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Introduction

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In 1950, J. P. Guilford raised the clarion call for creativity research in psychology – a clear voice to contrast the predominant focus on intelligence as the main driver in the understanding of the elusive genius (Guilford, 1950). He noted that creativity is difficult to study due to several factors, including: (1) the rare incidence of extremely creative acts, (2) the "accidental nature" (i.e., environmental influence) of many discoveries and inventions, and (3) the possible overlap between notions of intelligence and creativity. Unlike IQ tests, which had been well established for nearly 50 years, there were no similar reliable and valid tests of creative cognition. It was difficult (if not impossible) to observe, quantify, and measure creative behavior and/or moments of insight in lower animals, making comparative studies incredible to even imagine. And yet, he noted the importance of discovering the mechanisms relevant to unleashing, developing, and even growing creative potential in individuals and society as critical to education, industry, and government.

How have we done since Guilford's call? At the time of his American Psychological Association Presidential Address, he stated that he had conducted a search of the index of *Psychological Abstracts* for the terms "creativity, imagination, originality, thinking, and tests in these areas." He found that, of 121,000 titles listed, only 186 were within this search criteria – a measly two-tenths of 1%. We conducted a search in Scopus of all studies which extended from 1960 to the present using the same terms, and found 5481 documents subsequent to his call [creativity or originality or imagination or thinking (in article title) and psychol* (in article title, abstract, keywords)]. Of the 1,401,060 total (with psychol* in article title, abstract, keywords), the 5481 reflect .0039% of all psychological research: nearly four-tenths of 1% – or a 100% relative increase from before the call. We do not pretend that this is a strict "apples to apples" comparison, but we do note a clear increase in the study of creativity in the psychological sciences, with particular acceleration since 1995 (Figure 0.1).

The 1990s was the decade when creativity experienced a renaissance of sorts – when Jamison and Rothenberg independently noted that individuals with certain mental illnesses had a higher incidence of creativity (Jamison, 1993; Rothenberg, 1990); when Robert Sternberg emerged as a major voice in the field, formulating several theories of creativity (e.g., investment, propulsion) (Sternberg, 1999a; Sternberg & Lubart, 1996) and edited the landmark *Handbook of Creativity* toward the decade's end (Sternberg, 1999b; see also Kaufman & Sternberg, 2010); when the importance of personality in creative expression was highlighted again (Eysenck, 1995; Feist, 1998); and when the cognitive components of creativity began to emerge as tractable by rigorous empirical approaches (see Runco & Chand, 1995), among other notable developments. In large part this greater empirical rigor was made possible by largescale adoption of the *creative cognition approach* to research in creativity. The aims of this approach were described as follows by Ward, Smith, and Finke (1999):

> Creative cognition is a natural extension of its parent discipline, cognitive psychology, and it has two major goals. The first is to advance the

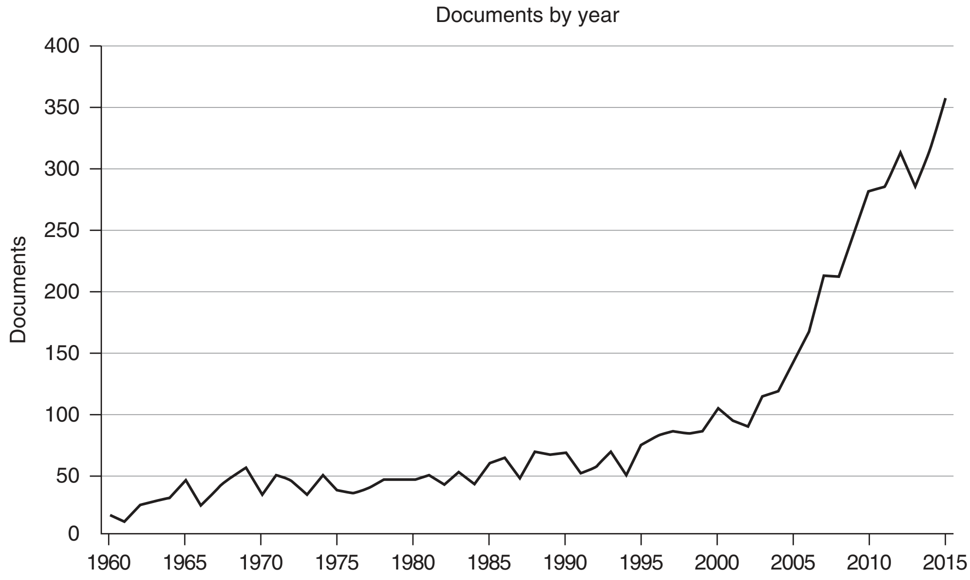

Figure 0.1 Frequency of studies of creativity in the psychological sciences. For a color version of this figure, see the color plate section.

> scientific understanding of creativity by adapting the concepts, theories, methods, and frameworks of mainstream cognitive psychology to the rigorous study and precise characterization of the fundamental cognitive operations that produce creative and noncreative thought … The second goal is to extend the scientific understanding of cognition in general and conducting experimental observations of the cognitive processes that operate when people are engaged in plainly *generative* tasks (p. 189, italics added).

Studying the components of creativity using generative (rather than receptive) tasks within the larger framework of cognitive psychology was instrumental in the conceptual and methodological maturation of creativity as a scientific discipline, and in retrospect served to bring it in line with theoretical and experimental approaches in cognitive neuroscience that would otherwise have been difficult to bridge in the decades to come.

The 1990s was also a decade that saw the emergence of the magnetic resonance imaging (MRI) machine in the study of human behavior, allowing researchers to peer farther into the human brain than they ever had before in examining the biological correlates of this unique human capability. Key psychological constructs were isolated by pioneers of the psychological study of creativity – including Amabile, Martindale, Kaufman, Ward, Feist, Runco, Simonton, Sternberg, and others – forming the theoretical and methodological bases of investigation by a new set of explorers of the human brain including Bechtereva, Beeman, Carlsson, Chavez, Heilman, Fink, and others – neuroscientists who turned their powerful instruments and intellect toward studying a construct that, at the time, was not funded by any granting agency and was not rewarded with high citation rates.

So now let's hone in on *the neuroscience of creativity* by removing the term "thinking," which would appear to be overly broad, and add "brain" to the "title, abstract, keyword" search criteria. This produces 523 articles, beginning with the first EEG study published in 1975, of 32 normal male subjects, using the Remote Associates Test (RAT) and the Alternate Uses Test (AUT), two reliable and valid measures of creative cognition that emerged following Guilford's call

(Martindale & Hines, 1975). Basal alpha levels were found to relate to differential performance across creativity and intelligence measures. The first interventional study could be said to involve 19 boys with Attention Deficit Hyperactivity Disorder (ADHD), compared to 21 control boys, which found no significant difference between ADHD and controls on the Torrance Test of Creative Thinking (TTCT) at baseline, or after the ADHD boys were treated with methylphenidate (Funk, Chessare, Weaver, & Exley, 1993). Neurologists joined in, finding that high levels of artistic creativity emerged in certain cases of frontotemporal dementia (Miller et al., 1998). By the dawn of the twenty-first century, creativity studies were firmly established within the neurosciences, with every imaginable neuroscientific modality being utilized to better understand this elusive construct. Indeed, by 2015, neuroscientific studies of creativity (Figure 0.2) represented roughly 15% of all creativity studies in the psychological sciences, with a remarkable acceleration observable around the year 2000 (Figure 0.2).

Scientific progress in a field can be measured along a continuum from mere observations to the emergence of theoretical "consensus" supported by "normal" science (Kuhn, 1962). Along the way, various pitfalls and waystations can be expected, and the neuroscience of creativity has not escaped this natural progression. The brilliant mathematician, Poincaré, used introspection to determine the source of his own creative process, and discovered that it was not represented by one, nebulous construct, inscrutable to science, but that it consisted of several discrete stages – preparation, incubation, intimation, illumination, and verification – each independent of one another, yet working in harmony to produce creative achievement (Poincaré, 1913). Several "folk psychologies" emerged, each attempting to make sense of initial observations, but lacking the scientific basis necessary to hold up under increased scrutiny: right brain locus, "mad genius," creativity *as* divergent thinking, etc. These attempts at understanding creativity are akin to the tale of the blind man and the elephant, each being convinced that they are touching (variously) a wall, snake, spear, tree, fan, and rope (Saxe, 1872). Eventually, however, a sighted man comes along and sees the elephant

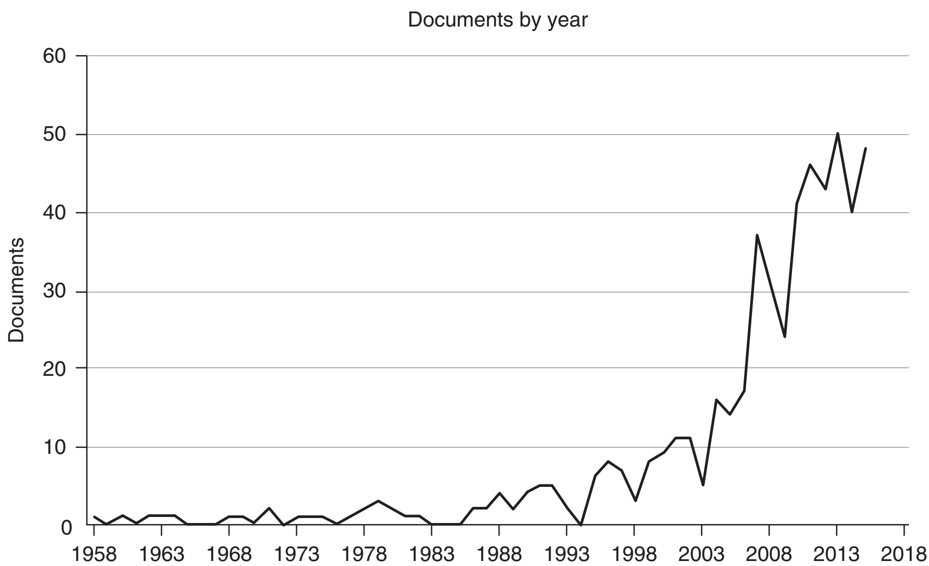

Figure 0.2 Frequency of studies on the brain bases of creativity. For a color version of this figure, see the color plate section.

in its entirety. It is our contention that the field has progressed to a point that we can leave such folk psychologies behind, and move firmly into a "normal" neuroscience of creativity.

Several hazards and pitfalls remain, however. If creativity is to be a viable neuroscientific construct it should conform to several scientific conditions. First, it should have a definition that lends itself to scientific inquiry. The production of something novel and useful (and perhaps surprising) is such a discrete definition. Importantly, it is not overly broad, and its components can have tractable neuronal correlates. Second, creativity should be explored in both human and non-human animals to determine whether creative cognition is a general brain "feature" or a more specific ability unique to higher mammals. Third, hypotheses should be generated regarding the emergence of creativity across evolutionary time: how and why might creative cognition have emerged to address environmental demands? Fourth, creativity should be explored as a dynamic interplay of multiple brain networks, engaged to serve context-specific demands, as opposed to "bits and pieces" of brain deemed "central" to creativity, the latter approach having the whiff of neurophrenology. With this basic framework, and a multimodal approach (i.e., both in terms of theoretically driven neuroimaging techniques, and their integration with behavioral, genetic, lesion, clinical, and intervention approaches), we can be hopeful in our ability to create a new and important discipline within the cognitive neurosciences.

We believe that the 30 chapters in this first *Cambridge Handbook of the Neuroscience of Creativity* represent the very best that the field has to offer. The chapters range widely in their scope, addressing general and long-standing questions about the nature of creative cognition. These include the overlap between intelligence and creativity, the association between psychopathology, pharmacology and creativity, the role of hemispheric asymmetry in creativity, the contribution of attention, memory, imagination, and language to creativity, as well as the questions of individual differences and domain generality vs. specificity in creativity. Other fundamental issues to be tackled in this book involve the relationship between motivations and drives with creativity, as well as the effect of the aging brain on creativity. There are also very specific (and novel) approaches to understanding creativity in musicians, polymaths, and animal models, as well as the introduction of new dynamic models to both intelligence and creativity.

We have gently edited all of the chapters, with our goal being to allow the voices and ideas of the authors to come through as distinctly and with as high fidelity as possible – which we feel is appropriate for a first volume in a nascent field. We have gently nudged all authors to adopt a "network" approach to their conceptualizations of creative cognition in the brain – which is the current state of the art within the neurosciences – and pulls the field away from the tendency to "localize" creativity within a distinct region or regions of the brain. We have been delighted by the novelty and quality of the chapters, and hope that you will find them to be useful in your work and thoughts regarding how creativity is manifested in the brains of humans and non-humans over evolutionary time. Some of the ideas might even surprise you. Finally, as editors of this volume, we are delighted to observe that within the span of only two decades a summary of the neuroscientific approaches to creativity requires an entire handbook rather than a single chapter in a handbook (see Martindale, 1999). We look forward to the future growth of this area with great excitement.

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Part I

Fundamental Concepts

1 Creative Ideas and the Creative Process: Good News and Bad News for the Neuroscience of Creativity

Dean Keith Simonton

Every neuroscientist is likely familiar with phrenology, the first science devoted to the proposition that the diverse psychological functions – or mental "faculties" – were located in specific parts of the brain. Who has not seen a phrenology chart with the borders between the various faculties precisely delineated on the cranium? To be sure, phrenology is now considered a notorious example of a pseudo-science. Yet that contemporary judgement often ignores the fact that phrenology was founded by a genuine scientist, Franz Joseph Gall. Although Gall's ideas about the localization of function were based on some erroneous assumptions – most notably a close congruence between cerebral cortex and cranium – phrenology probably deserves more respect than other pseudo-sciences of those times, such as Franz Mesmer's mesmerism. True or not, a creativity researcher like me might find it remarkable that the extensive list of faculties – dozens of them – does not include creativity! Nor anything similar, whether imagination, inventiveness, or originality. The closest faculty to creativity is perhaps wit (or "mirthfulness"), but surely that concept remains remote. Hence, are modern neuroscientists willing to rush in where phrenologists might have feared to tread?

In this chapter, I want to discuss why neuroscientists should tread carefully when studying creativity. Unlike such phrenological faculties as sight, hearing, taste, and smell, the psychology of creativity is necessarily riddled with complexities that must be deeply considered if the neuroscience of creativity is to become a cumulative and coherent science (cf. Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Gonen-Yaacovi et al., 2013; Sawyer, 2011). These complexities can be assigned to two big questions. First, what is a creative idea? Second, by what process are creative ideas produced?

Creative Ideas – What and Who?

Presumably, the creative *process* generates creative ideas, the creative *person* engages in the creative process producing those ideas, and the creative *product* contains the creative ideas that the creative person acquires through that creative process. But observe that these statements all suppose that we know what the adjective "creative" actually means. Without a definition, these seemingly obvious assertions actually become meaningless. It turns out that defining creativity is no simple task (Simonton, 2016). In fact, the definition requires that we address two independent questions. We should begin by asking: *What* criteria must be used in judging an idea's creativity? Once that issue is resolved, we then must inquire: *Who* evaluates those criteria in assessing the idea's creativity?

What Are the Creativity Criteria?

For a very long time, many creativity researchers subscribed to what has been called the "standard definition," namely, "Creativity requires both originality and effectiveness" (Runco & Jaeger, 2012, p. 92). Thus, two criteria are imposed, albeit different researchers might substitute approximate synonyms for either criterion: (a) novelty or uniqueness for originality; and

(b) usefulness, utility, value, appropriateness, or meaningfulness for effectiveness (Simonton, 2016). However, others have argued that a third criterion *must* be added. For instance, Boden (2004) stipulated that creative ideas must be novel, valuable, and surprising, a three-criterion definition that closely corresponds to that used by the United States Patent Office, namely, new, useful, and nonobvious (Simonton, 2012b).

Recently, the three-part definition has been formally expressed by the following equation (Simonton, 2013a, 2016, 2017): $c = (1 - p)u(1 - v)$. Here, c is creativity, p is the idea's initial probability, so that $(1 - p)$ gives its originality, u is the finally assessed utility or usefulness, and v is the prior knowledge of the idea's utility, which makes $(1 - v)$ a gauge of its surprise (i.e., how much new knowledge is gained). The values for c, p, u, and v, as well as $(1 - p)$ and $(1 - v)$, all range between 0 and 1, like probabilities or proportions. Hence, minimum = 0, maximum = 1, and middling ≈ 0.5. Moreover, because c is the multiplicative function of the three factors, $c = 0$ if any of its components equals 0. In words, a creative idea must be original *and* useful *and* surprising. Each separate criterion is thus rendered necessary but not sufficient. For example, an utterly useless idea cannot be creative no matter how original and surprising – such as constructing a bank vault out of cellophane.

This three-criteria definition is vastly superior to the standard definition (Simonton, 2016). Indeed, the latter definition makes no sense whatsoever. After all, the two-criteria definition can be expressed as $c = (1 - p)u$, indicating that the most creative ideas have a low probability but a high utility. This then leads to a paradox: How can a highly useful idea have such a low probability? The only rational answer to that enigma is that the creator does not already know the utility, necessitating that the prior knowledge value v approach zero. For any reasonable creature, if a highly useful idea was already known to be useful, then its probability would have to be high rather than low. This logical and psychological necessity then mandates that $(1 - v)$ be added as the third factor. The standard definition is plainly untenable.

Three critical consequences follow necessarily from the three-criteria definition. These consequences concern incubation periods, domain-specific expertise, and uncreative ideas.

Incubation periods. Wallas (1926) offered a stage theory of creative problem-solving that remains frequently cited nearly a century later: Preparation, Incubation, Illumination, and Verification. The creator starts by preparing an understanding of the problem, encountering difficulties that then lead to the incubation period in which the individual is not consciously thinking about the problem. With sufficient incubation the creator may have an insight, eureka, or "ah-ha" experience in which a solution flashes to mind (Hélie & Sun, 2010). Yet because such inspirations are by no means guaranteed to work, this illumination phase must be followed by the verification phase in which the idea is directly tested, whether externally or internally (cf. Dennett, 1995). If this test fails to confirm the idea's utility, then the cycle will continue in the hope that an effective solution is finally found.

Yet is the incubation period actually required? Might not the creative individual skip directly from preparation to illumination? That is, as soon as the problem is properly understood, the solution might come to mind without any need to work on irrelevant tasks in the meantime (cf. Boden 2004). The three criteria provide a precise answer to this question: Both yes and no! The precision of the answer comes from recognizing that the correct response depends on the magnitude of creativity. If we can assume that utility is high and prior knowledge low, then creativity obviously maximizes as the initial probability goes to zero (i.e., if $u \rightarrow 1$ and $v \rightarrow 0$, then $c \rightarrow 1$ as $p \rightarrow 0$). Hence, the most creative ideas under these conditions would have an initial probability of zero ($p = 0$). So the importance of incubation follows from the definition.

At the same time, even when the initial probability exceeds zero ($p > 0$), the creativity can still exceed zero ($c > 0$). To illustrate, suppose that after the requisite preparation the creator has an immediate but moderate hunch that a certain low-probability idea will solve the problem. The parameter values might be $p = 0.2$, $u = 1$, and $v = 0.5$ (for the "hunch"), which yields $c = 0.4$. A lot of ordinary creativity probably operates at this middling level, reasonably creative ideas emerging without any incubation whatsoever.

Yet given this direct implication of the definition, we might ask whether the *length* of the incubation period has any relevance for an idea's creativity. The definition makes no provision for this duration having any impact. This omission follows from the plausible assumption that the time elapsed before the response strength exceeds zero is most likely the function of random stimuli (cf. Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995) and capricious trains of thought (cf. Mandler, 1995). The first recorded "Eureka!" moment in history occurred when Archimedes took a bath, yet the time that he waited before he felt he was (over)due for some personal hygiene should not determine the evaluation of the idea's creativity.

The good news: Researchers who study the neuroscience of creative insights are not wasting their time (e.g., Bowden, Jung-Beeman, Fleck, & Kounios, 2005). The incubation–illumination phase shift is not required for all creative ideas to emerge, but the cognitive shift is positively associated with the emergence of the most highly creative ideas.

Domain-specific expertise. Some researchers are inclined to believe that creativity is domain specific (Kaufman, Baer, & Glăveanu, 2017). Albert Einstein could no more paint *Guernica* than Pablo Picasso could work out the equations for the general theory of relativity. Yet such a belief conflates content with process. An analogy with language is useful here (Simonton, 2017). No doubt that someone who learns English cannot automatically speak Mandarin. Yet the kinds of psychological processes necessary to learn and apply either language must overlap considerably. Both languages require that the user recognize phonemes and morphemes, wrap the vocal apparatus around specific consonants, vowels, and tones, learn lexicons and master syntax, establish correspondences between the spoken and written word, and acquire the appropriate pragmatics of when to say this and when to say that to whom. If otherwise, then there would have to exist at least as many linguistics departments as there are world languages. We would also have to wonder why almost any *Homo sapiens* can master any human tongue on this planet, yet no non-human whatsoever can acquire even basic proficiency in any natural language. The human language "module" is generic, not specific.

Recall that the three-criteria definition parallels the standards used by the United States Patent Office to evaluate patent applications (www.uspto.gov/inventors/patents.jsp). In particular, the surprise criterion corresponds to the nonobvious criterion, the two just stressing different aspects of the prior knowledge value v. When $u = v = 1$, a useful idea is obvious, but when $u = 1$ but $v = 0$, the same idea is surprising. Significantly, when the Patent Office applies this criterion in evaluating applications, they refer not to the opinion of the average person on the street but rather to the judgment of somebody with "ordinary skill in the art" (www.uspto.gov/web/offices/pac/mpep/documents/2100_2141_03.htm). In other words, the idea cannot be derived directly from domain-specific expertise. A necessary even if not sufficient condition for $c \rightarrow 1$ is for $v \rightarrow 0$. This necessity does not mean that relevant expertise is absolutely irrelevant. On the contrary, such expertise is most often essential to constructing the utility criterion (Simonton, 2015). What does it actually signify to invent a better mousetrap or discover a cure for cancer? If a person has no knowledge of past solutions to the problem of invasive rodents or is completely ignorant of how various cancers appear and grow, then coming up with a highly effective device or medical intervention becomes impossible. It is just that knowing exactly what you're looking for does not ensure that you'll actually find what you're looking for.

Hence, more good news: Because creativity cannot just involve the direct application of domain-specific expertise, neuroscientists can concentrate their methods on whatever happens in the brain that produces surprising or nonobvious ideas. Creativity must be primarily domain-generic, not domain-specific (Simonton, 2017).

Uncreative ideas. According to the three-criteria definition, creativity can be optimized just a single way: Simultaneously maximize originality, utility, and surprise. If the idea is commonplace, useless, or obvious, or any combination of possible zero values, then an uncreative idea results. Each exerts veto power over the rest. In effect, this definition implies that ideas may be uncreative in multiple ways, seven to be exact (Simonton, 2016). Although not all possibilities are equally interesting or valuable, it is instructive to examine them all. So all eight potential outcomes are shown in Table 1.1.

The creative outcome is immediately followed by one representing routine, reproductive, or habitual thinking or behavior (e.g., $p = u = v = 1$). The idea is highly useful, that utility is known in advance, so that the initial probability is supremely high. Indeed, any rational creature would operate so that $p \rightarrow 1$ as $uv \rightarrow 1$ (aka "learning"). Closely related is the next outcome, rational suppression, in which the initial probability approaches zero because the idea is already known in advance to be useless (i.e., as $u \rightarrow 0$ and $v \rightarrow 1$, then $p \rightarrow 0$). These latter parameter values may have been "learned the hard way" through the extinction of maladaptive responses.

The next two outcomes both involve high-probability ideas but low prior knowledge values, with only the utilities differing. In the case of the fortuitous responses, the idea with the highest probability also has the highest utility, but the person is ignorant of the actual utility because the idea was just a "lucky guess" – such as winning the lottery using your mother's birthdate. In contrast, "problem-finding" occurs when a high probability idea is revealed to be useless, the individual having no prior knowledge of that inutility. This outcome can be considered a form of problem-finding because an idea that was expected to work based on past experience fails to work. The person is then

Table 1.1 *Creative and noncreative outcomes according to the three-criteria definition.*

Initial probability	Final utility	Prior knowledge	Outcome
$p \rightarrow 0$	$u \rightarrow 1$	$v \rightarrow 0$	Creative ideas or responses ($c \rightarrow 1$)
$p \rightarrow 1$	$u \rightarrow 1$	$v \rightarrow 1$	Routine, reproductive, or habitual ideas or responses
$p \rightarrow 0$	$u \rightarrow 0$	$v \rightarrow 1$	Rational suppression (e.g., extinguished responses)
$p \rightarrow 1$	$u \rightarrow 1$	$v \rightarrow 0$	Fortuitous responses (e.g., "lucky guesses")
$p \rightarrow 1$	$u \rightarrow 0$	$v \rightarrow 0$	Problem-finding (surprising expectation violations)
$p \rightarrow 0$	$u \rightarrow 1$	$v \rightarrow 1$	Irrational suppression
$p \rightarrow 1$	$u \rightarrow 0$	$v \rightarrow 1$	Irrational perseveration
$p \rightarrow 0$	$u \rightarrow 0$	$v \rightarrow 0$	Mind wandering or behavioral exploration

Note: The symbol "→" should be read "approaches." Table modified from Simonton (2016).