hold fire (stationary)
firestarter	use of cans to start fires
fishing	use of cans to catch fish
flashlight	use of cans to hold a portable electric light
flatware	use of cans to form utensils
float	use of cans' buoyancy for unspecified purpose
fondue	use of can to hold melted cheese
food	eat the can
foodcontainer	use of cans to hold food
frame	use of a can to hold a picture
frisbee	use of cans to form a thrown toy
fulcrum	use of cans to act as a pivot
funnel	use of cans to direct liquid into a small opening
furniture	use of cans to build furniture
game	use of cans to form game pieces
geocache	storing things in a can for the purpose of geocaching
glove	using cans to protect hands
goal	use of cans to mark a goal
golf	use of cans as golf holes
grater	to use a can to shred food
grease	use of cans to hold grease
gutter	use of cans to capture and direct rain from a building
hairpin	use of cans to hold hair in place
hammer	use of cans as an impact tool
handle	use of a can to form a handle for another object
hanger	use of cans to suspend clothing
hat	use of cans to cover or adorn the head
headlight	use of cans for car lights
helmet	use of cans to protect the head
hockeypuck	use of cans to play hockey
hook	bending or otherwise forming a curved shape with the cans to hold other objects
hourglass	use cans to form a clock using sand
house	use of cans to build a dwelling
icepack	use of cans to provide therapeutic cold
icepack	use cans to hold freezing water
insulation	use of cans to impede the transmission of energy
jewelry	use of cans as jewelry (non-specific)
jig	use of cans as a tool jig
juggle	use of cans as juggled objects
kaleidoscope	use of cans to house a kaleidoscope
keychain	use can to hold keys

kickthecan	use of cans to play 'kick the can'
ladder	use of cans as a ladder, step stool, etc.
lamp	use of cans to hold light bulbs
lampshade	use of cans to shade lamps
level	use of cans to determine how horizontal a surface is
lockpick	use of cans to open locks
luggage	use of can to hold something while travelling
magic	use of cans for magic tricks
magnet	using a can's innate magnetic properties
mailbox	use of cans to hold delivered mail
mannequin	use of cans to model clothes
maraca	use of cans to form shaking instruments
market	use of cans to delineate space
massage	use of cans to massage muscles
material	use of cans as a generic stock
Matryoshka	use cans to make nesting dolls
measure	use of cans to measure ingredients
missile	use of cans as projectiles
mobile	use of cans to form mobiles
model	use of cans to form models
mold	use of cans to mold other materials
muffler	use of a can to lessen engine noise
music	use of cans to make music (unspecified)
necklace	use of cans to adorn the neck
noisemaker	use of cans to make noise (unspecified)
ocean	use of cans in the manner of a seashell to hear the ocean
oilcan	use of can to hold oil in an engine
organizer	use of cans to organize a desk, etc.
ornament	use of cans to adorn a Christmas tree
oven	use of cans as an oven
paintcan	use of cans to hold paint
paintroller	use of cans to apply paint
pan	use of cans to hold cooking foods
paperclip	use of cans to hold paper together
paperweight	use of cans to hold down paper
pastryring	use of cans as a mold to hold dough or batter
paver	use of cans to form a path
pen	use of can as a pen
pencilcase	use of cans to hold writing implements
pet	use of cans for pet care
phonograph	use of cans to make a record player
pillow	to use a can as a cushion
pincushion	use to store pins and needles

pipe	use of cans to channel liquids
piston	use of cans as engine pistons
planter	use of cans to hold soil and plants
plate	use of cans as plates
plectrum	use of cans to pluck musical instruments
plug	use can to stop water flow
pole	use of cans to form a long pole
popcorn	use can to pop popcorn
projector	use of cans to project images
prosthesis	use can as an artificial limb
protection	use of cans to protect objects
protractor	use of can to measure angles
pulley	use of cans to redirect/magnify force in a rope
purifier	use of cans to make a water purifier
purse	use of cans as a purse
reef	use of cans as the base of a coral reef
reflector	use of cans to reflect light
ring	use of a can to make a ring
riser	use of cans to raise another object
robot	use of cans to hold electronics
rocket	use of cans to launch rockets
rollerskate	use of cans to make roller skates
rollingpin	use of cans to flatten dough
roofing	use of cans as roofing
ruler	use of cans to form straight edges
rust	use of cans' rusting to test environment
safe	use of cans to hold valuables
scarecrow	use of cans to make scarecrows
scoop	use of cans to portion a dry material
scraper	use of cans to make a scraping tool
secret	use of cans as a hiding place
shaker	use of cans to make a shaker for salt, pepper, etc.
shim	use of cans to level furniture
shockabsorber	using cans to absorb impacts
shoe	use of cans as footwear
shovel	use of cans to form a shovel
shower	use the can to form a showerhead
sieve	use of cans to drain liquid from solid material
sign	use of can as a sign
silencer	use of cans to silence or suppress a firearm
skimmer	use of cans as a skimmer
smoker	use of cans to hold smoke and cure food
spindle	use of cans as an axis for other objects to rotate around

spittoon	use of cans to hold saliva/tobacco juice
splint	to use a can to support an injured limb
spotlight	use of cans to hold a spotlight
spring	use of cans to form a spring
staff	use of cans to form a staff
stagelight	use of cans to form footlights
stair	use of cans to form staircases
stamp	use of cans to make stamps
stand	use of cans to hold up another object for temporary use
steeltoe	use cans to reinforce shoes
steering	use of can as steering wheel
stencil	use of cans as a template
stilt	use of cans to raise feet
stove	use of cans as a stove
straw	use cans to drink from a distance
structure	use of cans to build larger structures
support	use of cans to support another object
tambourine	use cans to form a tambourine
tapdance	use of cans to make noises while tap dancing
target	use of cans as a target for projectiles
tea	to use a can to hold loose tea leaves
tee	use the can to hold a golf ball before swinging
telephone	use of cans to make a string telephone
telescope	use of cans to hold lenses for magnifying distant objects
thermal	use of cans to transmit heat
timecapsule	use of cans to hold objects for future generations
toilet	use of cans to hold sewerage
torch	use of cans to hold fuel for light
torture	use of can to cause pain
totem	use cans to form a totem pole
toy	use of cans as playthings
trap	use of cans to capture small animals
trash	use of cans to hold refuse
treewrap	use cans to protect a plant
tripod	use of cans to hold a camera
tunnel	use cans as a path under a terrain feature
umbrella	use of cans to provide shade/block rain
vase	use of cans to hold cut flowers
walkway	using cans to form a walkway
wall	use of cans to build walls
wallpaper	use of cans to cover walls
watch	use of cans to form watch parts
water	use of cans to hold water

waterheater	use of cans to provide hot water
wateringcan	use of cans to hold water for plants
waterwheel	use of cans to harness water flow
weapon	use of cans to make weapons
wedding	use of cans as a noise maker on newlyweds' car
weight	use of cans to be heavy/hold heavy things
wheel	use of cans to roll
whetstone	use can to sharpen blades
windchime	use of cans as windchimes
windmill	use of cans as windmills
woodwind	use of cans as wind instruments
writingsurface	use of cans as writing surface
xylophone	use to form a xylophone-like instrument

Paperclip Keywords:

Keyword:	Meaning:
acupuncture	use of paperclips to perform acupuncture
antenna	use of paperclips to receive EM signals
armor	use of paperclips to make chainmail
arrow	use of paperclips as a bow-launched projectile
art	use of paperclips as art supply
awl	use of paperclips to make holes
bagclip	use of paperclips to seal a food bag
baking	use of paperclips to test a baked good for doneness
ball	use of paperclips as a ball in sports
ballast	use of paperclips as a weight for balance
balloon	use of paperclips to pop balloons
barbwire	use of paperclips to barb wires
basket	use of paperclips to weave baskets
bearing	use of paperclips as roller bearings
belt	use of paperclips to hold up pants
binder	use of paperclips as binder rings
birdnest	use of paperclips to build a nest
blade	sharpening paperclips to form cutting tools
boardgame	use of paperclips as tokens in a game
bookmark	use of paperclips to temporarily mark pages
bottleopener	use of paperclips to remove bottle caps
bow	use of paperclips to make a bow
bra	use of paperclips to make a bra
bracelet	making a chain of paperclips to form a bracelet

brand	heating a formed paperclip to make a branding iron
broach	use of paperclips as a broach
button	use of paperclips to replace a button
buttonpusher	use of paperclips to open a CD drive
cabletie	use of paperclips to hold together wires
cage	use of paperclips to form a cage
canopener	use of paperclips to open cans
capo	use of paperclips to hold down guitar strings
carabiner	use of paperclips to hold ropes
card	use of paperclips to hold cards
carpet	use of paperclips to weave a mat
catapult	use of paperclips to build a catapult
cauterize	heating paperclips to cauterize wounds
chain	making a chain of paperclips
chisel	use of paperclips as a chisel
choke	use of paperclips to restrict a fluid's flow
chopsticks	use of paperclips as chopsticks
cigarette	use of paperclips to hold cigarettes
clamp	use of paperclips to hold two objects together
clasp	use of paperclips to hold together clothes
claw	use of paperclips to form claws
cleaner	use of paperclips to clean recesses
clock	use of paperclips as clock parts
clothespin	use of paperclips to hold clothes on a line to dry
comb	use of paperclips to straighten hair
compass	magnetizing a paperclip to make a compass needle
cookiecutter	forming a paperclip into a shape to mold cookies
costume	use of paperclips to make a disguise
crowbar	use of paperclips to pry
cufflink	use of paperclips to hold together shirt cuffs
currency	use of paperclips as currency
curtain	use of paperclips to hang curtains
dipstick	use of paperclips to test oil level
distracter	use of paperclips for fidgeting
doorstop	use of paperclips to hold open doors
draincleaner	use of paperclips to clear drains
drumstick	use of paperclips to beat drums
duster	use of paperclips to clear dust
earring	use of paperclips as ear ornaments
earwax	use of paperclips to clean earwax
engraver	use of paperclips to scratch designs
Faradaycage	use of paperclips to block EM waves
fastener	use of paperclips in place of screws, nails, staples, etc.

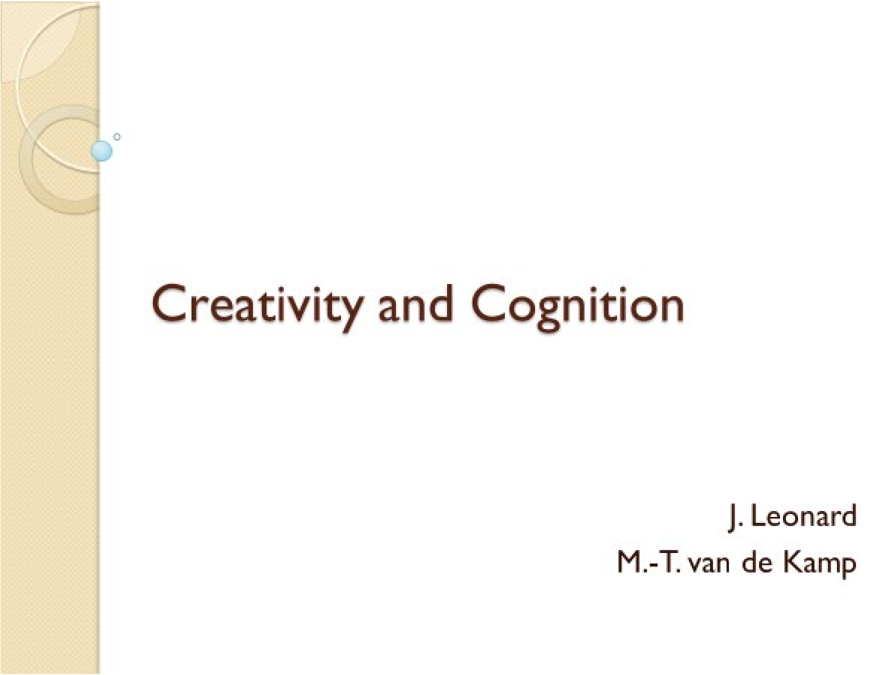
fatigue	use of paperclips to test fatigue strength
fence	use of paperclips to make a fence
filament	use of paperclips in a lightbulb
fishinghook	use of paperclips to catch fish (hook)
fishingpole	use of paperclips to catch fish (pole)
flagpole	use of paperclips to hang a flag
flatware	use of paperclips as generic cutlery
fork	use of paperclips to stab food
frame	use of paperclips to make a picture frame
friction	use of paperclips to generate heat
furniture	use of paperclips to build furniture
fuse	use of paperclips as fuses
garland	making a wreath of paperclips
glasses	use of paperclips to make eyeglass frames
glitter	grinding paperclips into glitter
goal	use of paperclips to form a scoring location
grater	use of paperclips to shred food
hairpin	use of paperclips to hold hairstyles
hammock	use of paperclips to form a hammock
handle	use of paperclips to form a handle
hanger	use of paperclips to hang clothes
headphone	use of paperclips to hold earpieces
hinge	use of paperclips to form hinges
hook	use of paperclips to form hooks for hanging generic objects
icepick	use of paperclips to chip ice
jewelry	use of paperclips for adornment
jumprope	forming paperclips into a chain to skip
key	use of paperclips to make a key
keychain	use of paperclips to hold keys
kite	use of paperclips to make a kite frame
knittingneedle	use of paperclips to knit
label	use of paperclips to remove labels
lacer	use of paperclips to draw shoelaces through holes
lance	use of paperclips to lance boils
lasso	forming paperclips into a chain to catch animals
latch	use of paperclips to hold a gate
leash	use of paperclips to form a leash
lettering	forming paperclips into the shape of letters for signs
letteropener	use of paperclips to open envelopes
lever	use of paperclips as a lever
lightningrod	use of paperclips to attract lightning
lockpick	use of paperclips to pick locks
magic	use of paperclips in magic tricks

magnet	use of paperclips' magnetic properties
makeup	use of paperclips to apply makeup
marshmallow	use of paperclips to roast marshmallows
material	use of paperclips as a material for other objects
measure	use of paperclips as a unit of measure
missile	use of paperclips as a projectile
model	use of paperclips to build models
moneyclip	use of paperclips to hold paper bills
music	use of paperclips to make instruments
nailcleaner	use of paperclips to clean under fingernails
nailpolish	use of paperclips to apply nail polish
necklace	forming a chain of paperclips to wear around the neck
needle	using paperclips to sew
net	forming paperclips into a net
noise	using paperclips to make nonmusical noise
noseclip	using paperclips to pinch nostrils together
nutcracker	using paperclips to open nuts
organizer	using paperclips to organize other items
ornament	using paperclips to hang [Christmas or other] ornaments
paintbrush	using paperclips to apply paint
paperweight	using paperclips to hold down light objects
peeler	using paperclips to peel vegetables
pen	use of paperclips to write with ink
pencilholder	use of paperclips to organize pencils
pendulum	use of paperclips as a weight at the end of a pendulum
penrest	use of paperclips to hold pen and ink
pet	use of paperclips to make items for pets
phonestand	use of paperclips to prop up a smartphone
pick	use of paperclips to dig
pin	use of paperclips as striaghtpins
pipe	use of paperclips as the base material for pipes
plant	use of paperclips to hold plants upright
plasma	putting a paperclip in a microwave to generate plasma
plectrum	use of paperclips in place of guitar picks
pointer	use of paperclips as pointers
poker	use of paperclips to tend a fire
pole	use of paperclips to form a pole
probe	use of paperclips to explore confined spaces
pulley	use of paperclips to make a pulley
pushrod	use of paperclips to make an engine pushrod
puzzle	use of paperclips as part of a puzzle
rake	use of paperclips to rake up leaves
resistor	use of paperclips as a wire to impede electrical flow

ring	use of paperclips to form finger rings
robot	use of paperclips to make robot parts
ruler	use of paperclips as a straightedge
sample	use of paperclips as a material sample
scraper	use of paperclips to scrape something clean
scratcher	use of paperclips to scratch
screwdriver	use of paperclips to drive screws
sculptingtool	use of paperclips to sculpt clay
sculpture	use of paperclips to form a sculpture
shim	use of paperclips to level furniture
shirtpoint	use of paperclips to reinforce a collar
shoelace	use of paperclips to tie shoes
sieve	use of paperclips to make a strainer
skewer	use of paperclips to hold food while cooking
slingshot	use of paperclips as the frame of a slingshot
solder	use of paperclips as solder
spacer	use of paperclips to maintain a gap
spit	use of paperclips to hold food over a fire
splint	use of paperclips to reinforce an injury
spoon	use of paperclips to form a spoon
spring	winding paperclips into a spring
stencil	tracing a form made from paperclips
stirrer	using paperclips to stir a liquid
stress	using paperclips to relieve stress
structure	using paperclips to build a building, bridge, etc.
stylus	using paperclips to play phonograph records
sundial	use of paperclips to form a sundial's gnomon
support	use of paperclips to support something else
surfacetension	use of paperclips to demonstrate surface tension
suspenders	use of paperclips as suspenders
switch	use of paperclips to form an electrical switch
sword	use of paperclips to make a sword
tape	use of paperclips to hold tape
tattoo	use of paperclips as tattooing needles
tea	use of paperclips to brew tea
thermal	use of paperclips' thermal properties
tieclip	use of paperclips to hold a tie together
token	use of paperclips as tokens
tongs	use of paperclips to make tongs
tool	use of paperclips as tools
toothbrush	use of paperclips to brush teeth
toothpick	use of paperclips to pick teeth
torture	use of paperclips as torture devices

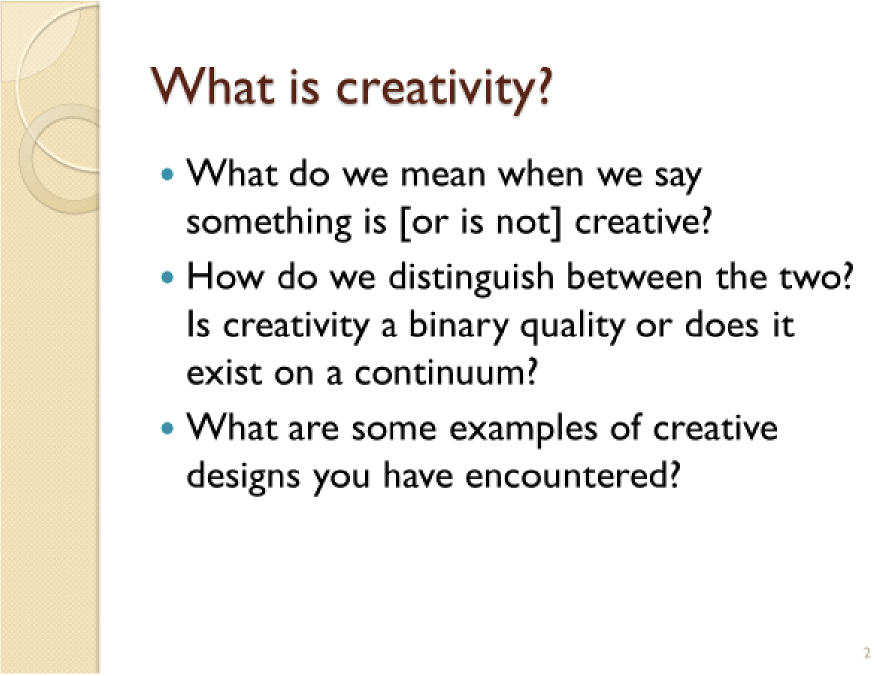
tourniquet	use of paperclips to staunch blood flow
toy	use of paperclips to make toys
trap	use of paperclips to make animal traps
tread	use of paperclips to add traction to shoes
trigger	use of paperclips to form a trigger
tweezer	use of paperclips to form tweezers
valve	use of paperclips to form a valve
watch	use of paperclips to make watch parts
weapon	use of paperclips to form generic weapons
weathervane	use of paperclips to tell wind direction
weight	use of paperclips as a weight
whisk	use of paperclips to make a whisk
windchime	use of paperclips to make windchimes
wire	use of paperclips to conduct electricity
zipper	use of paperclips to replace a zipper

Appendix C: Creativity Lecture Slides



Creativity and Cognition

J. Leonard
M.-T. van de Kamp

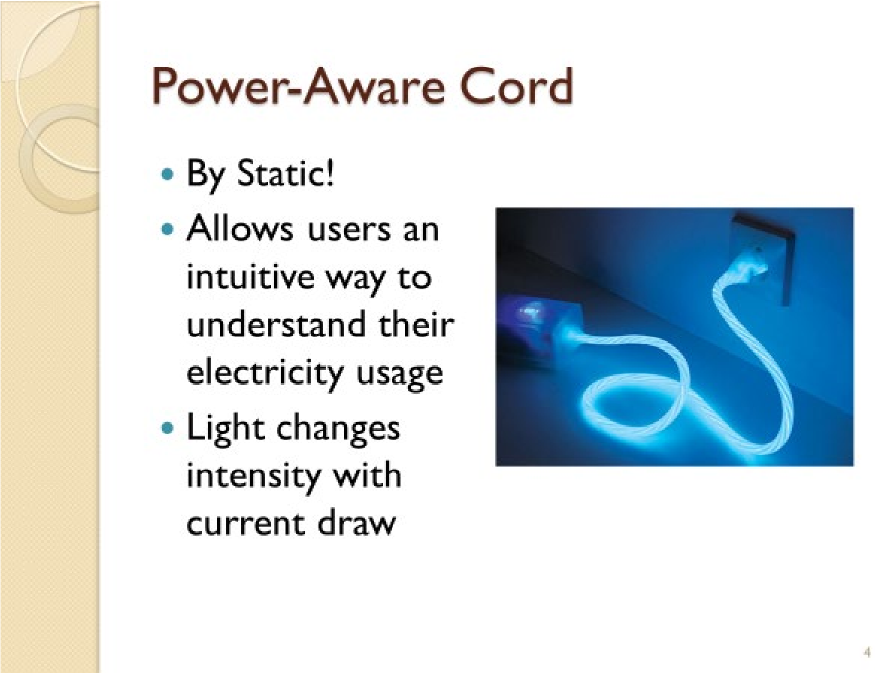


What is creativity?

- What do we mean when we say something is [or is not] creative?
- How do we distinguish between the two? Is creativity a binary quality or does it exist on a continuum?
- What are some examples of creative designs you have encountered?

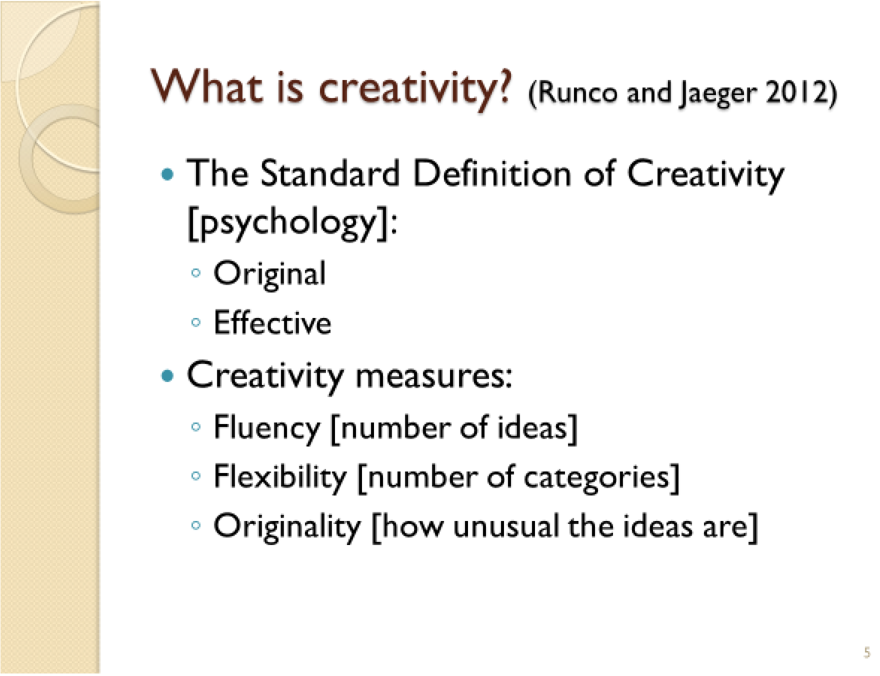
NeoNurture Incubator

- By Design that Matters
- Uses old car parts in place of expensive, delicate medical equipment
- Dashboard fans ventilate, headlights provide heat, etc.



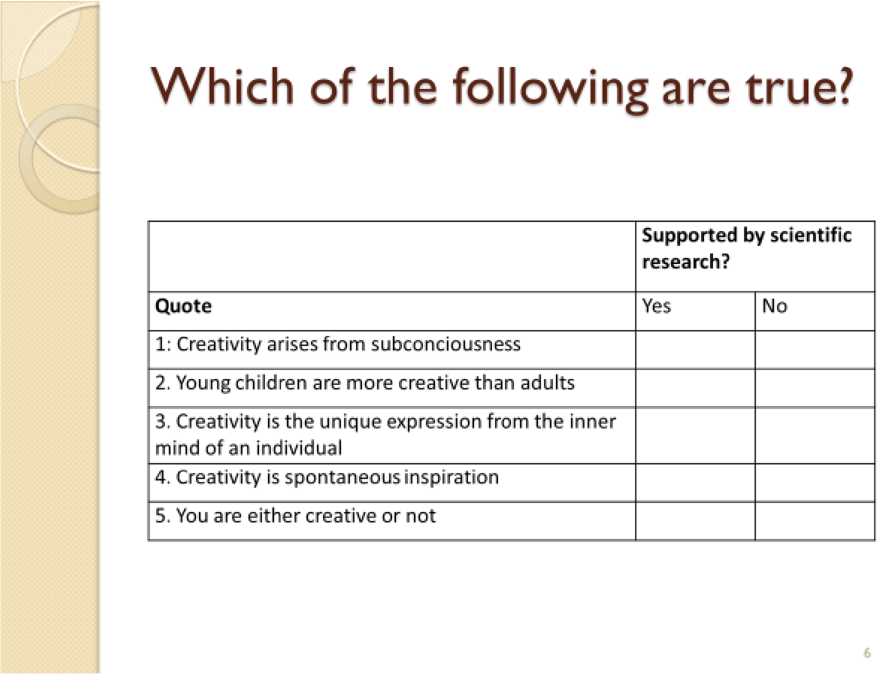
Power-Aware Cord

- By Static!
- Allows users an intuitive way to understand their electricity usage
- Light changes intensity with current draw



What is creativity? (Runco and Jaeger 2012)

- The Standard Definition of Creativity [psychology]:
  - Original
  - Effective
- Creativity measures:
  - Fluency [number of ideas]
  - Flexibility [number of categories]
  - Originality [how unusual the ideas are]



Which of the following are true?

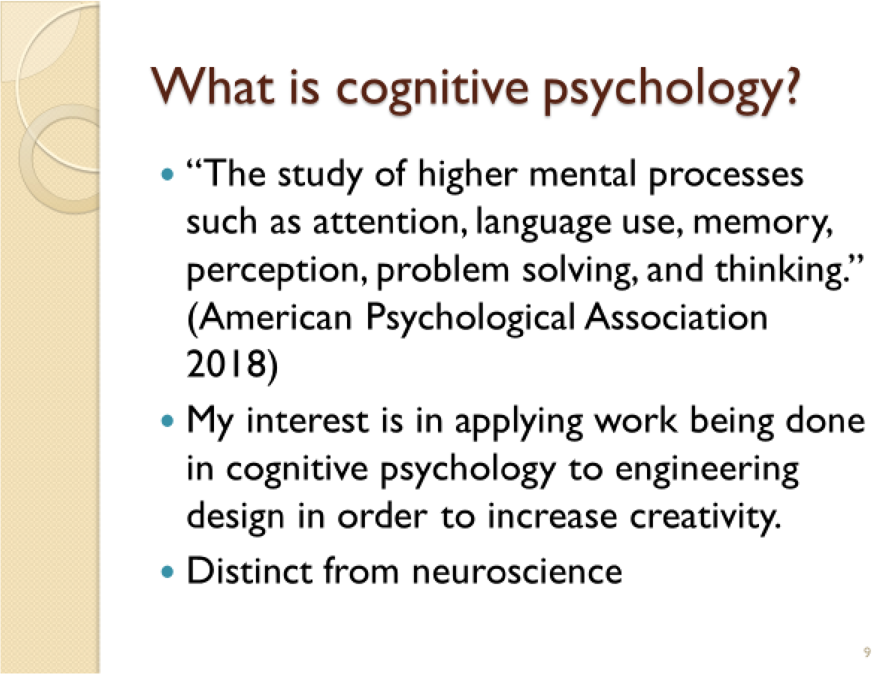
	Supported by scientific research?	
Quote	Yes	No
1: Creativity arises from subconciousness		
2. Young children are more creative than adults		
3. Creativity is the unique expression from the inner mind of an individual		
4. Creativity is spontaneous inspiration		
5. You are either creative or not		

None of these are true

	Supported by scientific research?	
Quote	Yes	No
1: Creativity arises from subconciousness		**X**
2. Young children are more creative than adults		**X**
3. Creativity is the unique expression from the inner mind of an individual		**X**
4. Creativity is spontaneous inspiration		**X**
5. You are either creative or not		**X**

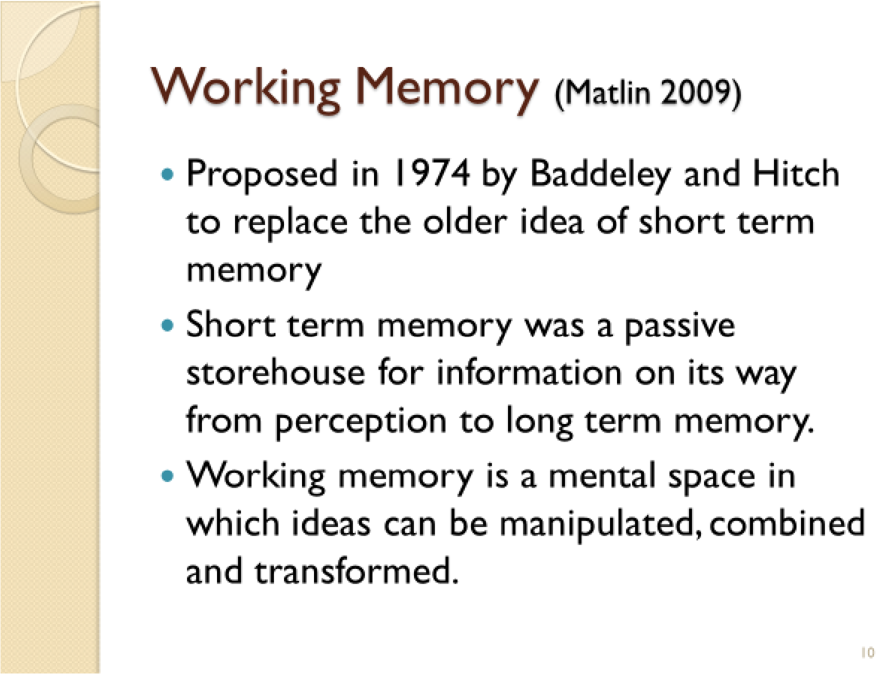
What creativity is not

- Creativity is not a talent, it is a skill
- Creativity can be improved through:
  - Practice
  - Strategy use
  - Exposure to new ideas



What is cognitive psychology?

- "The study of higher mental processes such as attention, language use, memory, perception, problem solving, and thinking." (American Psychological Association 2018)
- My interest is in applying work being done in cognitive psychology to engineering design in order to increase creativity.
- Distinct from neuroscience

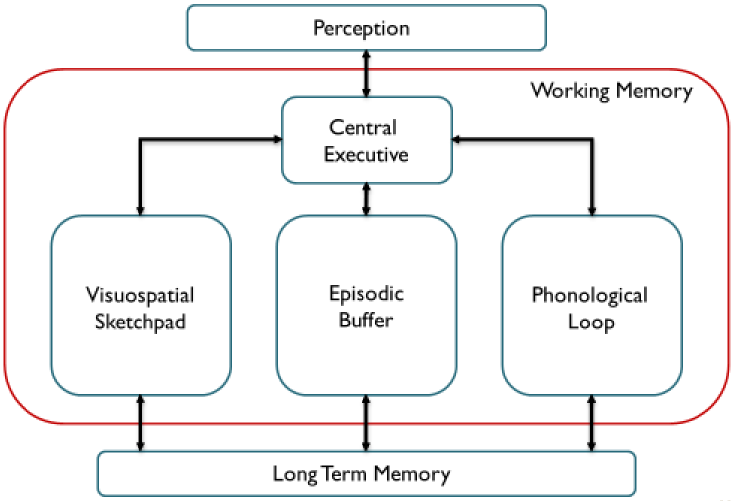


Working Memory (Matlin 2009)

- Proposed in 1974 by Baddeley and Hitch to replace the older idea of short term memory
- Short term memory was a passive storehouse for information on its way from perception to long term memory.
- Working memory is a mental space in which ideas can be manipulated, combined and transformed.

Baddeley's Working Memory Model

(Baddeley 2000, Matlin 2009)



Perception

Working Memory

Central Executive

Visuospatial Sketchpad

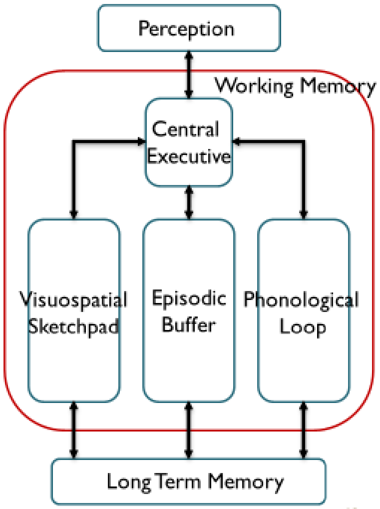
Episodic Buffer

Phonological Loop

Long Term Memory

Components of Working Memory

- Central Executive:
  - Resists interference and distractions
  - Inhibits responses
  - Allocates attention
  - Integrates the other components
  - Applies strategies
  - Does not store information



Perception

Working Memory

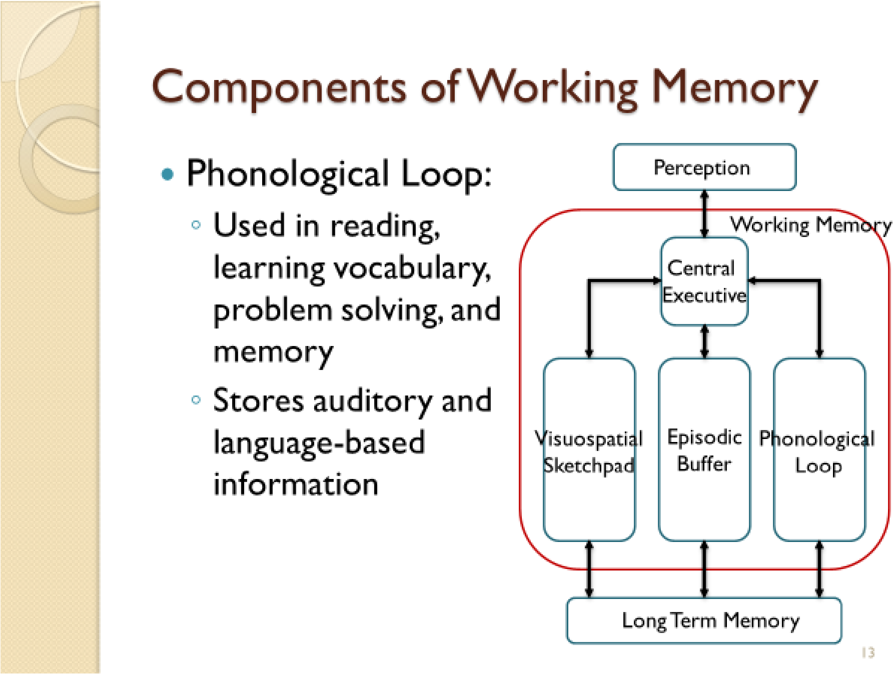
Central Executive

Visuospatial Sketchpad

Episodic Buffer

Phonological Loop

Long Term Memory



Components of Working Memory

- Phonological Loop:
  - Used in reading, learning vocabulary, problem solving, and memory
  - Stores auditory and language-based information

Perception

Working Memory

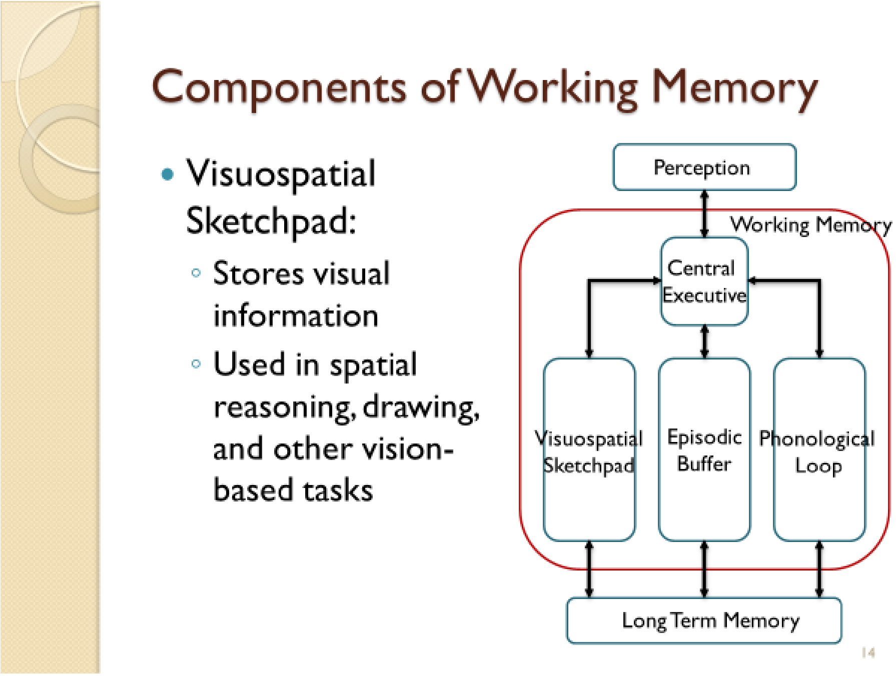
Central Executive

Visuospatial Sketchpad

Episodic Buffer

Phonological Loop

Long Term Memory



Components of Working Memory

- Visuospatial Sketchpad:
  - Stores visual information
  - Used in spatial reasoning, drawing, and other vision-based tasks

Perception

Working Memory

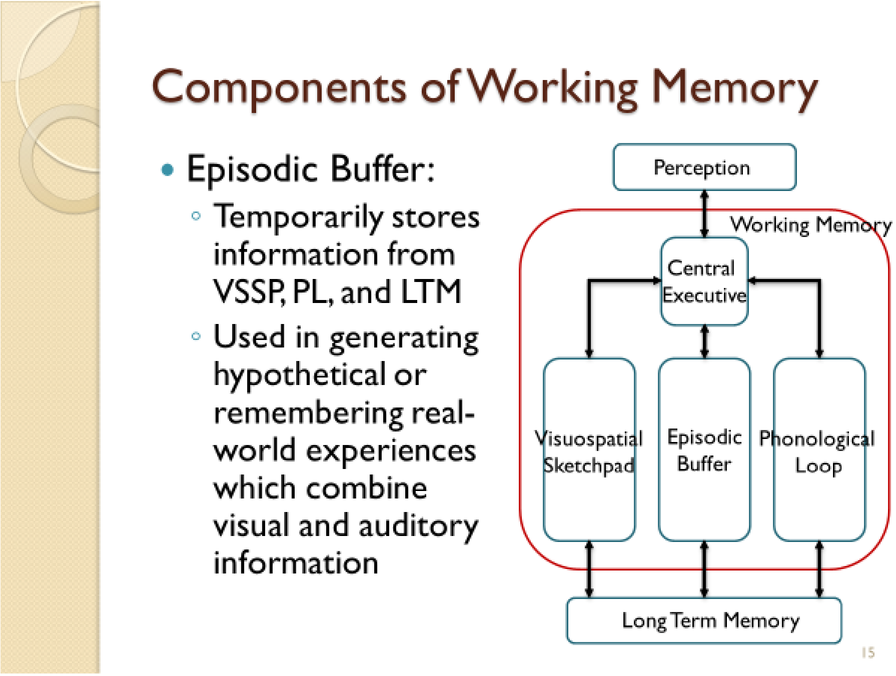
Central Executive

Visuospatial Sketchpad

Episodic Buffer

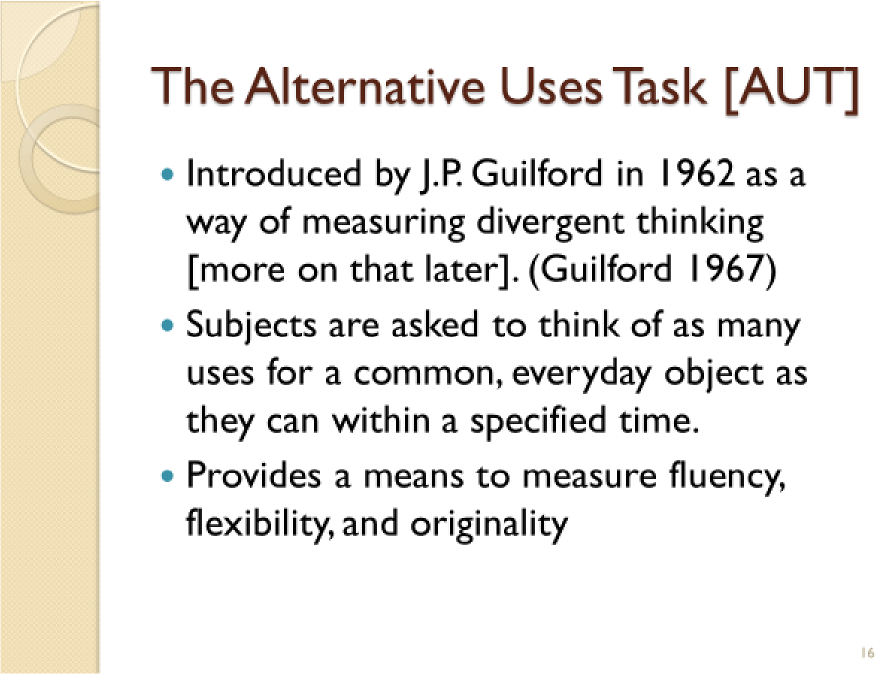
Phonological Loop

Long Term Memory



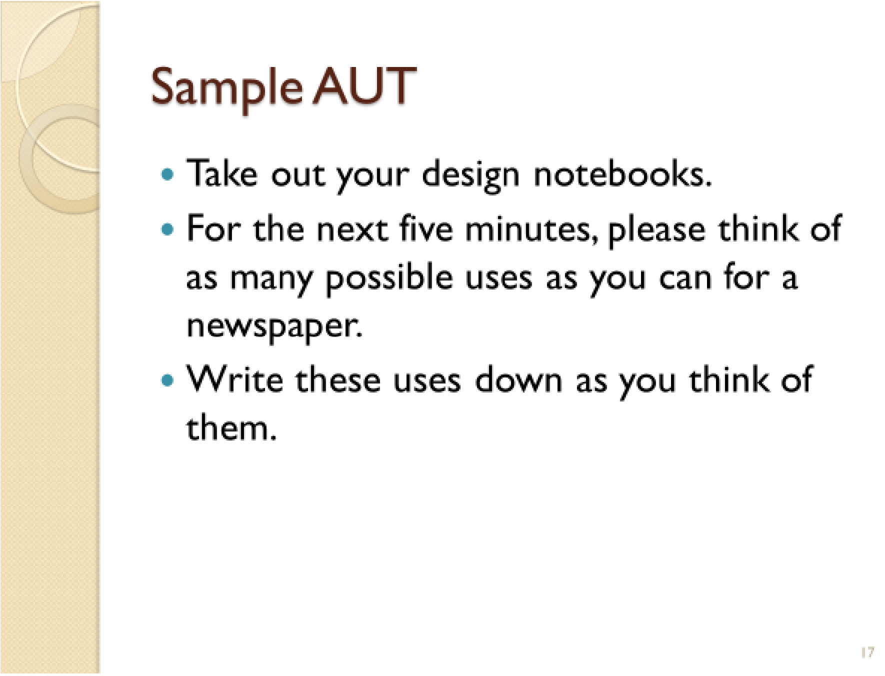
Components of Working Memory

- Episodic Buffer:
  - Temporarily stores information from VSSP, PL, and LTM
  - Used in generating hypothetical or remembering real-world experiences which combine visual and auditory information



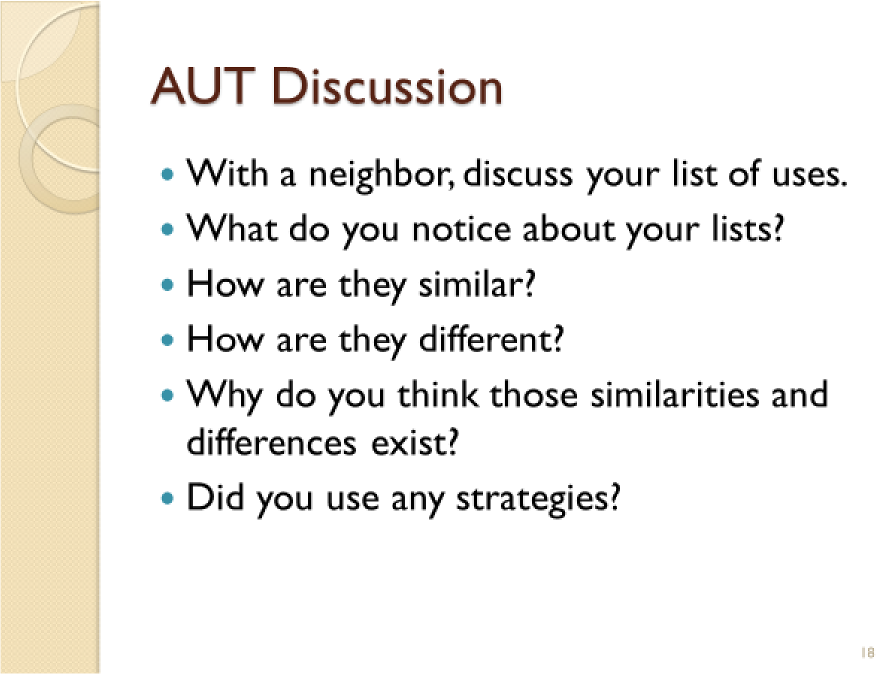
The Alternative Uses Task [AUT]

- Introduced by J.P. Guilford in 1962 as a way of measuring divergent thinking [more on that later]. (Guilford 1967)
- Subjects are asked to think of as many uses for a common, everyday object as they can within a specified time.
- Provides a means to measure fluency, flexibility, and originality



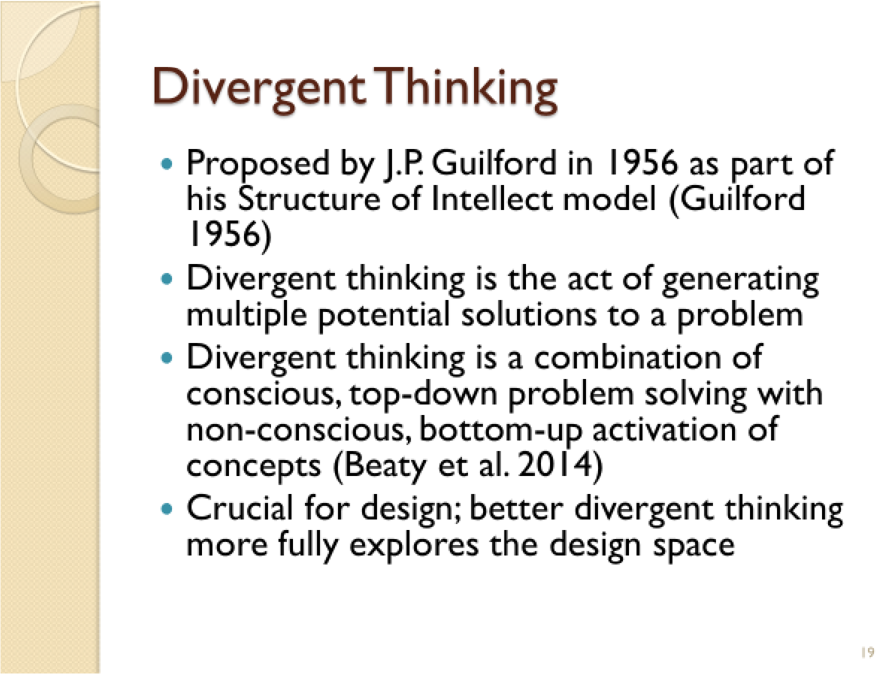
Sample AUT

- Take out your design notebooks.
- For the next five minutes, please think of as many possible uses as you can for a newspaper.
- Write these uses down as you think of them.



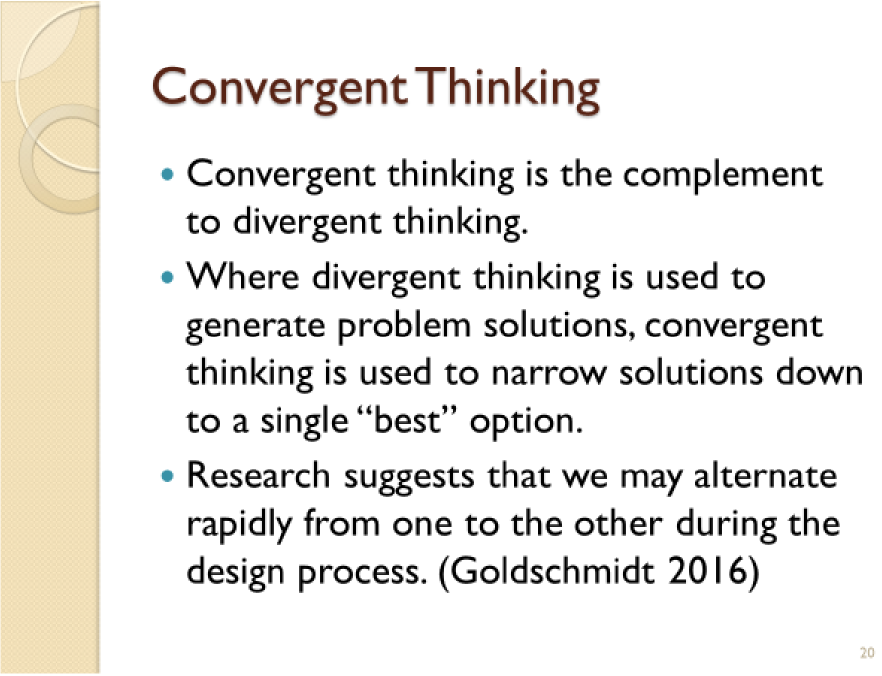
AUT Discussion

- With a neighbor, discuss your list of uses.
- What do you notice about your lists?
- How are they similar?
- How are they different?
- Why do you think those similarities and differences exist?
- Did you use any strategies?



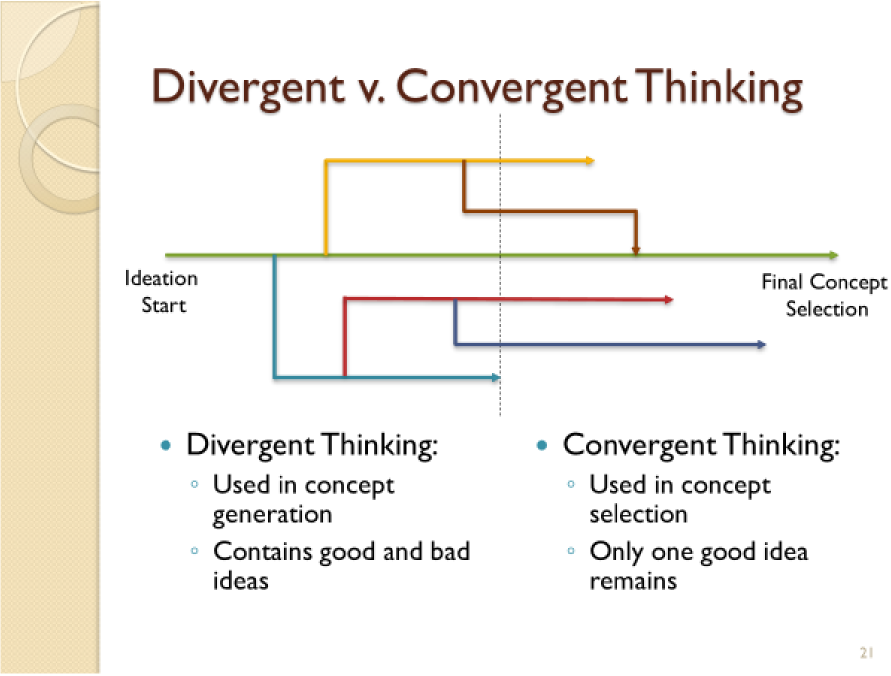
Divergent Thinking

- Proposed by J.P. Guilford in 1956 as part of his Structure of Intellect model (Guilford 1956)
- Divergent thinking is the act of generating multiple potential solutions to a problem
- Divergent thinking is a combination of conscious, top-down problem solving with non-conscious, bottom-up activation of concepts (Beaty et al. 2014)
- Crucial for design; better divergent thinking more fully explores the design space



Convergent Thinking

- Convergent thinking is the complement to divergent thinking.
- Where divergent thinking is used to generate problem solutions, convergent thinking is used to narrow solutions down to a single "best" option.
- Research suggests that we may alternate rapidly from one to the other during the design process. (Goldschmidt 2016)

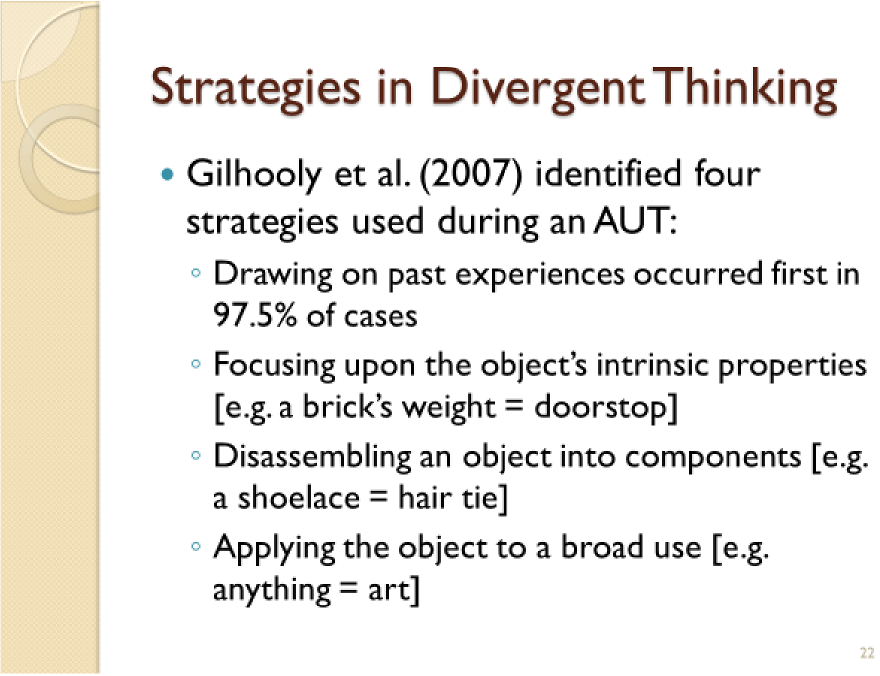


Divergent v. Convergent Thinking

Ideation Start

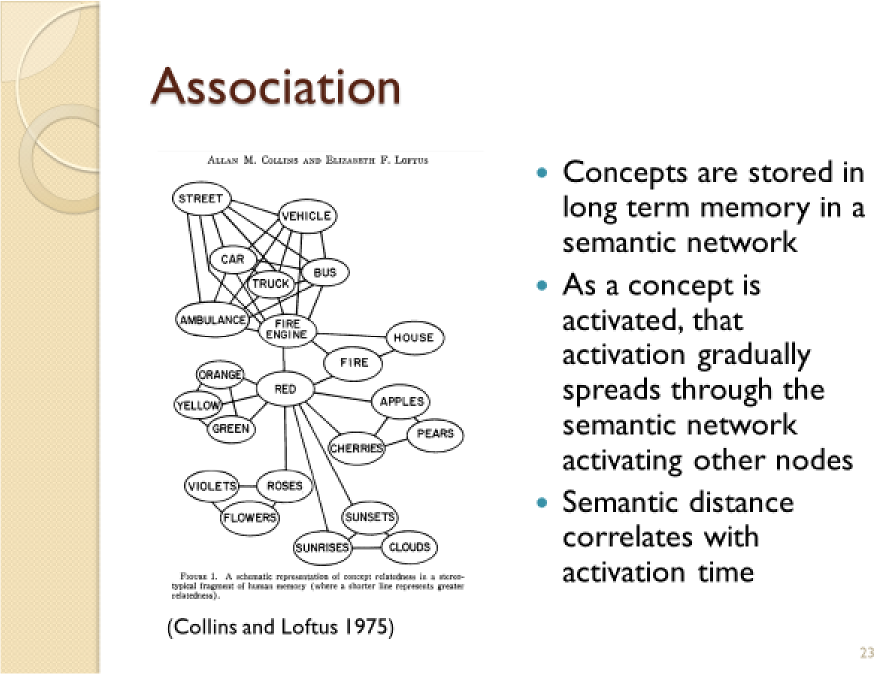
Final Concept Selection

- Divergent Thinking:
  - Used in concept generation
  - Contains good and bad ideas
- Convergent Thinking:
  - Used in concept selection
  - Only one good idea remains



Strategies in Divergent Thinking

- Gilhooly et al. (2007) identified four strategies used during an AUT:
  - Drawing on past experiences occurred first in 97.5% of cases
  - Focusing upon the object's intrinsic properties [e.g. a brick's weight = doorstop]
  - Disassembling an object into components [e.g. a shoelace = hair tie]
  - Applying the object to a broad use [e.g. anything = art]

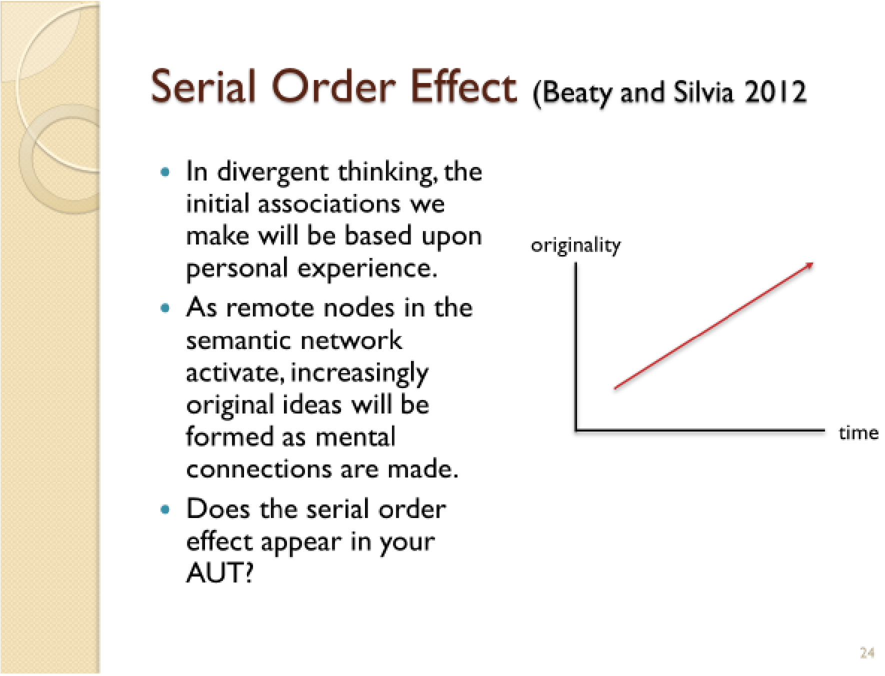


Association

FIGURE 1. A schematic representation of concept relatedness in a stereotypical fragment of human memory (where a shorter line represents greater relatedness).

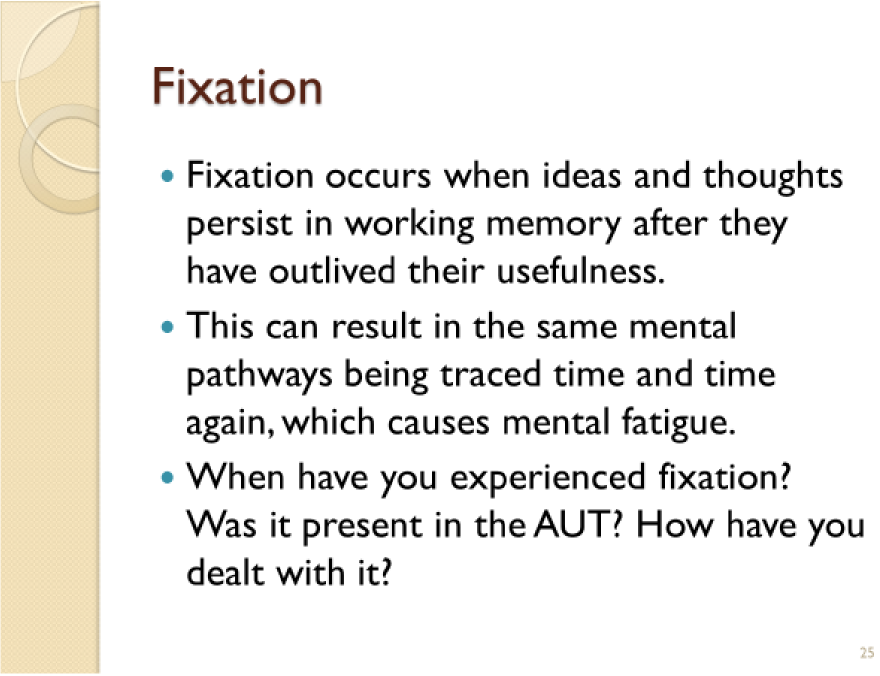
(Collins and Loftus 1975)

- Concepts are stored in long term memory in a semantic network
- As a concept is activated, that activation gradually spreads through the semantic network activating other nodes
- Semantic distance correlates with activation time



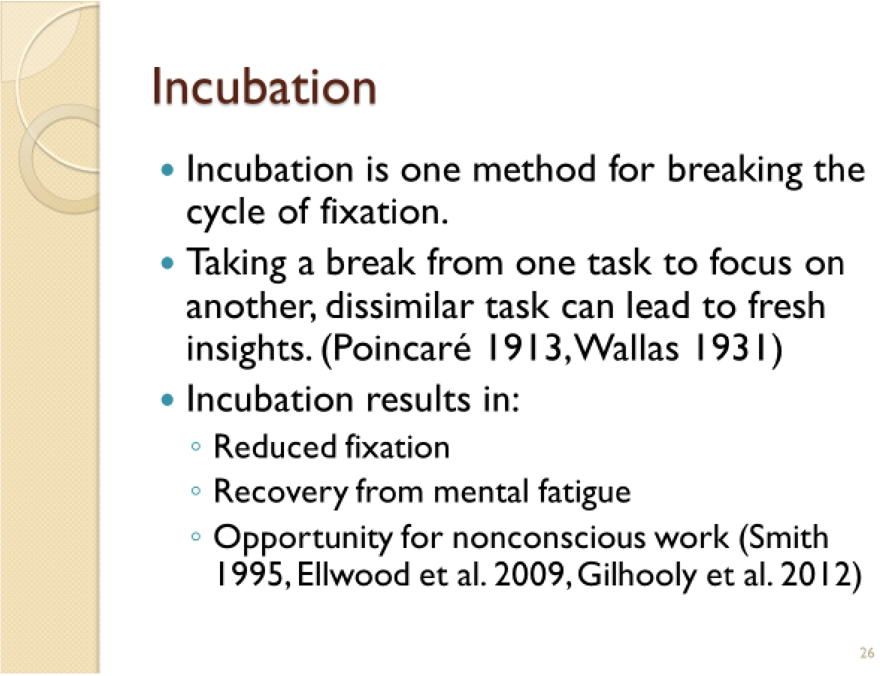
Serial Order Effect (Beaty and Silvia 2012

- In divergent thinking, the initial associations we make will be based upon personal experience.
- As remote nodes in the semantic network activate, increasingly original ideas will be formed as mental connections are made.
- Does the serial order effect appear in your AUT?



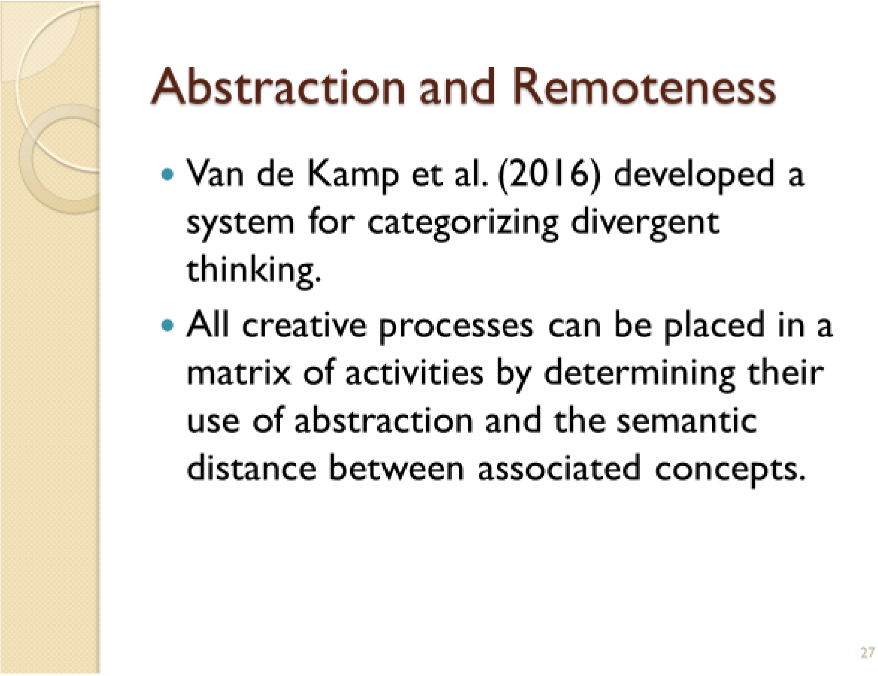
Fixation

- Fixation occurs when ideas and thoughts persist in working memory after they have outlived their usefulness.
- This can result in the same mental pathways being traced time and time again, which causes mental fatigue.
- When have you experienced fixation? Was it present in the AUT? How have you dealt with it?



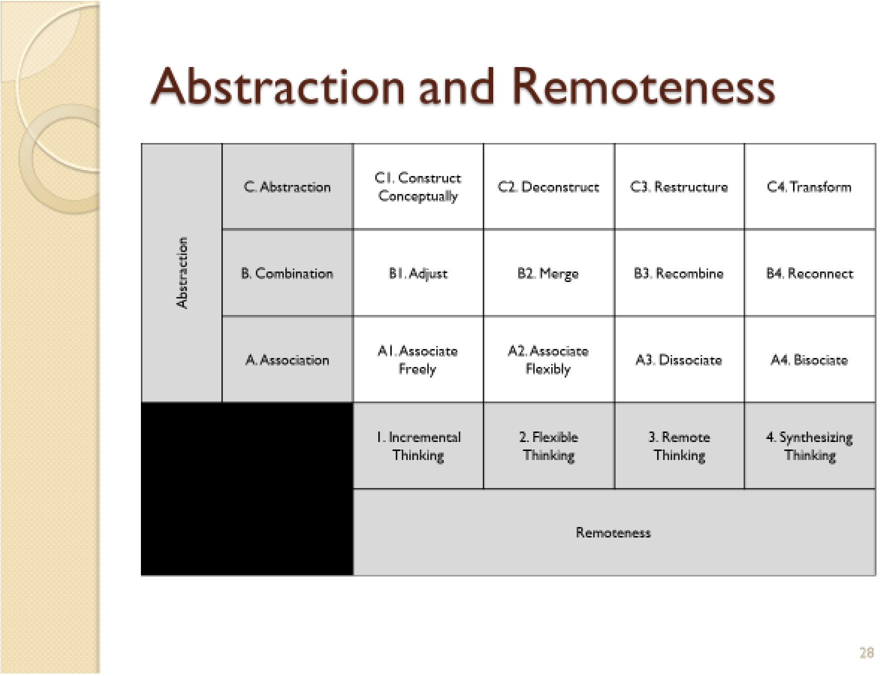
Incubation

- Incubation is one method for breaking the cycle of fixation.
- Taking a break from one task to focus on another, dissimilar task can lead to fresh insights. (Poincaré 1913, Wallas 1931)
- Incubation results in:
  - Reduced fixation
  - Recovery from mental fatigue
  - Opportunity for nonconscious work (Smith 1995, Ellwood et al. 2009, Gilhooly et al. 2012)



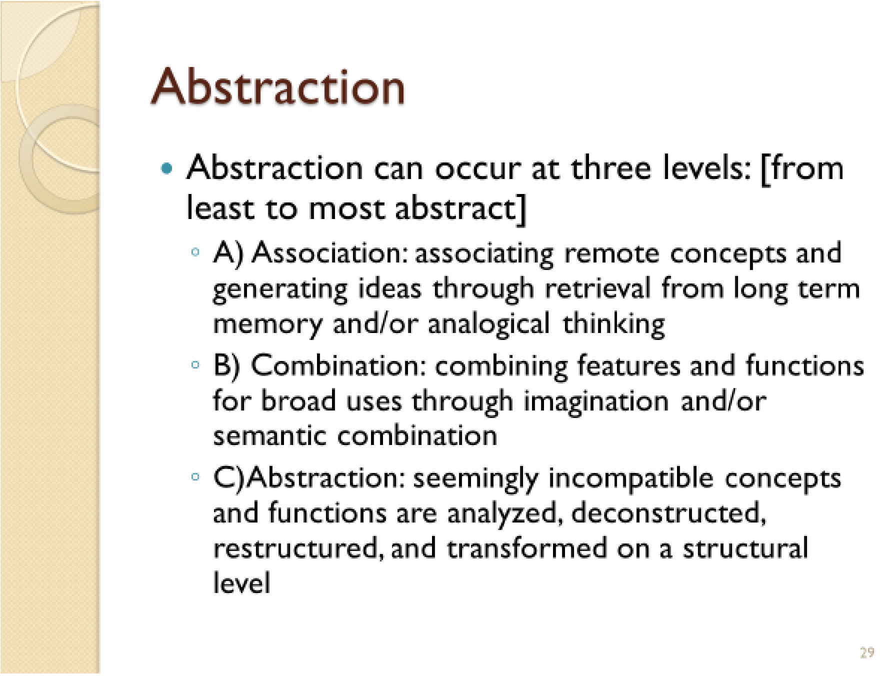
Abstraction and Remoteness

- Van de Kamp et al. (2016) developed a system for categorizing divergent thinking.
- All creative processes can be placed in a matrix of activities by determining their use of abstraction and the semantic distance between associated concepts.



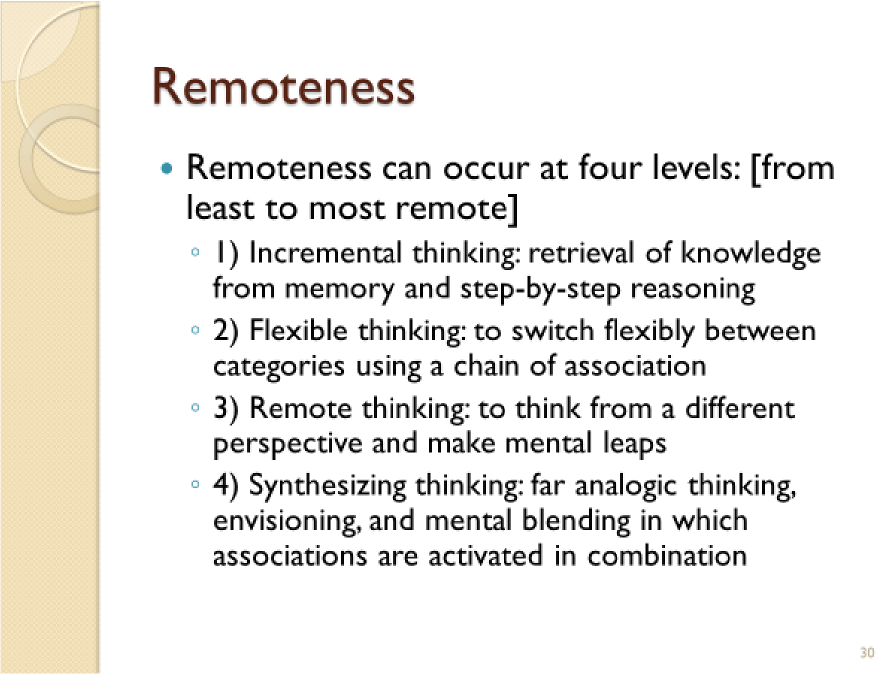
Abstraction and Remoteness

Abstraction	C. Abstraction	C1. Construct Conceptually	C2. Deconstruct	C3. Restructure	C4. Transform
	B. Combination	B1. Adjust	B2. Merge	B3. Recombine	B4. Reconnect
	A. Association	A1. Associate Freely	A2. Associate Flexibly	A3. Dissociate	A4. Bisociate
		1. Incremental Thinking	2. Flexible Thinking	3. Remote Thinking	4. Synthesizing Thinking
		Remoteness			



Abstraction

- Abstraction can occur at three levels: [from least to most abstract]
    - A) Association: associating remote concepts and generating ideas through retrieval from long term memory and/or analogical thinking
    - B) Combination: combining features and functions for broad uses through imagination and/or semantic combination
    - C)Abstraction: seemingly incompatible concepts and functions are analyzed, deconstructed, restructured, and transformed on a structural level



Remoteness

- Remoteness can occur at four levels: [from least to most remote]
    - 1) Incremental thinking: retrieval of knowledge from memory and step-by-step reasoning
    - 2) Flexible thinking: to switch flexibly between categories using a chain of association
    - 3) Remote thinking: to think from a different perspective and make mental leaps
    - 4) Synthesizing thinking: far analogic thinking, envisioning, and mental blending in which associations are activated in combination

Abstraction and Remoteness Examples

- A2.) Flexible association: switching between associative chains of ideas, using episodic and semantic memory [e.g. metaphor]
- B2.) Merging: all features of two objects or functions are combined into a single, hybrid form
- C2.) Deconstruction: critical analysis of concepts, functions, and contexts into separate structures, then recombining [e.g. Phonebloks]

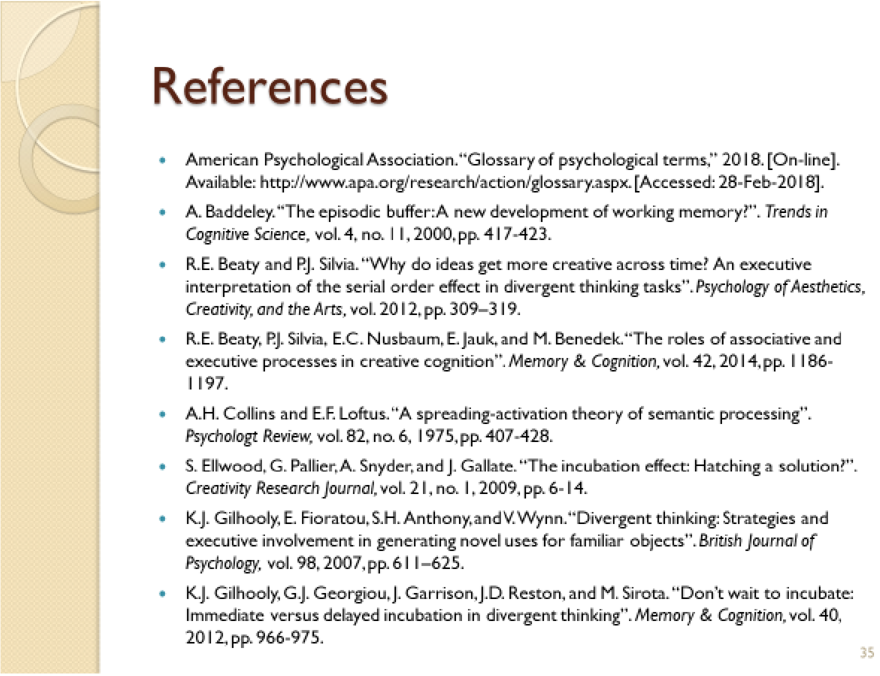
Phonebloks

- By Dave Hakkens
- Attempts to reduce electronic waste by developing a modular smartphone
- Allows for gradual upgrading and replacement of components

How can we be creative?

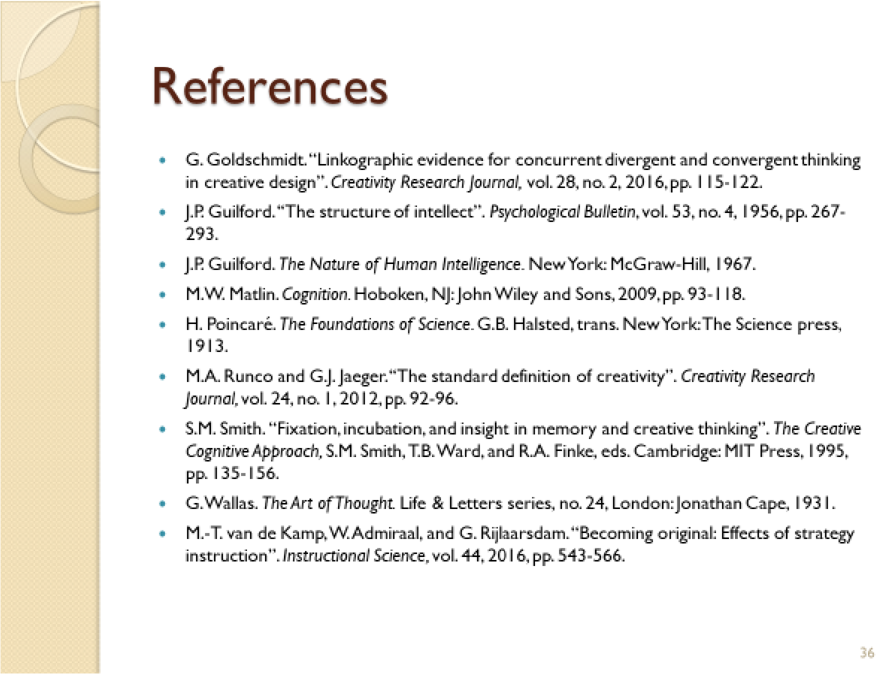
- Practice being creative
- Do not self-edit during divergent thinking
- Be mindful of your thought process
- Use design strategies [viz. the rest of this course]

Questions or comments?



References

- American Psychological Association. "Glossary of psychological terms," 2018. [On-line]. Available: http://www.apa.org/research/action/glossary.aspx. [Accessed: 28-Feb-2018].
- A. Baddeley. "The episodic buffer: A new development of working memory?". *Trends in Cognitive Science*, vol. 4, no. 11, 2000, pp. 417-423.
- R.E. Beaty and P.J. Silvia. "Why do ideas get more creative across time? An executive interpretation of the serial order effect in divergent thinking tasks". *Psychology of Aesthetics, Creativity, and the Arts*, vol. 2012, pp. 309–319.
- R.E. Beaty, P.J. Silvia, E.C. Nusbaum, E. Jauk, and M. Benedek. "The roles of associative and executive processes in creative cognition". *Memory & Cognition*, vol. 42, 2014, pp. 1186-1197.
- A.H. Collins and E.F. Loftus. "A spreading-activation theory of semantic processing". *Psychologt Review*, vol. 82, no. 6, 1975, pp. 407-428.
- S. Ellwood, G. Pallier, A. Snyder, and J. Gallate. "The incubation effect: Hatching a solution?". *Creativity Research Journal*, vol. 21, no. 1, 2009, pp. 6-14.
- K.J. Gilhooly, E. Fioratou, S.H. Anthony, and V. Wynn. "Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects". *British Journal of Psychology*, vol. 98, 2007, pp. 611–625.
- K.J. Gilhooly, G.J. Georgiou, J. Garrison, J.D. Reston, and M. Sirota. "Don't wait to incubate: Immediate versus delayed incubation in divergent thinking". *Memory & Cognition*, vol. 40, 2012, pp. 966-975.

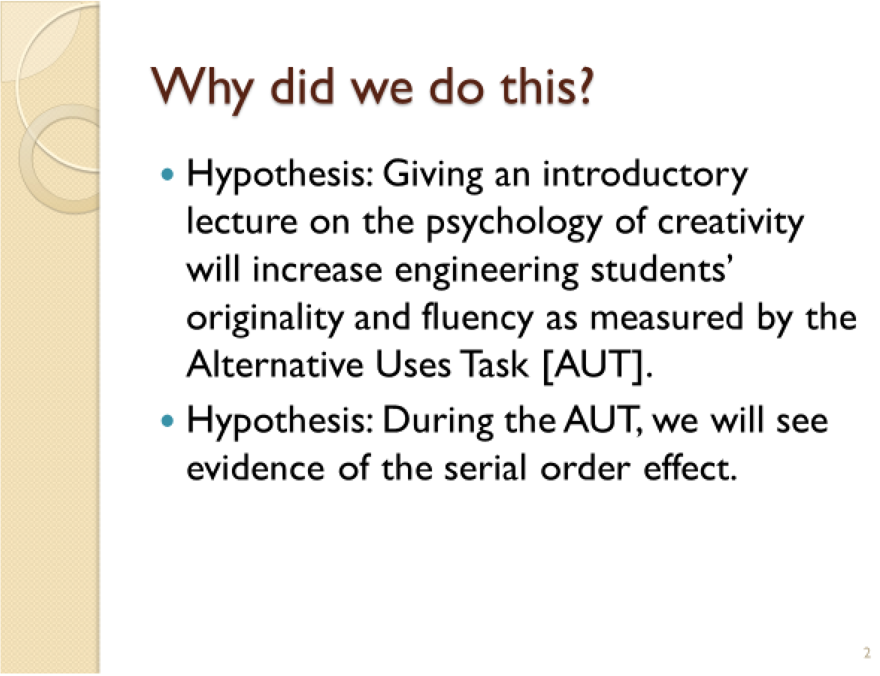


References

- G. Goldschmidt. "Linkographic evidence for concurrent divergent and convergent thinking in creative design". *Creativity Research Journal*, vol. 28, no. 2, 2016, pp. 115-122.
- J.P. Guilford. "The structure of intellect". *Psychological Bulletin*, vol. 53, no. 4, 1956, pp. 267-293.
- J.P. Guilford. *The Nature of Human Intelligence*. New York: McGraw-Hill, 1967.
- M.W. Matlin. *Cognition*. Hoboken, NJ: John Wiley and Sons, 2009, pp. 93-118.
- H. Poincaré. *The Foundations of Science*. G.B. Halsted, trans. New York: The Science press, 1913.
- M.A. Runco and G.J. Jaeger. "The standard definition of creativity". *Creativity Research Journal*, vol. 24, no. 1, 2012, pp. 92-96.
- S.M. Smith. "Fixation, incubation, and insight in memory and creative thinking". *The Creative Cognitive Approach*, S.M. Smith, T.B. Ward, and R.A. Finke, eds. Cambridge: MIT Press, 1995, pp. 135-156.
- G. Wallas. *The Art of Thought.* Life & Letters series, no. 24, London: Jonathan Cape, 1931.
- M.-T. van de Kamp, W. Admiraal, and G. Rijlaarsdam. "Becoming original: Effects of strategy instruction". *Instructional Science*, vol. 44, 2016, pp. 543-566.

Creativity AUT Results

J. Leonard



Why did we do this?

- Hypothesis: Giving an introductory lecture on the psychology of creativity will increase engineering students' originality and fluency as measured by the Alternative Uses Task [AUT].
- Hypothesis: During the AUT, we will see evidence of the serial order effect.

What did I do with your data?

- Typed all of your answers into a spreadsheet
- Assigned each of those answers a keyword from a list of ~200
- Counted the number of people who used each keyword
- Calculated commonality for each keyword
- $commonality = \frac{no.of\ people\ using\ keyword}{n}$
- e.g. a commonality of 0.250 means a quarter of you had the same idea

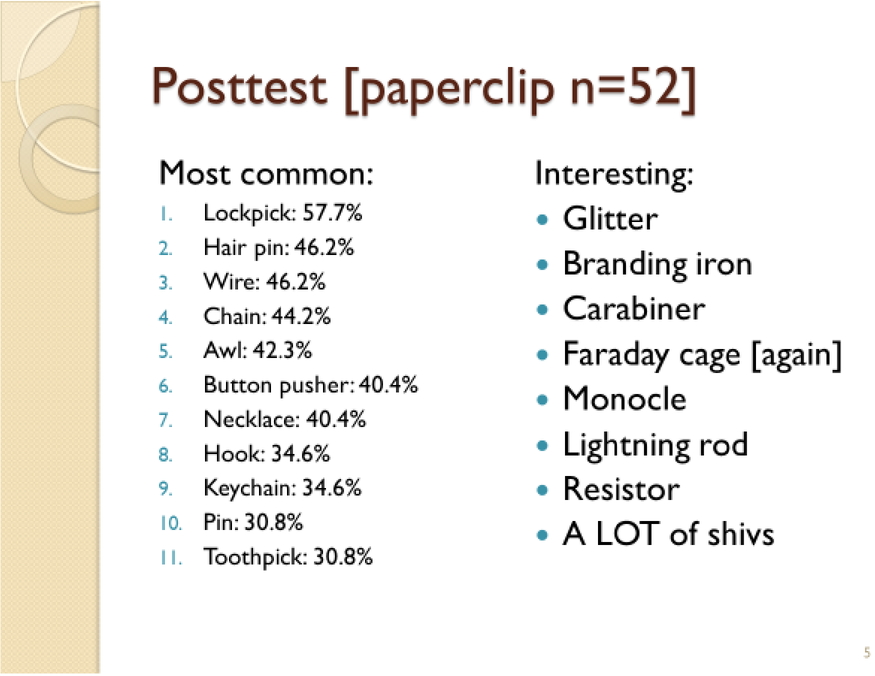
Pretest [tin can n=62]

Most common:

1. Planter: 58.1%
2. Pencil case: 53.2%
3. Telephone: 46.8%
4. Cup: 45.2%
5. Container: 40.3%
6. Structure: 37.1%
7. Art: 29.0%
8. Blade: 27.4%
9. Food container: 27.4%
10. Candle: 25.8%
11. Material: 25.8%

Interesting:

- Cheese press
- Anti-cheating blinder
- Hermit crab shell
- Steam engine
- Faraday cage
- Dietary Sn supplement [toxic]
- Matryoshka dolls



Posttest [paperclip n=52]

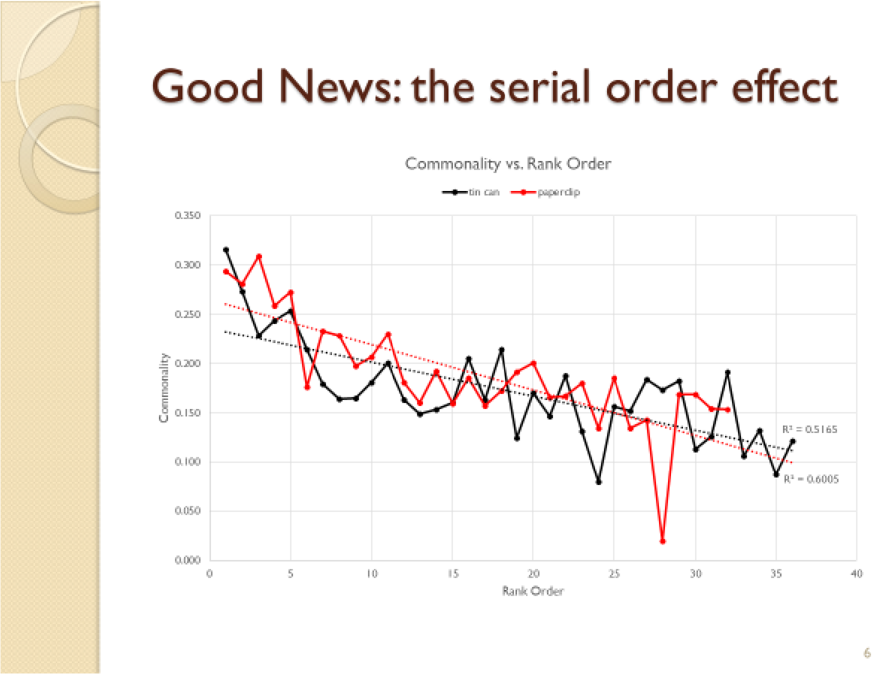
Most common:

1. Lockpick: 57.7%
2. Hair pin: 46.2%
3. Wire: 46.2%
4. Chain: 44.2%
5. Awl: 42.3%
6. Button pusher: 40.4%
7. Necklace: 40.4%
8. Hook: 34.6%
9. Keychain: 34.6%
10. Pin: 30.8%
11. Toothpick: 30.8%

Interesting:

- Glitter
- Branding iron
- Carabiner
- Faraday cage [again]
- Monocle
- Lightning rod
- Resistor
- A LOT of shivs

5



Good News: the serial order effect

6

Bad News: the efficacy of psychology lectures

- ANOVA between pretests and data from previous years: 99.0% chance identical [n=62]
- ANOVA between posttests and data from previous years: 73.7% chance identical [n=52]
- Posttests have higher commonalities than control
- Possible increase in fluency, but not statistically significant

Some statistics:

Tin Can	Pretest avg. comonality by student:	Previous years' avg. commonality:	Pretest fluency:	Previous years' fluency:
average	0.205	0.205	19.46	19.06
std dev	0.044	0.040	9.66	7.81
n	52	62	52	62

Paperclip	Posttest avg. comonality by student:	Previous years' avg. commonality:	Posttest fluency:	Previous years' fluency:
average	0.231	0.228	16.52	15.20
std dev	0.052	0.058	9.16	7.32
n	52	54	52	54

What did we learn?

- Do you think the paperclip and the tin can tasks were similar in difficulty?
- Did you find this subject/exercise useful?
- Do you have any questions?

References:

[1] K. Kazerounian and S. Foley. “Barriers to creativity in Engineering education: A study of instructors’ and students’ perceptions”. *Journal of Mechanical Design,* vol. 129, 2007, pp. 761-768.

[2] D.H. Cropley. “Creativity in engineering,” in *Multidisciplinary Contributions to the Science of Creative Thinking,* G.E. Corazza and S. Agnoli, Eds. London: Springer, 2016, pp. 155-173.

[3] C. Baille. “Enhancing creativity in engineering students”. *Engineering Science and Education Journal,* vol. 11, no. 5, 2002, pp.185-192.

[4] S. Törnkvist. “Creativity: Can it be taught? The case of engineering education”. *European Journal of Engineering Education,* vol. 23, no. 1, 1998, pp. 5-12.

[5] M.A. Runco and G.J. Jaeger. “The standard definition of creativity”. *Creativity Research Journal,* vol. 24, no. 1, 2012, pp. 92-96.

[6] G. Thompson and M. Lordan. “A review of creativity principles applied to engineering design”. *Proceedings of the Institution of Mechanical Engineers,* vol. 213, part E, 1999, pp. 17-31.

[7] J.P. Guilford. “The structure of intellect”. *Psychological Bulletin*, vol. 53, no. 4, 1956, pp. 267-293.

[8] T.F. Peters. “How creative engineers think”. *Civil Engineering,* vol. 68, no. 3, 1998, pp. 48-51.

[9] Z. Liu and D.J. Schönwetter. “Teaching creativity in engineering”. *International Journal of Engineering Education,* vol. 20, no. 5, 2004, pp. 801-808.

[10] C. Zhou. “Teaching engineering students creativity: A review of applied strategies”. *Journal on Efficiency and Responsibility in Education and Science,* vol. 5, no. 2, 2012, pp. 99-114.

[11] S.R. Daly, E.A. Mosyjowski, and C.M. Seifert. “Teaching creativity in engineering courses”. *Journal of Engineering Education,* vol. 103, no. 3, 2014, pp. 417-449.

[12] D.H. Cropley. *Creativity in Engineering: Novel Solutions to Complex Problems.* San Diego: Academic Press, 2015.

[13] M. Rhodes. “An analysis of creativity”. *Phi Delta Kappan,* vol. 42, no. 7, 1961, pp. 305-310.

[14] G. Scott, L.E. Leritz, and M.D. Mumford. “The effectiveness of creativity training: A quantitative review”. *Creativity Research Journal,* vol. 16, no. 4, pp. 361-388.

[15] J. Cagan. “The cognition of engineering design – An opportunity of impact”. *Cognitive Science,* vol. 31, 2007, pp. 193-195.

[16] J.P. Guilford. “Traits of creativity,” in *Creativity and its Cultivation,* H.H. Anderson, Ed. New York: Harper, 1959, pp. 142-161.

[17] M.A. Wallach and N. Kogan. *Modes of Thinking in Young Children: A Study of the Creativity–Intelligence Distinction.* New York: Holt, Rinehart, & Winston, 1965.

[18] J.P. Guilford. *The Nature of Human Intelligence.* New York: McGraw-Hill, 1967.

[19] S.A. Mednick. "Remote associates test". *Journal of Creative Behavior,* vol. 2, 1968, pp. 213–214.

[20] S.A. Mednick. "The associative basis of the creative process". *Psychological Review,* vol. 69, 1962, pp. 220-232.

[21] R.E. Beaty, P.J. Silvia, E.C. Nusbaum, E. Jauk, and M. Benedek. "The roles of associative and executive processes in creative cognition". *Memory & Cognition,* vol. 42, 2014, pp. 1186-1197.

[22] M.A. Runco and S. Acar. "Divergent thinking as an indicator of creative potential". *Creativity Research Journal,* vol. 24, no. 1, 2012, pp. 66-75.

[23] B. Kudrowitz and C. Dippo. "When does a paper clip become a sundial? Exploring the progression of originality in the alternative uses test". *Journal of Integrated Design and Process Science,* vol. 17, no. 4, 2013, pp. 3-18.

[24] H. Poincaré. *The Foundations of Science.* G.B. Halsted, trans. New York: The Science press, 1913.

[25] G. Wallas. *The Art of Thought.* Life & Letters series, no. 24, London: Jonathan Cape, 1931.

[26] S. Ellwood, G. Pallier, A. Snyder, and J. Gallate. "The incubation effect: Hatching a solution?". *Creativity Research Journal,* vol. 21, no. 1, 2009, pp. 6-14.

[27] S.M. Smith. "Fixation, incubation, and insight in memory and creative thinking". *The Creative Cognitive Approach,* S.M. Smith, T.B. Ward, and R.A. Finke, Eds. Cambridge: MIT Press, 1995, pp. 135-156.

[28] D.J. Treffinger, G.C. Young, E.C. Selby, C. Shepardson. *Assessing Creativity: A Guide for Educators.* Sarasota, FL: Center for Creative Learning, 2002.

[29] A.F. Osborn. *Applied Imagination: Principles and Procedures of Creative Problem Solving, 3rd Ed.* New York: Scribners, 1963.

[30] W.J.J. Gordon. *Synectics.* London: Macmillan, 1961.

[31] A.B. Van Gundy. *Managing Group Creativity: A Modular Approach to Problem Solving.* New York: American Management Associations, 1984.

[32] M.S. Allen. *The Allen Morphologizer.* Englewood Cliffs, NJ: Prentice Hall, 1962.

[33] J. Sternberg. "Creativity as a Habit," in *Creativity: A Handbook for Teachers,* A.-G. Tan, Ed. Singapore: World Scientific, 2007.

[34] J.J. Shah, S.V. Kulkarni, and N. Vargas-Hernandez. "Evaluation of idea generation methods for conceptual design: Effectiveness metrics and design of experiments". *Journal of Mechanical Design,* vol. 122, no. 4, 2000, pp. 377-384.

[35] J.J. Shah, R.E. Millsap, J. Woodward, and S.M. Smith. “Applied tests of design skills – Part I: divergent thinking”. *Journal of Mechanical Design,* vol. 134, no. 2, 2012, pp. 1-10.

[36] J.J. Shah, J. Woodward, and S.M. Smith. “Applied tests of design skills – Part II: visual thinking”. *Journal of Mechanical Design,* vol. 135, no. 7, 2013, pp. 1-11.

[37] M. Khorshidi, J.J. Shah, and J. Woodward. “Applied tests of design skills – Part III: abstract reasoning”. *Journal of Mechanical Design,* vol. 136, no. 10, 2014, pp. 1-11.

[38] G. Goldschmidt. “Linkography: Assessing design productivity”. *Proc. Tenth European Cybernetics and Systems Research,* R. Trappl, ed., Vienna, Austria, 1990, pp. 291-298.

[39] G. Goldschmidt. “Criteria for design evaluation: A process oriented paradigm”. in *Evaluating and Predicting Design Performance,* Y.E. Kalay, ed., NY: John Wiley & Sons, 1992, pp. 67-79.

[40] M. Pourmohamadi and J.S. Gero. “LINKOgrapher: An analysis tool to study design protocols based on FBS coding scheme”. *Int. Conf. Engineering Design: ICED 11,* Copenhagen, Denmark, 2011, pp. 1-10.

[41] R. van der Lugt. “Developing a graphic tool for creative problem-solving in design groups”. *Design Studies,* vol. 21, 2000, pp. 505-522.

[42] K.J. Gilhooly, E. Fioratou, S.H. Anthony, and V. Wynn. "Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects". *British Journal of Psychology,* vol. 98, 2007, pp. 611–625.

[43] O. Vartanian, C. Martindale, and J. Kwiatowski. "Creative potential, attention, and speed of information processing". *Personality and Individual Differences,* vol. 43, 2009, pp. 1470–1480.

[44] E.C. Nusbaum and P.J. Silvia. "Are intelligence and creativity really so different? Fluid intelligence, executive processes, and strategy use in divergent thinking". *Intelligence,* vol. 39, 2011, pp. 36-45.

[45] R.E. Beaty and P.J. Silvia. "Why do ideas get more creative across time? An executive interpretation of the serial order effect in divergent thinking tasks". *Psychology of Aesthetics, Creativity, and the Arts,* vol. 2012, pp. 309–319.

[46] P.R. Christensen, J.P. Guilford, and R.C. Wilson. "Relations of creative responses to working time and instructions". *Journal of Experimental Psychology,* vol. 53, 1957, pp. 82–88.

[47] M. Benedek and A.C. Neubauer. "Revisiting Mednick's model on creativity-related differences in associative hierarchies: Evidence for a common path to uncommon thought". *Journal of Creative Behavior,* vol. 47, 2013, pp. 273–289.

[48] R.E. Beaty, P.J. Silvia, E.C. Nusbaum, E. Jauk, and M. Benedek. "The roles of associative and executive processes in creative cognition". *Memory & Cognition,* vol. 42, 2014, pp. 1186-1197.

[49] B.C. Storm and T.N. Patel. “Forgetting as a consequence and enabler of creative thinking”. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* vol. 40, no. 6, 2014, pp.1594-1609.

[50] M.-T. van de Kamp, W. Admiraal, J. van Drie, and G. Rijlaarsdam. “Enhancing divergent thinking in visual arts education: Effects of explicit instruction of met-cognition”. *British Journal of Educational Psychology,* vol. 85, 2015, pp. 46-58.

[51] M.-T. van de Kamp, W. Admiraal, and G. Rijlaarsdam. “Becoming original: Effects of strategy instruction.” *Instructional Science,* vol. 44, 2016, pp. 543-566.

[52] E. Segal. “Incubation in insight problem solving”. *Creativity Research Journal,* vol. 16, no. 1, 2004, pp. 141-148.

[53] A. Snyder, J. Mitchell, S. Ellwood, A. Yates, and G. Pallier “Nonconscious idea generation”. *Psychological Reports,* vol. 94, 2004, pp. 1325-1330.

[54] K.J. Gilhooly, G.J. Georgiou, J. Garrison, J.D. Reston, and M. Sirota. “Don’t wait to incubate: Immediate versus delayed incubation in divergent thinking”. *Memory & Cognition,* vol. 40, 2012, pp. 966-975.

[55] S. Ghosh. “An exercise in teaching creativity in undergraduate engineering students through challenging examinations and open-ended design problems”. *IEEE Transactions on Education,* vol. 36, no. 1, 1993, pp. 113-119.

[56] J.C. Conwell, G.D. Catalano, and J.E. Beard. “A case study in creative problem solving in engineering design”. *Journal of Engineering Education,* vol. 82, no. 4, 1993, pp. 227-231.

[57] P.A. Johnson. “Problem-based, cooperative learning in the engineering classroom”. *Journal of Professional Issues in Engineering Education and Practice,* vol. 125, no. 1, 1999, pp.8-11.

[58] D.H. Cropley and A.J. Cropley. “Fostering creativity in engineering undergraduates”. *High Ability Studies,* vol. 11, no. 2, 2000, pp. 207-219.

[59] K.K. Urban and H.G. Jellen. *Test for Creative Thinking – Drawing Production.* Lisse, NL: Swets and Zietlinger, 1996.

[60] C. Charyton and G.E. Snelbecker. “General, artistic and scientific creativity attributes of engineering and music students”. *Creativity Research Journal,* vol. 19, nos. 2-3, 2007, pp. 213-225.

[61] H.G. Gough. “A creative personality scale for the adjective check list”. *Journal of Personality and Social Psychology,* vol. 37, 1979, pp. 1398-1405.

[62] H.G. Gough. “Assessment of creative potential in psychology and the development of a creative temperament scale for the CPI,” in *Advances in Psychology Assessment,* J.C. Rosen and P. McReynolds, Eds. New York: Plenum, 1992, pp. 225-257.

[63] G.E. Snelbecker, T. McConologue, and J.M. Feldman. “Cognitive risk tolerance survey”. Unpublished manuscript, 2001.

[64] E.E. Gordon. *Studies in harmonic and rhythm improvisation readiness record.* Chicago: GIA Publications, 2000.

[65] C.H. Lawshe and D.H. Harris. *Manual of Instructions to Accompany Purdue Creativity Test Forms G and H.* Princeton, NJ: Educational Testing Services, 1960.

[66] B.M. Kudrowitz and D. Wallace. "Assessing the quality of ideas from prolific early-stage product ideation". *Journal of Engineering Design,* vol. 24, no. 2, 2013, pp. 120-139.

[67] G. Goldschmidt. "The designer as a team of one." *Design Studies,* vol. 16, no. 2, 1995, pp. 189-209.

[68] R. Vidal, E. Mulet, and E. Gómez-Senent. "Effectiveness of the means of expression in creative problem-solving in design groups". *Journal of Engineering Design,* vol. 15, no. 3, 2004, pp. 285-298.

[69] J.W.T. Kan, Z. Bilda, and J.S. Gero. "Comparing entropy measures of idea links in design protocols: Linkography entropy measurement and analysis of differently conditioned design sessions". *Artificial Intelligence for Design, Analysis, and Manufacturing,* vol. 21, 2007, pp. 367-377.

[70] G. Goldschmidt. "Linkographic evidence for concurrent divergent and convergent thinking in creative design". *Creativity Research Journal,* vol. 28, no. 2, 2016, pp. 115-122.

[71] A. Baddeley. “The episodic buffer: A new development of working memory?”. *Trends in Cognitive Science,* vol. 4, no. 11, 2000, pp. 417-423.

[72] M. Dinar, J.J. Shah, J. Cagan, L. Leifer, J. Linsey, S.M. Smith, and N. Vargas-Hernandez. “Empirical studies of designer thinking: Past, present, and future”. *Journal of Mechanical Design,* vol. 137, 2015, pp. 1-13.