What is the Nature of Creativity: Understanding the Role of Executive and Associative Processes in Creative Thinking

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By

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What is the Nature of Creativity: Understanding the Role of Executive and Associative Processes in Creative Thinking

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Chapter 1: Introduction

As Julius Caesar and his army prepared for the Battle of Pharsalus in 48 BC, the lynchpin battle in his war against opponent General Pompey Magnus, he faced nearly certain defeat. Caesar was outnumbered by his opponent four to one. With the high ground advantage over the battlefield and support from many allies, Pompey reasoned he'd be the victor. Caesar was experiencing a "wicked problem" as it's come to be known in military settings. Nearly everyone, given those facts to reason with, would have predicted a loss for Caesar. Despite this, Caesar outmaneuvered him and won the battle with a much smaller, battle-fatigued army. How did this happen? Both Pompey and Caesar were highly skilled military strategists, and there is no doubt that both men possessed high intelligence. What else could account for this incredible turn of events?

Caesar's tactics were uncommon, novel, and unanticipated by Pompey, and he employed several innovative strategic positions that undermined an overconfident general. In the field or when investigating an open-ended or ambiguous problem, creative thinking is tapped to facilitate rapid decisions in challenging circumstances where there are many unknowns. For Caesar, operation success required more than basic competence as found in higher order cognitive abilities such as intelligence, retrieval ability, attention, and fluency. It also required creative thinking.

Chapter 2: Background

2.1 A nation built on ideas

By 1930 every major corporation in America was actively funding a secretive personnel unit tasked with generating original, unique, creative ideas that benefited the company's bottom-line, or provided an edge in the market (Osborn, 1953). As private interest in creativity increased, so did the interest of the U.S. Military. The onset of World War II lead to an increased interest in cognitive selection and training. Research and development on intelligence during World War I lead to major advances in the study and methodology of intelligence research. The military's study of creativity during World War II would have many of the same effects on the field of creativity (Guilford, 1950; 1958).

Military research became focused on new selectors of military personnel. Aided by newly developed statistical knowledge of classical test theory and more advanced statistical techniques like factor analysis, researchers were able to begin exploring tests other than intelligence indicators to predict combat readiness and success. These studies were among the first to employ task batteries with rigorous analytic techniques and large sample sizes to replicate and clearly define creativity (Wilson et al., 1954; Christensen, Guilford, & Wilson, 1957).

Though creativity has been studied for quite some time, the underlying mechanisms responsible for creative responses and their psychometric properties remain poorly understood. The criticism that creativity has lagged in both theoretical and applied advancements is not only shared by the majority of academic researchers (for a review see Runco,1990), these issues are also documented independently in extensive investigations done by the United States military

(Kettner, Guilford, & Christensen, 1959) and in several reviews of creativity and its corporate applications (Osborn, 1953).

Creativity and innovation

The origins of the study of creative problem solving can be traced to early studies of "imagination" as it was referred to in early studies, and was inspired by an interest in problem solving and idea generation, with a focus on "original" thinking. From the start, creativity has been linked to intelligence. Prominent scholars (Osborn, 1953; Parnes, 1967), as well as military psychologists such as Joy Guilford, believed that when intelligent individuals were faced with an ambiguous or novel problem, they would generate a larger number of potential solutions than those with lower intelligence. Literature related to idea generation and creative thinking dates back to the 1800s, predating the popular fluency or creativity paradigms that usually come to mind today. Notably, a task designed in 1895 by Bourdon, a French psychologist, claimed to assess association by calculating “the number of ideas arising in the mind within one minute on a given suggestion,” a clear predecessor to today’s ideational fluency (Nicolas, 2015).

Prompted by Guilford’s call to action in his 1950 address to the APA, a series of large-scale factor analyses sponsored by the Office of Naval Research were among the first attempts to define the link between intelligence and creativity using large task batteries, rigorous analytic techniques, and large sample sizes (Wilson et al., 1954; Christensen, Guilford, & Wilson, 1957). Although these early studies provided evidence to support the role of creativity in reasoning, it also revealed several factors related to the quantity of ideas a subject could produce. Arguably the most interesting discovery was an unanticipated, distinct factor related to the quality of ideas. This was a replication of previous work by H.L. Hargreaves who found a distinction between the number of ideas produced and the uniqueness of those ideas, believing the latter to be a combination of g, fluency, and memory (1927). This factor was explained as the uniqueness of ideas, appropriately termed “originality”. More recent research has also replicated the unique link between originality and intelligence at the latent level (Benedeck et al., 2012).

2.2 What’s original about creativity?

Two Types of Creative-thinking

To effectively understand the cognitive mechanisms of creativity, it’s useful to review the mental processes or types of thinking believed to be involved in creative production. Creative thinking involves at least two facets. First is the ability to generate the maximum number of solutions or possibilities that could occur in a given problem space. This process is referred to as divergent thinking (DT). After generating all of these hypotheses, the subject must then evaluate the usefulness of those ideas before deciding on a single course of action. The ability to identify and select the most optimal decision from the divergent process is referred to as convergent thinking (CT).

To date, tests of divergent thinking have received the most attention. Common forms of these measures are the Alternative Uses task, where a subject generates as many different uses for a common object as possible (Guilford et al., 1978). Variations of this task include Elaboration of Figures where subjects use simple shapes to develop a cohesive picture, and the Consequences Test where the subject finds solutions or implications of a problem. For instance, in the Torrance Test of Creativity, subjects imagine what problems might ensue if they had the ability to fly (Goff & Torrance, 2002). Tests of divergent thinking are intended to require novel thinking and it is here that we find abilities that are most important to “creative thinking”.

Divergent production doesn’t mean unconventional by definition, but divergent thinking typically leads to original results (Guilford, 1967).

Convergent thinking tasks such as the Remote Associates Test (Mednick, 1962) have also seen less extensive use. Unlike divergent production tasks that may give subjects credit for a broad range of responses, each item on a test of convergent thinking such as the RAT has a single correct answer that is scored as a 1 or 0. In this task, subjects are shown three common words with no obvious connection between them. The goal is to find a target word that ties all three together (e.g. falling - actor - dust where star is the word that relates the other three). Early work on the RAT has demonstrated sizeable correlations with traditional measures of IQ and reasoning (Taft & Rossiter, 1966, Mednick & Andrews, 1967).

Although researchers of creativity have long assumed that both of these processes are related to reasoning, there is surprisingly little evidence supporting this idea. Creativity researchers tend to rely on one paradigm over the other to assess creativity. Today’s pressing questions should be directed toward understanding the relationship between these facets of creativity as well as the component processes that govern them.

Table 1. A comparison of divergent thinking and convergent thinking

DIVERGENT THINKING	CONVERGENT THINKING
Popularized by Guilford’s *Unusual Uses* task paradigm	Popularized by Mednick’s *Remote Associates Test*
Psychometric investigation	Experimental investigation
Emphasis on creation on novel ideas	Emphasis on associative processes
Creativity construct situated in Guilford’s Structure of Intellect theory	Creativity operationalized using Mednick’s theory of associative processes

Although many researchers are aware that both of these processes are important, there has been extremely little evidence investigating how strongly they are related, or whether both processes are equally important for selection purposes. In fact, several lines of research indicate that divergent thinking and convergent thinking are separable based on various experimental manipulations and studies of atypical populations. For instance, subjects with ADHD diagnoses outperform normal subjects on divergent thinking tasks, but show no difference on measures of convergent thinking (White & Shah, 2006). Researchers have also found that sleep deprivation impairs divergent thinking performance, but not convergent processes (Horne, 1988).

Although there is a new body of work that has found large latent correlations between creativity, long-term retrieval (Silvia et al., 2013; Beaty et al., 2014) and fluid intelligence, many of these studies suffer from measurement issues and methodological flaws. And while tests assessing creativity have demonstrated reliability, evidence of predictive validity is mixed, most likely due to variations in administration and scoring (Kim 2005; 2008). Most studies only use originality and fluency to characterize creativity, and studies that do report multiple factors often find conflicting results on the relationship between originality and fluency (Torrance, 1965; Dixon, 1979; Hocevar, 1979).

2.3 Creativity and Intelligence: One and the Same?

Creativity as a Capacity

Creativity has an extensive history investigating its link to intelligence. Joy Guilford believed that when intelligent individuals were faced with an ambiguous or novel problem, they would generate a larger number of potential solutions than those with lower intelligence. Guilford based his ideas on L.L. Thurstone, although Thurstone doubted that creativity and intelligence were highly related (Thurstone, 1950). However, Guilford theorized that creativity was an aspect of if not isomorphic to the construct of intelligence. In his address to the APA in 1950, Guilford outlined his ideas about the cognitive abilities of creative individuals in a new theory of human abilities referred to as the "Structure of Intellect" (Guilford, 1956; Guilford, 1967), a model inspired by Thurstone's *Primary Mental Abilities* (1938). Guilford extended Thurstone's ideas on fluency and applied them to his research on creativity, exploring tasks of Divergent Thinking (DT).

As Guilford studied the psychometrics of creativity, Sarnoff Mednick approached the problem from an experimental perspective (Mednick, 1962; Mednick & Mednick, 1967). In 1964, he published a seminal article titled "The associative basis of the creative process." In this article he lays out a specific theory of creativity as well as its associative mechanisms. He further devised his own instrument to measure this hypothesis which he called the Remote Associates Test (RAT), one of the most valid indicators used to assess convergent thinking today.

Creativity and Fluency

In "Primary Mental Abilities," L. L. Thurstone proposed that intelligent individuals would also be highly fluent (1934; 1938). Fluency tasks involve rapid generation of words, phrases, or ideas in response to a specific condition or context. In ideational tasks, a subset or specific type of fluency task, the subject lists as many animal names, occupations, or words beginning with the letter "C" as possible. Thurstone showed that performance on measures of verbal fluency were facilitated by flexibility, the ability to shift categories and employ different strategies to rapidly produce distinct ideas, as well as the ability to employ different strategies that facilitate a change in context (Thurstone, 1934; 1938; Thurstone & Thurstone, 1941).

As creativity is usually assessed by fluency, it comes as no surprise that creativity is highly related to verbal fluency. For instance, there is a distinct correlation between the number of unusual uses for a brick or knife the subject can generate and the number of animal names or job occupations they can produce on tests of verbal fluency (Guilford, 1950). Both tasks require subjects to quickly generate specific responses to a given prompt. However, unlike tasks of verbal fluency, tests of divergent thinking are intended to require novel thinking, which places less emphasis on the subject's previous knowledge structures (e.g. crystallized intelligence) and more emphasis on originality.

More recent studies in this area suggest that measures of fluid intelligence, verbal fluency, and tests of creativity could be reduced to a single factor solution (Silvia et al., 2008; Nusbaum et al., 2011). In line with these findings, many researchers assert that fluency and creativity should share many of the same cognitive mechanisms (Christensen, Guilford, & Wilson, 1957; Simonton, 2002). Interestingly, differences between individuals with high and low working memory capacity are visible within a minute of retrieval on verbal fluency tasks (Rosen & Engle, 1997) and are not merely influenced by the number of animals names that high working memory span subjects know (Unsworth, Spillers, & Brewer, 2011). This relationship between working memory capacity and verbal fluency, along with the attentional demands of performing tasks of verbal fluency, (Rosen & Engle, 1999; Unsworth et al., 2011) suggest that memory and attention in particular might be integral to creative performance.

This hypothesis is further supported by the finding that individual differences in working memory capacity predict performance on tasks of verbal fluency in extreme groups designs and at the latent level, (Rosen & Engle, 1999; Unsworth et al., 2011; Shipstead et al., 2015 under review) which suggests that memory should be integral to creative performance. Researchers investigating the processes that facilitate performance on measures of divergent thinking have found evidence for the role of broad retrieval ability (Silvia et al., 2013) fluid intelligence (Silvia, 2008; Nusbaum& Silvia, 2011a,; Benedek et al., 2012) and the ability to generate ideational strategies (Gilhooly, Fioratou, Anthony, & Wynn, 2007).

Creativity and Memory

Previous research has also shown that working memory capacity (WMC) predicts individual differences in fluency (Rosen & Engle, 1997; Shipstead et al., 2014). Given the ideation involved in both divergent thinking and fluency tasks, several researchers have begun to investigate the relationship between creative thinking and working memory capacity.

To date, one of the least explored areas in creativity is the role of memory. Guilford (1956) originally hypothesized that memory abilities should not contribute substantially to creative performance. However, in *The Nature of Human Intelligence*, Guilford (1967) argues that "memory storage" underlies all problem solving and creative performance.

A student of the prominent psychometrician and psychologist Charles Spearman, H.L. Hargreaves conducted the first large-scale study of creativity. He administered five groups of tests including indicators of “imagination,” intelligence, memory, speed, and perseveration. He found that creativity operated in conjunction with several other cognitive constructs. Of note, he detected a “memory” component. He argued that creativity was far from unitary as his results identified this memory factor and an additional factor he called speed that was assessed by writing speed and the quickness subjects copied a writing sample (1927). This finding aligned with theories by several of his contemporaries who contended there was a common factor related to novel idea generation and speededness which they termed “cleverness” (Webb, 1915; Garnett & Thompson, 1919).

Although most research on creativity has been focused on divergent thinking, several researchers have focused on convergent thinking and use task paradigms such as the RAT to assess creativity. They find that it is related to effortful retrieval, maintenance of attention, and has a clear relationship with fluid intelligence (Chuderski, 2014; De Creu, et al, 2013). Recent suggests that both executive and associative processes are used in creative cognition (Beaty et al., 2014). Using latent semantic analysis, their work links convergent processes with verbal fluency and fluid intelligence. Since working memory capacity is one of the strongest predictors of fluid intelligence, convergent thinking should be related to working memory capacity as well (Engle et al., 1999; Kane et al.,. 2004: Oberauer, 2007, Hicks et al., 2015).

The underlying mechanisms responsible for creative responses and their psychometric properties remain poorly understood. Further, even less is known about the relationship between the quality and quantity of the ideas subjects generate, despite a body of literature that specifies its importance. Common reasons given for this limitation is that researchers disagree on the most appropriate way to score creative responses. Responding to this criticism, we've developed a method of evaluating the quality of creative responses in divergent thinking tasks that will be explained in the sections that follow. Our assessment of divergent thinking considers the quality and originality of responses with no emphasis on the ability to generate a large quantity of ideas. In doing so, we hope to reveal more robust relationships among creative and executive processes.

Chapter 3: Present Study

3.1 Aims

The first aim of the present study was to investigate the relationship between creativity and constructs reflecting executive control as well as associative abilities. This will lead to a more comprehensive understanding of the underlying factor structure of creativity.

Our second goal is to determine the relationship between key components of creative production: divergent and convergent thinking and intelligence. Some researchers have argued that this relationship can be explained by individual differences in associative processes such as fluency (Lee et al., 2013), while others have argued that the relationship between creativity and intelligence is dependent on executive processes such as working memory capacity (Silvia et al, 2009).

Chapter 4: Method

4.1 Subjects

Data were collected from students at the Georgia Institute of Technology, community members in Atlanta, Georgia, and participants at Indiana University Purdue-Columbus (IUPC) in Columbus, Indiana. Subjects were between 18 and 30 years of age. University subjects received partial credit for a course or were paid for participation. Community subjects received monetary compensation. Participants were run in groups of 1-5. All tasks were administered on a computer. In addition, some tasks required responses to be written down on a sheet of paper provided by the experimenter (Torrance test of creativity and verbal fluency). The current study includes data from 450 subjects.[1]

4.2 Procedure

Conventional Scoring Procedures

Common approaches to unlocking creative potential include the assessment of social and personality traits, analyzing past behaviors of subjects thought to be “creative,” investigating the context where creativity occurs, and various combinations of these methods. The most popular approach by far is the application of specific scoring procedures to evaluate responses on novel ideation tasks.

Within the psychometric literature, scoring procedures for creativity tasks fall broadly into two categories. Objective scoring procedures were first used by Wallach and Kogan. In this procedure, a subject is given credit for responses that are not repeated by anyone else in the

[1] Please see Draheim, Hicks, & Engle (2015) for a more in depth description of the study. In addition, a sample of 72 subjects were reserved for the purpose of cross-validating the scoring procedure with new raters.

sample (1965). Subjects are given a binary score (0 if the response is repeated, 1 if it is unique to the sample). This method is dependent on the ability level of the subject as well as the sample size. As the ability level of the subjects and the sample size increase, the likelihood of finding a response that is entirely unique to only one subject decreases. This method penalizes larger samples because the chance of any single response being unique goes down as the sample size increases.

Objective scoring is further limited because it doesn't clearly address the quality of responses. If a response is unique to the sample, but is inapplicable or inappropriate, is it still deemed "creative"? The binary scoring methods often used in objective scoring don't have concrete rules for dealing with these responses. Subjective scoring captures quality of responses by using multiple raters to judge each creative item according to a set of preconceived criteria. Although this method is substantially more time consuming, it allows researchers to investigate the quantity and quality of creative responses.

Subjective scoring reduces the confound between fluency and originality or "uniqueness" as each response is rated separately and valued on its own merit apart from other responses in the sample. Whereas objective scoring methods restrict the definition of creativity to what is strictly novel, regardless of its other qualities, a subjective scoring approach allows repeated responses to be rated as creative. Scoring procedures developed recently address this issue, such as the snapshot scoring method developed by Silvia and colleagues (2009). Using this method, raters assign a single, "holistic," value from 1-5 to a response set. Raters are asked to evaluate the total set of responses on *uncommonness*, *remoteness*, and *cleverness*. It is important to note that a creative response set can fall into only one of these categories and still be classified as "creative." The benefits of this method are two-fold: 1) the snapshot method can be scored much faster than traditional procedures, and most importantly, 2) there is little to no relationship between originality and fluency using this method. This indicates that the procedure is not simply tapping the subject's fluency ability. The scoring procedure also emphasizes the importance of considering the *cleverness* construct in particular. The rater instructions emphasize the importance of the cleverness facet in particular for making creativity judgments and note that the most "creative" response sets will be clever based on the specific qualities thought to be most important to creativity: *humor, irony, smart, insightful* (Hargreaves, 1927; Christensen et al., 1957; Silvia et al., 2008; Benedek et al., 2013).

4.3 Task Selection

Creativity

Divergent thinking - Torrance Test of Creativity (Goff & Torrance, 2002)

Since our goal was to determine if a single factor would converge across spatial and verbal domains of divergent thinking, we selected the most popular test used to assess creativity as well as the most predictive according to a recent meta-analysis (Kim et al., 2005) – the Abbreviated Torrance Test for Adults (ATTA) (Goff & Torrance, 2002). This test is a shortened version of the Torrance Test of Creative Thinking (TTCT) that takes 15 minutes to administer and consists of one verbal and two figural divergent thinking tasks. Descriptions and images of each task are included below. These tasks are nearly identical to earlier paradigms used to assess divergent thinking (Guilford, 1957, Guilford, Frick, Christensen, & Merrifield, 1957).

The verbal “Consequences” task asks the subject to generate as many responses as possible to the question: “imagine what problems would arise if you could walk on air or fly” (Figure 1).

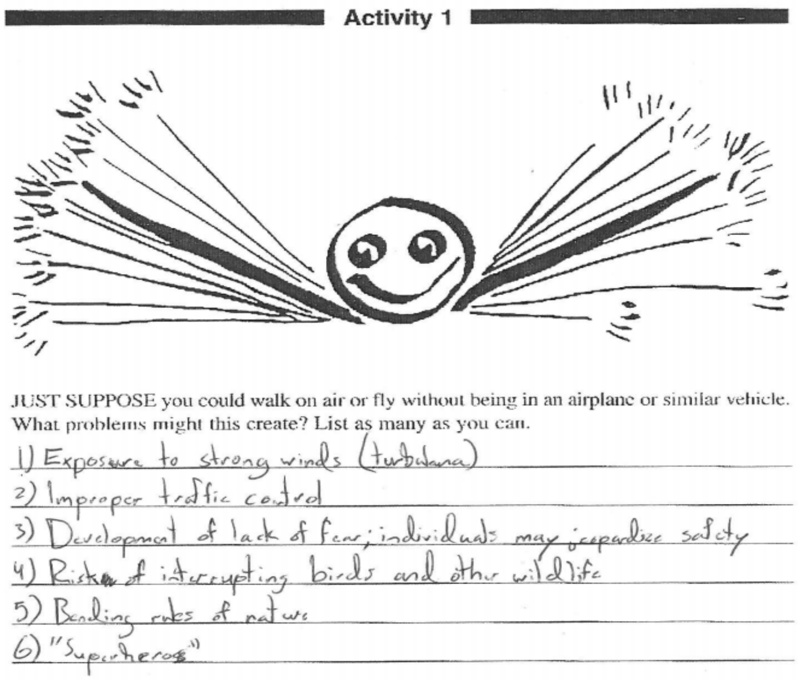

Figure 1. Activity 1 “Consequences” from the Abbreviated Torrance Test for Adults

The figural tasks are “Picture Completion” and “Picture Construction,” and require the subject to use abstract shapes to create an “unusual” and “interesting” picture complete with a title (based on Guilford’s Plot Title Test of Originality). In the “Picture Completion” task subjects receive the written instruction to: “Use the incomplete figures below to make some pictures. Try to make your pictures unusual. Your pictures should communicate as interesting and as complete as story as possible.” (Figure 2). For “Picture Construction,” subjects are told to:

"See how many objects or pictures you can make from the triangles below, just as you did with the incomplete figures. Remember to create titles for pictures." (Figure 3).

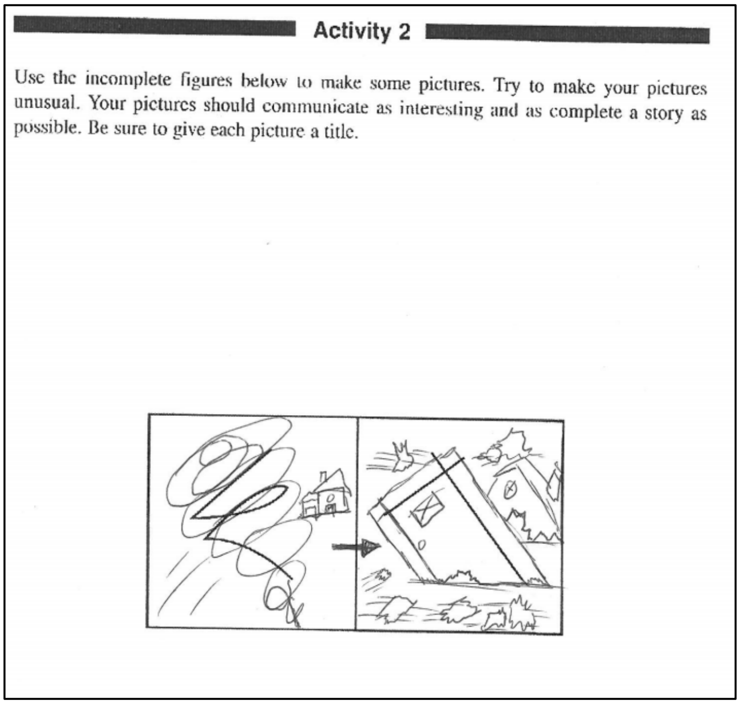

Figure 2. Activity 2 "Picture Completion" from the Abbreviated Torrance Test for Adults.

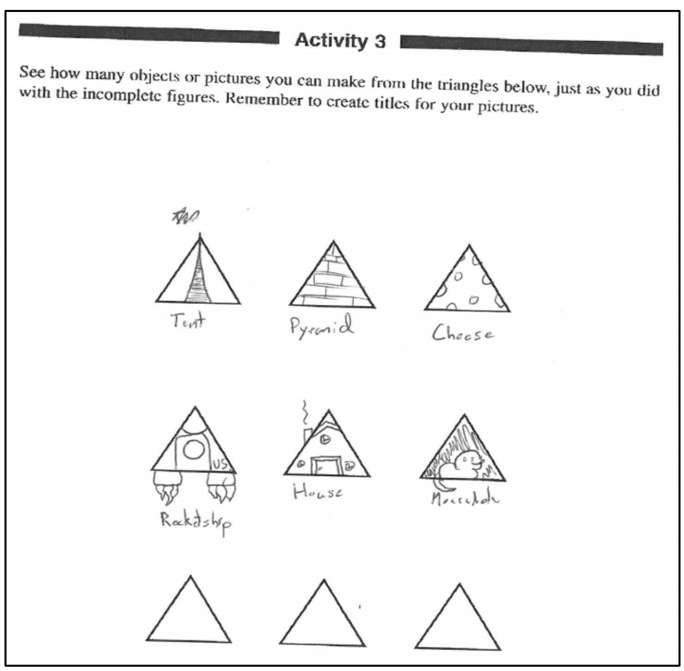

Figure 3. Activity3 "Picture Construction" from the Abbreviated Torrance Test for Adults.

A Novel Scoring Procedure

Creative thinking has demonstrated its importance to society, business, and many military settings (Royal Naval; American Navy). What is undeniable about the successful uses of creative thinking in all these sectors is the ability to generate and implement novel, original, and innovative ideas. The thoughtful reader may wonder why the field isn't focused on original responses. However, measuring originality apart from fluency has proven more challenging than it may appear.

Therefore, we developed a scoring procedure that placed a high emphasis on scoring original responses. Each rater was told to evaluate only those responses that evoked a subjective impression of creativity. This way each rater only considers creative responses when making their judgments (as opposed to considering an entire set of responses where some are creative and some are not). Raters then assigned scores of 1-3 on four specific attributes (humor, insight, irony, knowledge) that best classifies the reason the response was judged to be creative.

This modified approach can assess the verbal and figural components of the Torrance using the same rules and attributes. This procedure allows raters to quickly identify and describe creative figural responses, making the overall creativity score more robust by streamlining the scoring process across all three activities in the Torrance task. This is important, as the figural tasks included in the Torrance test are routinely excluded from studies because they do not conform to traditional scoring rules and present an added level of complexity for raters.

Each subject was scored by three independent raters. When a rater judged a given response to be creative they were asked to describe what made the response creative by indicating one or more of the following facets on a scale of 1-3.

1. ***Humor*** **–** if the response is light-hearted and funny.
2. ***Ironic*****–** response is opposite to what is expected, usually dry humor.
3. ***Smart*** **–** response incorporates crystallized knowledge.
4. ***Insightful*** **–** if the response is viewed from a different perspective than the norm.

Each quality of a given creative response was rated on a scale from 1-3, where a rating of 1 was given if the response barely met the criteria and a rating of 3 was given if the rater thought the response could not have been made any better.

In the Consequences task raters indicated a unique word from each verbal response thought to be creative. This word was written in order to identify whether each rater scored the same response. For the Figure completion task raters indicated whether a creative response was made using only the left-hand image, only the right-hand image, or a combination of both images.

On the Picture Construction task, subjects were asked to create one or more images using nine triangles. Subjects had the option to title their responses. All four qualities were rated on a scale from 1-3 and the title was given a 1 or a 0 depending on whether it added significantly to the response's overall cleverness or originality.

Visual comparison of each rater's scores was examined side by side in order to determine inter-rater consistency. In the case of a discrepancy between 1 or more raters the subject's folder was put aside so that raters could convene to discuss the items with obvious disagreements. Consensus was reach by majority (2 out of 3 raters agreed). In these cases, one or more raters adjusted their scored based on a discussion of the criteria.

Convergent thinking – Remote Associates Test (RAT)

The RAT (Mednick, 1962; Mednick & Mednick, 1967) is a measure of convergent thinking that requires participants to find a solution associated with a presentation of three word cues (Figure 4). This test is based on Mednick's *associative theory of creativity* explained as "the forming of associative elements into new combinations which either meet specific requirements or are in some way useful" (see Figure 4).In his theory, Mednick maintained that creative individuals have flatter associative hierarchies. He proposed that they were better at making remote or distant connections. As an example, a creative thinker would retrieve more remote associations to a prompt of "table" than a less creative thinker would. The creative individual is more likely to retrieve a more distant association (e.g. "leg") while a less creative individual would have a steep associative hierarchy where the cue triggers responses with higher associative strength (e.g. “chair” or “cloth”).

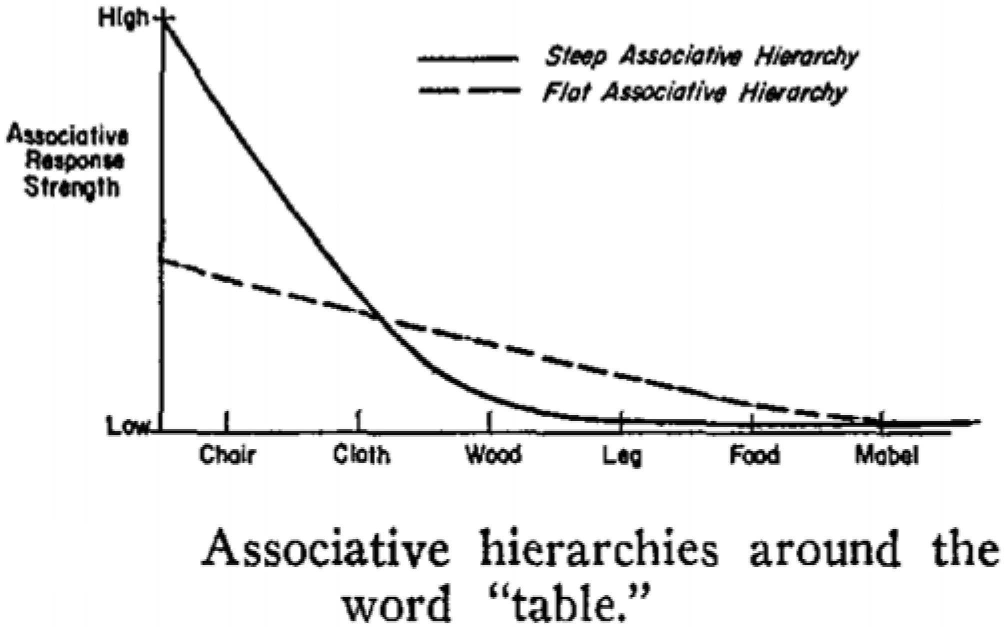

Figure 4. Mednick’s Associative hierarchies (Mednick, 1962).

The inclusion of the Remote Associates Test was taken after much consideration. The RAT has demonstrated its psychometric utility above other measures of CT. Many of the paradigms in use today that reflect convergent ability (i.e., 9 dots problem) have poor reliability (Chuderski, 2014). Recent studies that have assessed convergent thinking using the RAT have found it to be the only task that loaded significantly on the “convergent thinking” factor above r=.10 (Lee et al., 2013).

Verbal fluency

The verbal fluency task paradigm is influenced by Thurstone's Word Fluency Test, a component of his Primary Mental Abilities Test (Thurstone, 1938; Thurstone & Thurstone & Thurstone, 1949). In this experiment, three verbal fluency tasks were used. All three followed the same general procedure. Two of the tasks were semantic fluency tasks in which subjects were asked to list as many names in a given category as they could – *jobs* or *animal names*. We also administered a letter fluency task, often referred to as phonemic fluency. On this task, a subject lists as many *words that start with the letter "c"* as possible. Test-takers were given a sheet of paper. The computer provided them with a category. The test-takers then spent two minutes writing down as many category exemplars as possible. The end of the tasks was signaled by a beep played via headphones. The dependent variable was the number of unique, cue-relevant, exemplars produced.

Working memory capacity

The *Automated Operation Span* (Unsworth et al., 2005) requires the subject to first complete a practice procedure in which they answer a series of simple math operations (1x2 + 1 = ?); after the math practice, subjects' maximum time allotted to solve the math problems on the real trials is calculated by their mean reaction time plus 2.5 standard deviations. Subjects also perform a practice procedure where they are presented with two letters and are required to recall them in the order they were presented. After the practice phase, subjects are presented with the real trials that combine the math and letter procedures of the experiment. Subjects are presented with a list of 15 trials of 3-7 randomized letters interleaved with simple math operations. After each list is complete, subjects are required to recall the letters in the order presented.

The Symmetry Span (Unsworth, Redick, Heitz, Broadway, & Engle, 2009) task is a spatial version of the complex span which requires the subject to judge whether a picture is symmetrical while remembering 2-5 specific locations highlighted on a 4x4 grid. We also administered the *Reading Span* task. Subjects read several sentences that are followed by a letter that they are asked to remember. After several iterations of this, subjects are asked to recall the letters seen during the trial in correct serial order. The subject is evaluated on the total number of letters recalled.

Rotation Span

In the rotation-span task, the subject sees a letter that is rotated to one of eight angles on the computer screen (i.e., the letter “f” is turned clockwise on its side). After, subjects saw the statement “This letter is facing in the normal direction” and must judge whether the letter is in the normal direction or mirror-reversed. Following the rotation judgement, subjects see either a long or short arrow pointing to one of eight directions. After several of these letter and arrow presentations, subjects see a recall screen with 8 large arrows and 8 eight small arrows. They were asked to click on the arrows in the order in which they had seen them. There were three to ten arrows presented during each trial.

Letter Number Sequencing (LNS) (Emery, Myerson, & Hale, 2007)

This task is based on the WAIS–III/WMS–III Letter–Number Sequencing subtest and is thought to tap working memory capacity as well as processing speed due to the speeded nature of the task. In the LNS, subjects see alternating numbers and letters presented at a rate of about one item per second (e.g., 2, L, 7, K). Following the series, participants were asked to recall each list with the numbers in numerical order (2,7), followed by the letters in alphabetical order (K,L). The task started with a two-item list (one number, one letter). A block of three trials at this length were run. If subjects recalled at least one list correctly, three more trials of three-item lists followed. The task ended when one of the following things happened: 1) the subject could not recall one list from a block, or 2) the subject finished a block of 9-item lists. The dependent variable was the number of lists, both numbers and letters that were accurately recalled.

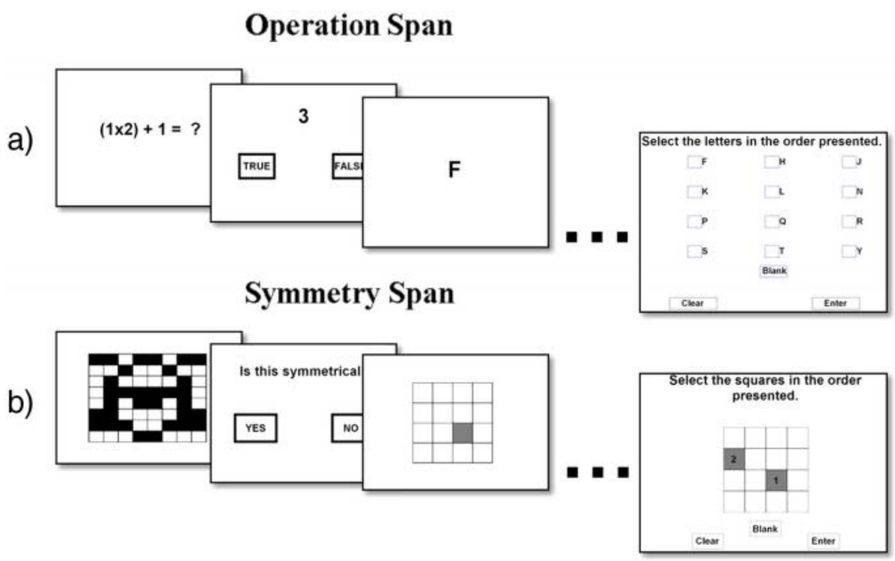

Figure 5. Examples of the (a) operation span where letters are interleaved with simple math problems, (b) and Symmetry span where subjects make symmetry judgments and remember correct position of each highlighted square (Harrison et al., 2013).

Fluid intelligence

Three fluid intelligence tasks were administered including the *Ravens Advanced Progressive Matricies (RAPM) (Raven, 1990),* the *Number Series* (Thurstone, 1938), and the *Letter Sets* task (Ekstrom, French, Harman, & Dermen, 1976). In the RAPM, a matrix reasoning task, subjects are shown a 3x3 grid of images with the bottom right image missing. Subjects were asked to choose the image that logically belongs in the bottom right of the grid from a list of available options. In the *Number Series* task subjects are shown a series of numbers that follow a logical rule. The subject's task is to determine the next number in the sequence and to choose it from a set of available options. The *Letter Sets* task presents the subject with groups of letters (e.g., AAAA, BBBB, CCCC, and ZXYB) Participants must select the group of letters that does not follow the same rule that governs the other sets of letters.

Visual Arrays

Three versions of the *Visual Arrays* task paradigm *(*Luck & Vogel, 1997) were administered. Subjects begin with the brief presentation of an arrangement of simple shapes such as colored squares. On each trial, subjects were asked to indicate whether or not a specific aspect of the object has changed, relative to its initial presentation (e.g., has the box's color changed?).

Visual arrays - color change (Luck & Vogel, 1997). Subjects are given a brief presentation of an array of 4, 6, or 8 colored boxes of different colors including white, black, yellow, green, blue, and purple. Subjects go through 28 trials of each array size, half of these are change-trials. After a short delay, the shapes reappear with one item encircled. Subjects then indicate if the color of the highlighted box has changed.

Visual arrays - orientation change (Luck & Vogel, 1997). Subjects go through 40 trials where arrays of 5 or 7 colored bars, either red or blue, are shown at horizontal, vertical, or 45° angles. Similar to the color change task, subjects indicate with a key press if the bars have changed positions (e.g., horizontal bars change to vertical).

Visual arrays - selective orientation (Vogel, McCollough, & Machizawa, 2005). In this task, subjects are told to focus on the either the red or blue bars and to expect an orientation change. 10 or 14 bars were shown. After a delay, only the to-be-remembered bars are shown on the screen. A white dot was overlaid on one bar to indicate that the subject needed to make a judgment on the particular bar (i.e. had the bar changed orientation?). We ran 40 trials at each set size, and half of these were change-trials.

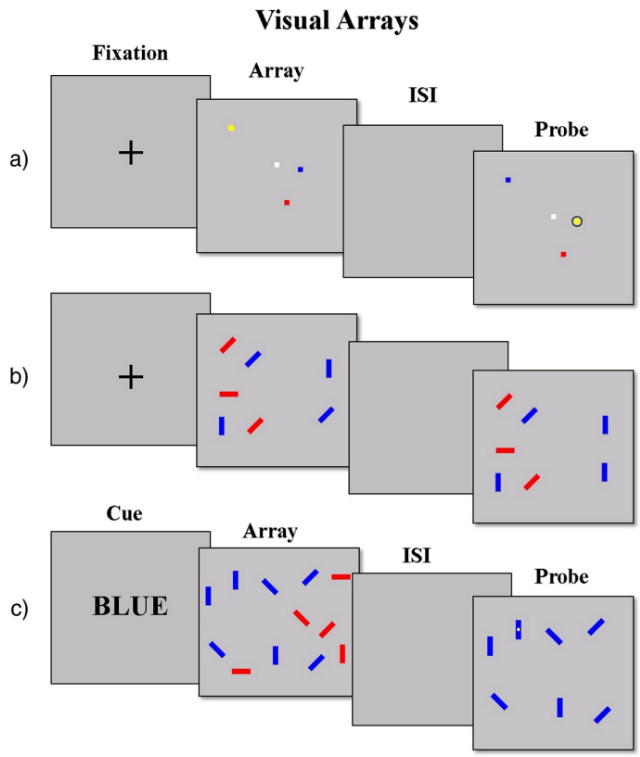

Figure 6. The Visual Arrays tasks (adapted from Shipstead et al., 2014). In (a) subjects judge whether an encircled box has changed color since its initial presentation. (b) The subject indicates whether the position of any of the boxes has changed since the initial presentation (i.e., changed orientation from vertical to horizontal). (c) The subject judges whether the box with a white dot has changed position.

Attention

Antisaccade

In 1978, Hallett and Lightstone discovered that if a cued area is highlighted briefly during a saccade, subjects' eyes will complete the saccade, and then divert to the target area (1978). The antisaccade task paradigm is used to measure a subject's ability to resist a proponent response and is thought to tap attention more generally.

We used two versions of this task (adapted from Roberts et al., 1994). In the traditional *Antisaccade task*, each trial started with a "***" fixation-point on a computer screen that lasted for approximately 200-1800 milliseconds. This was followed by a blank screen for 50 milliseconds, that was immediately followed by a "=" symbol that flashed twice over a period of 300 milliseconds on either the right or left hand side of the screen. After the flash, a letter was presented on the opposite side of the screen for 100 milliseconds and masked by the number "8". Test-takers were given 10,000 milliseconds to recall whether the masked letter had been "R", "B", or "P". The dependent variable was accuracy across 60 trials.

In the *Antisaccade-Beep* task, subjects are asked to report a letter that is shown briefly on one side of a computer screen. While the letter is being presented, an attention-grabbing flash appears in their peripheral vision (on the opposite side of the screen). The task starts with a "+" symbol on a computer screen that is shown for 1,000 or 2,000 milliseconds. Subjects wear headsets so that they can hear a warning "beep" that signals a new trial was about to begin. The beep was included to facilitate bottom-up focus on the task. The "beep" was followed by a "*" symbol that flashes on the left or right hand side of the screen for 300 milliseconds. At the same time, a letter "O" or "Q" is flashing on the opposite side of the screen for 100 milliseconds. Subjects have 5,000 milliseconds to report the letters they saw. The dependent variable was accuracy during the course of 48 trials.

The Stroop Task

This task required test-takers to report the hue in which a color-word was presented (e.g., hue: red; word: "BLUE"). Blue, green, and red were used. Participants responded by pressing one of three keys with colored stickers. The task included 162 trials. On 54 trials the word and hue were congruent. On 54 trials the word and hue were incongruent. To increase the role of endogenous attention control an additional 54 congruent filler trials were included (see Kane & Engle, 2003). The dependent variable was created by combining response time (RT) and accuracy for congruent and incongruent trials using the binning method of Hughes et al. (201 4). The details of this method can be found in the section titled "Dependent variable for response time tasks".

The Arrow Flanker

This task (Eriksen & Schultz, 1979) required test-takers to report the direction in which a central arrow was pointing. Flanking characters included congruent arrows (e.g., → → → → →), incongruent arrows (e.g., ← ← → ← ←), or a neutral arrow (e.g., ─ ─ → ─ ─). In total, 72 congruent, 72 incongruent, and 72 neutral trials were run.

A second flanker task was administered, but it was taken out of analyses due to low accuracy on neutral trials (< 70%). This task was based on Lavie's (1995) low-perceptual load condition was run.The binning procedure was used to score tasks that included reaction time (i.e., Stroop, Arrow Flankers).

Recent studies have demonstrated an increase in validity and reliability using this method instead of traditional difference scores (which are notoriously unreliable). The binning procedure is sensitive to a subject’s speed-accuracy trade-off, for instance, a subject’s tendency to sacrifice speed to be more accurate (Hughes et al., 2014; Draheim, Hicks, & Engle, 2015).

Chapter 5: Results

Since structural equation modeling (SEM) will be the primary statistical procedure used throughout our analyses, it is important to highlight the best methods for reading and judging the models presented in this study. There are five primary fit indices that readers should be able to interpret. The first is the standardized root mean square residual (SRMR). It estimates how well the specified model represents the raw variance–covariance matrix. To determine how well the model reproduces the correlation matrix, researchers use the root mean square error of approximation (RMSEA). Guidelines for cut-off values for these indices vary greatly in the literature. Values of ≤ 0.08 for SRMR and ≤ 0.10 for the RMSEA are recommended (Kline, 2011; MacCallum et al., 1996). However, other researchers have argued for more stringent cut values (i.e., ≤ 0.06 for SRMR and ≤ 0.08 for RMSEA (Hu & Bentler, 1999).

Another frequently cited index for reporting model fit in structural equation analyses is the chi square, which is a goodness of fit test. Ideally, the chi square is not significant, but it is highly influenced by the sample size, with high sample sizes almost always resulting in a significant chi square. Therefore, another statistic that is typically reported is the chi square divided by degrees of freedom (chi square/df), where values less than 3 are considered favorable. The comparative fit index (CFI) and non-normed fit index (NNFI) compare the model to a null model. The CFI and NNFI are relatively insensitive to sample size, but the CFI can be ineffective if most of the variables have small correlations among them. Reported cut-off values for acceptable fit on these indices is also variable in the literature. Kline (2011) suggests 0.90 or above, while Hu and Bentler (1999) recommend values of 0.95 and above. See Kline (2011) for a more in depth discussion on fit indices.

Descriptive statistics for each task are included in Table 2. In order to maximize the power of our study we handled missing data in EQS 6.2 by applying the Expectation-Maximization algorithm (Bentler & Wu, 2005). Less than 5% of the current dataset contained missing values, which were due to computer and/or experimenter errors.

Table 2. Descriptive Statistics for Each Task.

Variable	Min	Max	M	SD	Sk	Kurtosis
Ospan	3.00	75.00	53.74	15.45	-0.80	-0.08
Rspan	0.00	42.00	24.73	9.73	-0.41	-0.61
Sspan	3.00	42.00	26.35	9.16	-0.40	-0.57
LNS	0.00	23.00	10.84	4.14	0.00	-0.03
Raven	0.00	18.00	8.64	3.91	-0.02	-0.91
LS	1.00	29.00	15.26	5.47	0.02	-0.71
NS	0.00	15.00	8.52	3.58	-0.19	-0.88
VA1	-1.00	5.76	3.35	1.48	-0.81	0.02
VA2	-3.04	5.77	2.64	1.60	-0.81	0.89
VA4	-1.68	5.00	1.59	1.34	0.13	-0.57
Beepsacc	0.29	1.00	0.79	0.17	-0.71	-0.52
Antisacc	0.20	0.98	0.55	0.65	0.16	-0.77
Stroop	-152.63	479.20	135.98	101.33	0.68	1.05
AF	-49.97	260.85	99.82	47.12	0.75	1.37
VF1	6.00	41.00	21.79	7.28	0.02	-0.82
VF2	4.00	36.00	20.15	5.96	0.17	-0.18
VF3	5.00	34.00	19.24	5.91	0.07	-0.36
RATodd	0.00	5.00	2.56	1.33	-0.09	-0.61
RATeven	-0.13	4.00	0.71	0.90	1.24	1.09
DT Rater 1	0.00	70.00	10.12	11.48	1.89	4.60
DT Rater 2	0.00	46.00	13.16	10.05	0.74	0.01
DT Rater 3	0.00	52.00	13.17	9.58	0.80	0.68

Note. Ospan = Automated Operation Span, Sspan = Symmetry Span; Rspan = Rotation Span; LNS = Letter Number Sequencing; Raven = Raven's Advanced Progressive Matrices; LS = Letter Sets; NS = Number Series; VA1 = Visual Arrays, color judgement; VA2 = Visual Arrays, orientation judgement; VA4 = Visual Arrays, selective orientation judgement; Beepsacc = Beep Saccade; Antisacc = Antisaccade; AF = Arrow Flanker; VF1 = Verbal Fluency, animal names; VF2 = Verbal Fluency, letter "c"; VF3 = Verbal Fluency, jobs; RAT = Remote Associate Test (odd and even items); DT = Abbreviated Torrance Test for Adults (ATTA), values reported for all three raters.

All indicators were initially submitted to a confirmatory factor analysis (CFA) including creativity, verbal fluency, working memory capacity, fluid intelligence, and attention. See Table 3 for a list of factor correlations for the confirmatory factor analysis. Model fit was acceptable (CFI = 0.93, NNFI = 0.96, SRMR = 0.04, RMSEA = 0.04) (see Table 4).

Table 3.
Fit statistics for confirmatory factor analysis.

χ^2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI
325.947	188	1.73	0.04	0.04	0.97	0.97

Table 4.
Factor correlations for CFA

	WMC	gF	VA	Attention	VF	CT	DT
WMC	-						
gF	0.90	-					
VA	0.81	0.87	-				
Attention	0.82	0.84	0.79	-			
VF	0.61	0.79	0.62	0.62	-		
CT	0.46	0.56	0.48	0.50	0.58	-	
DT	0.60	0.72	0.56	0.57	0.71	0.45	-

Note. WMC = Working Memory Capacity (a factor comprised of the Complex Span: Operation Span, Rotation Span, and Symmetry Span tasks and the Letter Number Sequence task); gF = Fluid Intelligence 3 tasks: Raven's Advanced Progressive Matrices, Letter Sets, Number Series); VA = Visual Arrays (3 tasks: color, orientation, and selective orientation judgements); Attention = a factor consisting of Beep Saccade, Antisaccade, and Stroop; VF = Verbal Fluency, two categorical fluency tasks, one phonemic (letter) fluency task); CT = Convergent Thinking, Remote Associates Test (odd and even); DT = Divergent Thinking, Abbreviated Torrance Test for Adults (ATTA) across three raters)

Next, we conducted a structural equation model to better understand the relationship between working memory capacity and factors of divergent and convergent thinking. Previous research has shown that working memory capacity can be separated into both the scope and control of attention (Shipstead, Redick, Hicks & Engle, 2012; Chow & Conway, 2014). Therefore, we created latent factors for each of these constructs to predict convergent and divergent thinking. We also correlated the disturbance terms between convergent and divergent thinking in order to determine whether the two constructs shared any variance after accounting for performance on the WMspan and WMva factors (see Figure 7). The model was a good fit to the data (see Table 5).

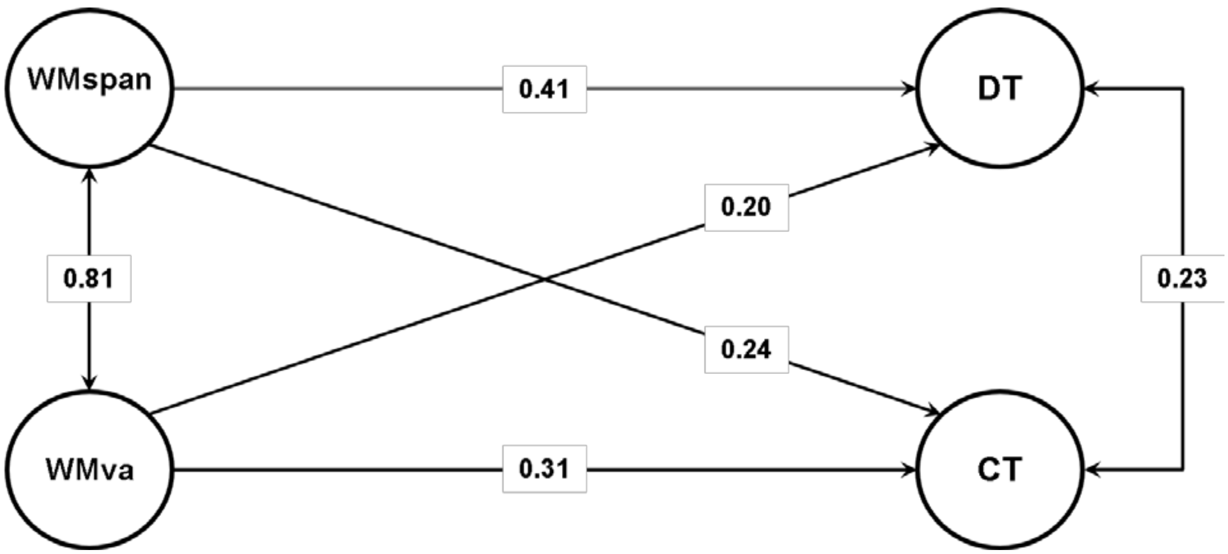

Figure 7. *Structural Model 1.* WMspan = Working Memory Capacity (a factor comprised of the Complex Span: Operation Span, Rotation Span, and Symmetry Span tasks and the Letter Number Sequence task); WMva = Visual Arrays (3 tasks: color, orientation, and selective orientation judgements); CT = Convergent Thinking, Remote Associates Test (odd and even); DT = Divergent Thinking, Abbreviated Torrance Test for Adults (ATTA) across three raters).

Table 5.
Fit statistics for Model 1.

χ^2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI
104.78	49.00	2.14	0.05	0.04	0.96	0.97

The WMspan and WMva factors shared a substantial relationship (r=.81) and both predicted unique variance in both DT and CT. The Complex Span factor predicted 16% unique variance in DT and roughly 6% unique variance in CT. The Visual Arrays factor predicted an additional 4% of the variance in DT and 9.6% of the variance in CT. Although both factors were significant predictors of both DT and CT, the disturbance term between CT and DT remained significant (r=.23). Therefore, DT and CT shared a significant relationship above and beyond both the Complex Span and Visual Arrays.

We conducted a second structural equation model which included a factor of Attention Control in addition to the WMspan and WMva factors to determine whether Attention Control accounted for any additional variance in DT and/or CT and whether it could account for the relationship between DT and CT (see Figure 8).

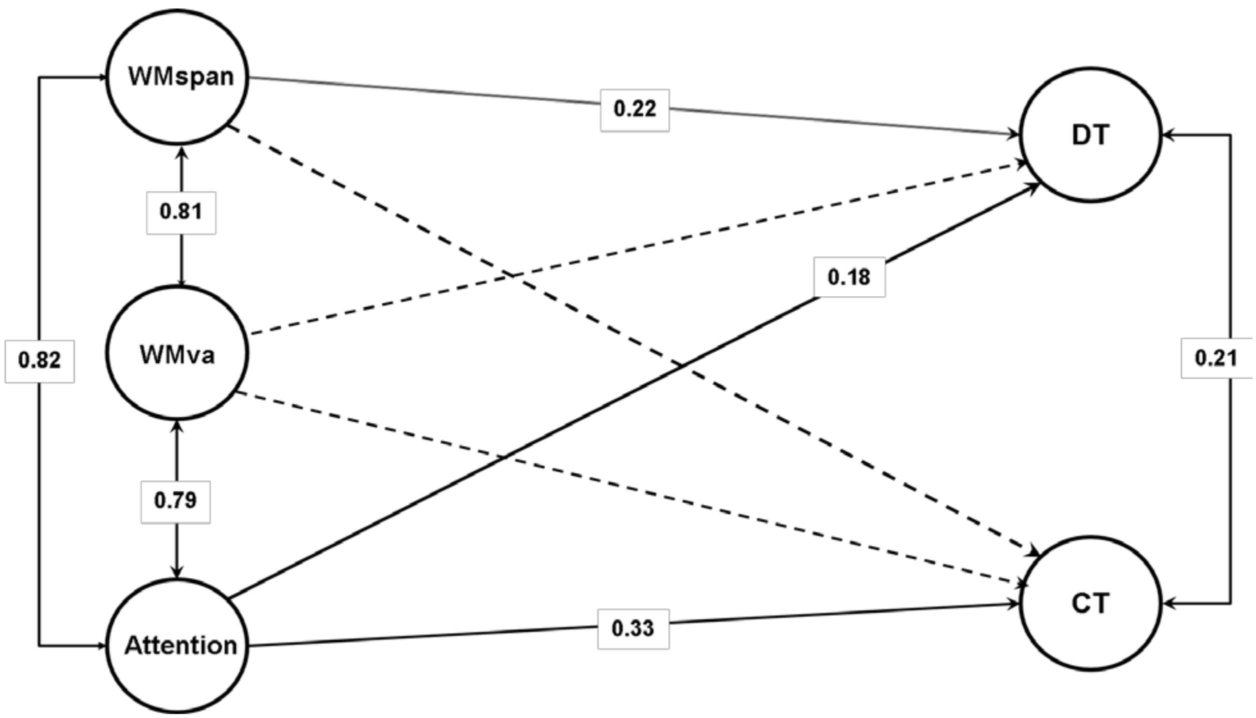

Figure 8. *Structural Model 2.* WMspan = Working Memory Capacity (a factor comprised of the Complex Span: Operation Span, Rotation Span, and Symmetry Span tasks and the Letter Number Sequence task); WMva = Visual Arrays (3 tasks: color, orientation, and selective orientation judgements); Attention = a factor consisting of Beep Saccade, Antisaccade, and Stroop; CT = Convergent Thinking, Remote Associates Test (odd and even); DT = Divergent Thinking, Abbreviated Torrance Test for Adults (ATTA) across three raters).

Table 6.
Fit statistics for Model 2.

χ^2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI
166.57	94.00	1.77	0.04	0.04	0.97	0.97

The model fit was acceptable (see Table 6). After including Attention Control, the WMva factor was no longer predictive of DT or CT. In addition, the WMspan factor no longer predicted CT. Attention Control was a modest predictor of DT (r=.18), but contributed more variance to CT (r=.33). However, including Attention Control did not account for the relationship between DT and CT (the correlated error terms remained significant, r=.21). Since the WMva failed to predict DT or CT after including Attention Control it was dropped from further models.

Next, we included Verbal Fluency as a predictor of both DT and CT (see Figure 9). Model fit was good (see Table 7). Attention Control no longer predicted DT or CT when Verbal Fluency was included as a predictor. The WMspan factor was a modest predictor of DT, but failed to predict CT. Verbal Fluency was a significant predictor of both DT (r=.54) and CT (r=.44). Further, the WMspan and Verbal Fluency factors fully accounted for the relationship between DT and CT (the error terms were no longer correlated).

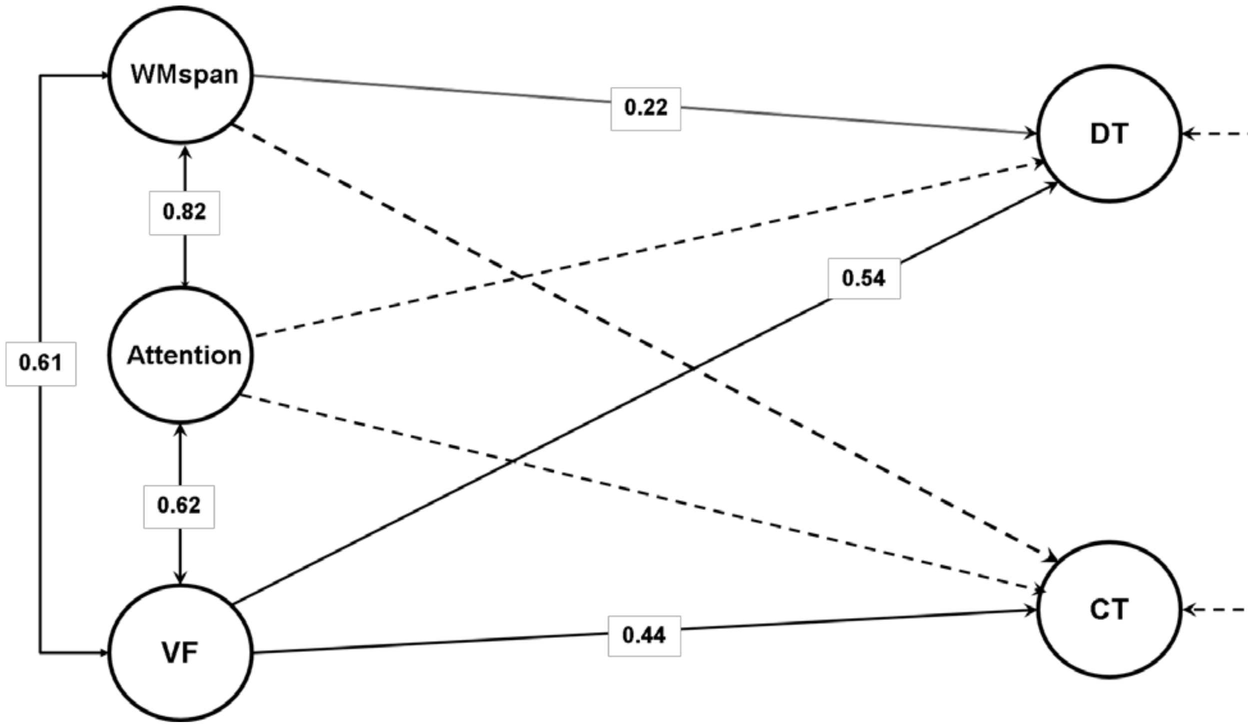

Figure 9. *Structural Model 3.* WMspan = Working Memory Capacity (a factor comprised of the Complex Span: Operation Span, Rotation Span, and Symmetry Span tasks and the Letter Number Sequence task); Attention = a factor consisting of Beep Saccade, Antisaccade, and Stroop; VF = Verbal Fluency, two categorical fluency tasks, one phonemic (letter) fluency task); CT = Convergent Thinking, Remote Associates Test (odd and even); DT = Divergent Thinking, Abbreviated Torrance Test for Adults (ATTA) across three raters).

Table 7.
Fit statistics for Model 3.

χ^2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI
172.87	94.00	1.84	0.04	0.04	0.97	0.97

Last, we investigated the relationship between creativity and intelligence. We used factors of DT and CT to predict fluid intelligence (gF). Although both facets of creativity were uniquely related to fluid intelligence, DT was the strongest predictor, accounting for 36% of the variance in gF compared to the 7.8% accounted for by CT (see Figure 10).

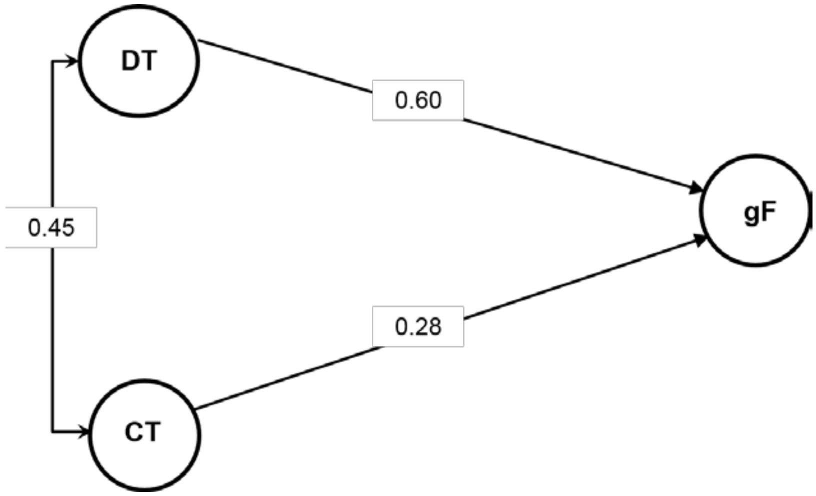

Figure 10. *Structural Model 4.* gF = Fluid Intelligence (a factor comprised of: Raven's Advanced Progressive Matrices, Letter Sets, Number Series); CT = Convergent Thinking, Remote Associates Test (odd and even); DT = Divergent Thinking, Abbreviated Torrance Test for Adults (ATTA) across three raters).

Table 8.
Fit statistics for Model 4.

χ^2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI
37.31	17.00	2.19	0.05	0.03	0.98	0.99

Chapter 6: Discussion

Conclusion

Researchers spanning numerous industries and academic disciplines have been driven to understand the origin of creative thought. For well over a century, psychologists have tried to define that which allows the most captivating people and products among us to be creative. James M. Baldwin's 1893 primer on psychology, *Elements of Psychology*, is one of the first manuscripts to discuss "imagination" alongside correlates of memory and association. This early discussion of "imagination" is, to our knowledge, one of the first references to imagination and its candidate component processes. Researchers had observed similarities in creative thinking across the humanities and the sciences that were contrary to the traditional beliefs of the day which consigned creativity to the visual arts. Baldwin recognized that creativity was a general ability and intimately related to intelligence, memory, and attention. He writes, "imagination is often used to denote the general representative function of mind, the power of representing by images, thus including memory and association, as well as the constructive working up of images" (Baldwin, 1893).

Our understanding of cognition has progressed substantially in the past century, due largely to the arrival of more robust psychometric approaches. Despite this, the field is only beginning to evaluate the many approaches and theories used to guide the study of creativity. This criticism is echoed in nearly every review of creativity research to emerge in the past several decades. The study of creativity is not a straightforward exercise, as researchers in the field can attest. Because of this, an important aim of this study was to outline and evaluate common themes in the evolving conception of creativity and the instruments used to study it.

This research verifies two separable components of creative problem solving (divergent thinking and convergent thinking). These results show that creativity and its component processes of divergent thinking and convergent thinking share an intimate link with constructs of higher order cognition. The relationship between creativity and intelligence can be understood through both controlled processes and associative abilities. While similar points have been argued before (Silvia et al., 2009; 2011), this work illustrates that the relationship between creativity and gF cannot be illustrated by either executive or associative processes alone.

This study included more rigorous task batteries than most studies of creativity, a larger sample size, and novel scoring procedure that emphasized the quality of creative ideas. This work contributes new evidence that the most predictive aspect of creative problem solving is divergent thinking.

Future Directions

A common theme addressed in the creativity literature is the idea that original or unusual ideas are more remote or distant in semantic space. Studying divergent thinking and other ideation tasks such as verbal fluency in terms of semantic associations can show researchers what connects one idea to the next. This approach is not entirely new (e.g., Mednick's associative hierarchies), but the difference in recent cases is the use of computerized software to parse and categorize creative responses, such as the ideas generated on a divergent thinking test.

Recent studies have employed modern qualitative analytical techniques such as latent semantic analysis and cognitive modeling to understand the associative processes that underlie creativity (Acar & Runco, 2014). This research is made easier by the widespread availability of semantic network databases such as WordNet and IdeaFisher. Modern methods including latent semantic analysis present a useful and objective way to operationalize originality. In their investigation of the associative processes contained in divergent thinking, Acar and Runco (2014), evaluated the utility of three different lexical databases that contain detailed parameters for calculating and describing distances between ideas. Across all methods, more creative individuals made more remote associations. This finding also correlated with a scale used to assess creative values and attitudes. Creativity assessments could be made much more efficient using similar software. In line with their findings, other research groups are now using latent semantic analysis to operationalize originality (Dumas & Dunbar, 2014, Beaty et al., 2014, Benedek et al., 2014, Jones & Estes, 2015). Keeping with efforts to streamline creativity assessment, researchers have also started validating online measures of divergent thinking (Hass, 2014).

These approaches may also be used to evaluate performance on verbal fluency tasks. Current approaches to scoring verbal fluency tasks include simple counts of fluency and the more popular approach of evaluating category clusters and switches from one category to another (Troyer et al., 1997). New methods such as latent semantic analysis extend this process, allowing researchers to calculate semantic distance and other parameters related to the pairwise association strength between two words (Ledoux et al., 2014). This is of particular interest to the clinical research community since measures of verbal fluency are frequently used to assess cognitive abilities and neurological disorders such as dementia (Pakhomov & Hemmy, 2014) and several mental disorders (Diederich & Song, 2014). Assessing the semantic distance of ideas generated on divergent thinking tasks will help us link creative production more directly to the real-world strategies being used to generate them.

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