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Review

Creative thought as blind-variation and selective-retention: Combinatorial models of exceptional creativity

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Abstract

Campbell (1960) proposed that creative thought should be conceived as a blind-variation and selective-retention process (BVSR). This article reviews the developments that have taken place in the half century that has elapsed since his proposal, with special focus on the use of combinatorial models as formal representations of the general theory. After defining the key concepts of blind variants, creative thought, and disciplinary context, the combinatorial models are specified in terms of individual domain samples, variable field size, ideational combination, and disciplinary communication. Empirical implications are then derived with respect to individual, domain, and field systems. These abstract combinatorial models are next provided substantive reinforcement with respect to findings concerning the cognitive processes, personality traits, developmental factors, and social contexts that contribute to creativity. The review concludes with some suggestions regarding future efforts to explicate creativity according to BVSR theory.

Keywords: Blind variation; Donald Campbell; Combinatorial models; Creativity

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1. Introduction

In a classic theoretical article, the psychologist Campbell [15] proposed that creativity is best understood as entailing the two-stage process of blind-variation and selective-retention (or BVSR). The most critical part of BVSR concerns the concept of "blindness". For Campbell, ideational variations are considered blind to the extent that their emission is (a) "independent of the environmental conditions of the occasion of their occurrence" and (b) "uncorrelated with the solution, in that specific correct trials are no more likely to occur at anyone point in a series of trials than another, nor than specific incorrect trials" (p. 381). Although Campbell argued that Darwinian evolution by natural selection also operated according to the same BVSR principle, it is important to recognize that Campbell definitely did not predicate his theory of creativity on a direct *analogy* with organic evolution [64,80]. On the contrary, he clearly viewed BVSR as a superordinate process that included several manifestations as special cases. The latter included not just biological evolution but also perception, learning, and creativity. In fact, Campbell explicitly pointed out that the first conjecture that creativity depends on effectively blind variations was historically antecedent to Darwin's theory of evolution (see [7]). In this light, it is technically a mistake to label Campbell's position as strictly "Darwinian", an error made frequently by both advocates [168] and opponents [29,80].

Later researchers have expanded the central BVSR approach into a universal selection theory that encompasses many additional phenomena in disciplines as diverse as immunology, neuroscience, psychiatry, linguistics, computer science, anthropology, and philosophy (e.g., [28,91]). Campbell's [15] views have been especially influential in the development of evolutionary epistemology [16,17], a philosophical system that attempted to find an empirical basis for the theory of knowledge [55]. To be sure, each of these BVSR extensions must acknowledge the manifest disparities among the various phenomena in which this mechanism is said to operate [31,105]. To illustrate, where biological evolution requires simultaneous variation and external (environmental) selection, creative thought normally uses sequential variation and internal (cognitive) selection. What the two phenomena share is a mutual dependence on the capacity for generating blind variants, whether those variants constitute organisms of a particular species or ideas in a specific domain.

This common dependence on blind variants may also have a parallel basis. The variants that feed biological evolution are produced by two combinatorial processes: genetic recombination and the mutation of genes. The former combinatorial process operates at the chromosomal level, whereas the latter process functions at the molecular level. In a like manner, creativity may rely on ideational variants that are generated by one or more combinatorial mechanisms. Naturally, the details of these two combinatorial procedures would be disparate. Where biological variations can be, at least in theory, random, psychological variations may only be blind. Although all random variations are inexorably blind, blind variations are *not* inevitably random, and are actually seldom so [15]. Hence, both biological evolution and human creativity may depend on blind combinatorial variations, but do so via radically divergent means.

The importance of blind combinatorial variations has been suggested by the introspective reports of some eminent creators. For example, the mathematician Hadamard [51] held that creativity demands the discovery of uncommon but still effective ideational combinations. To do so, it becomes "necessary to construct the very numerous possible combinations, among which the useful ones are to be found" (p. 29). Although he added, "it cannot be avoided that this first operation take place, to a certain extent, at random, so that the role of chance is hardly doubtful in this first step of the mental process" (pp. 29–30), we need not take the assertion too literally. It suffices to say that the combinatorial process he describes is at least blind even if not random.

Another mathematician, Henri Poincaré [118], provided an even more detailed account of the hypothesized combinatorial process. He described one episode of discovery by remembering how "ideas rose in crowds; I felt them collide until pairs interlocked, so to speak, making a stable combination" (p. 387). These colliding images were compared to "the hooked atoms of Epicurus" that chaotically bump against each other "like the molecules of gas in the kinematic theory of gases" so "their mutual impacts may produce new combinations" (p. 393). Although this quote implies a blind combinatorial process, it actually operates under some constraints: "The mobilized atoms are … not any atoms whatsoever; they are those from which we might reasonably expect the desired solution. Then the mobilized atoms undergo impacts which make them enter into combinations among themselves or with other atoms at rest which they struck against in their course" (p. 389). Consequently, "the only combinations that have a chance of forming are those where at least one of the elements is one of those atoms freely chosen by our will. Now, it is evidently among these that is found what I called the good combination" (p. 389). The latter combination, of course, is one most likely to be selectively retained.

The physicist and chemist Michael Faraday once reported "the world little knows how many of the thoughts and theories which have passed through the mind of a scientific investigator have been crushed in silence and secrecy by his own severe criticism and adverse examinations; that in the most successful instances not a tenth of the suggestions, the hopes, the wishes, the preliminary conclusions have been realized" (quoted in [10, p. 79]). This low success rate is reflected in Poincaré's [118] admission that "among the great numbers of combinations blindly formed … almost all are without interest and without utility" (p. 392). One reason why the odds are so small is that the useful or interesting combinations

> are those which reveal to us unsuspected kinship between other facts, long known, but wrongly believed to be strangers to one another. … [Accordingly,] among chosen combinations the most fertile will often be those formed of elements drawn from domains which are far apart. Not that I mean as sufficing for invention the bringing together of objects as disparate as possible; most combinations so formed would be entirely sterile. But certain among them, very rare, are the most fruitful of all. (p. 386)

This last assertion provides reason to suspect that ideational variations are blind, even if they are not required to be totally random. That inference stems from the fact that the most fruitful combinations are often found where least expected. This fits the formal definition of blindness to be given shortly.

In sum, a prima facie case has been made that creativity may be contingent on the capacity to proliferate blind combinatorial variations. That is, it should be possible to translate Campbell's [15] BVSR theory of creativity into combinatorial models. An asset of this translation is the facility with which it supports more comprehensive explanations and precise predictions that are empirically testable. It is the goal of this review to realize the potential of this application.

I begin with some necessary definitions, and from there put forward the corresponding model specifications. From the latter I advance to working out the empirical implications, followed by substantiations of the models in terms of relevant psychological research.

2. Definitions

Before the BVSR theory of creativity can be developed in terms of combinatorial models, it is first necessary to define the key concepts. These involve blind ideational variants, creative thought, and disciplinary context.

2.1. Blind ideational variants

Although the concept of blindness constitutes the single most critical feature of Campbell's [15] BVSR theory, he never provided a precise definition of the term. Hence, it is essential to define this concept before continuing further. This task can be best accomplished by modifying the definition used in evolutionary biology (e.g., [187], cf. [80]). The modification is designed to render it more inclusive with respect to all BVSR phenomena, including creativity. The modified definition has the additional advantage that it defines the opposite of blindness, namely sightedness. To simplify matters, the definition will be confined to just two variants, but the extension to three or more variants is reasonably straightforward. I start with sighted variants because they put the blind variants into proper context.

Let X and Y be two possible ideational variants, with respective probabilities of $p(X)$ and $p(Y)$. Here "possible" means conceivable or permissible rather than inconceivable, impermissible, or impossible on either *a priori* or *a posteriori* grounds (e.g., domain-specific expertise). Given this supposition of "guided" pre-selection, we can affirm that both $p(X) > 0$ and $p(Y) > 0$. Corresponding to each of these variants is a fitness value w, which shall be notated as $w(X)$ and $w(Y)$, respectively. This fitness parameter can be taken as the probability that the variant will survive the process of selective retention. Without loss in generality, we can posit that $p(X) > p(Y)$. Under these conditions, the two ideational variants are *sighted* if $w(X) > w(Y) \rightarrow p(X) > p(Y)$, where the symbol "→" means "implies" (i.e., in the sense of conditional probability of the relative probabilities given the relative fitness values). In other words, variant X is more probable than other variant Y precisely *because* variant X is more fit – useful, functional, or adaptive – than is variant Y.

When the preceding conditions do not hold, then the two ideational variants can be considered *blind*. For example, the two possible ideational variants might possess equal probabilities despite the fact that their fitness values are very unequal; i.e., $p(X) = p(Y)$ although $w(X) \neq w(Y)$. The former equality cannot possibly be implied by the latter inequality. An illustration would be a scientist who narrowed the possible explanations of a phenomenon down to two mutually exclusive hypotheses (i.e., $X \rightarrow$ not-Y and $Y \rightarrow$ not-X), but cannot know which is actually true without resorting to an experimental test. Another example is when the relative magnitudes of the two probabilities and their corresponding fitness values are completely reversed, so that one inequality cannot possibly imply the other inequality; e.g., $p(X) < p(Y)$ although $w(X) > w(Y)$. The solution that is most likely to work is the very one that is most likely to be tried last. The first attempt to solve a problem may fail because a creator adopts a standard approach that does not accommodate certain novelties. The problem solver then enters an incubation period in which he or she becomes open to less probable lines of attack, one of which provides the solution.

Speaking more generally, anytime the differential probabilities of two or more variants is not automatically implied by the differential fitness values of those variants, then the variants are blind rather than sighted.

2.2. Creative thought

Creative thought is defined as the process or set of processes that generate ideas that are both (a) original, novel, or surprising and (c) useful or adaptive [132]. The first criterion distinguishes creativity from the conventional or routine, whereas the second criterion separates creativity from psychopathology, which can also produce originality. Moreover, creativity is a multiplicative rather than additive function of originality and utility, each of which can be considered ratio scaled variables [184]. Such a multiplicative function demands that if an idea lacks either originality or utility, then the idea also lacks creativity. Someone who reinvents the wheel (zero originality but high utility) or makes a wheel entirely out of soap bubbles (high originality but zero utility) cannot be considered creative.

Finally, it is necessary to distinguish ordinary creativity from exceptional creativity ([170]; see also [11]). Where the former refers to everyday problem solving, the latter is confined to creativity that yields products that contribute to a particular discipline, whether in the arts or sciences. Examples include journal articles, patents, computer programs, paintings, poems, novels, musical compositions, motion pictures, video games, and architectural designs. The more extensive and enduring the contribution, the more exceptional is the creativity. The current review article concentrates on exceptional creativity because the latter is most likely to engage BVSR mechanisms.

It should be apparent that the definition of creative thought closely parallels Campbell's [15] concept of blind-variation and selective-retention. The blind variation generates the originality of an idea whereas the selective-retention determines the idea's utility.

2.3. Disciplinary context

Because this article focuses on exceptional rather than ordinary creativity, the phenomenon must be conceived in a disciplinary context. Solid-state physicists contribute to solid-state physics, evolutionary biologists to evolutionary biology, cognitive psychologists to cognitive psychology, macroeconomists to macroeconomics, and so forth. From the standpoint of a BVSR model, probably the most fruitful conception of this disciplinary context is Csikszentmihályi's [26,27] systems perspective. In this perspective, creativity is situated in the dynamic interaction of three disciplinary components. First is the *individual* who contributes original ideas to the discipline. The individual embodies the psychological aspect of creativity, that is, the locus of the cognitive processes that generate creative ideas. Second is the *domain* containing the set of ideas that defines a given discipline. The domain represents the intellectual or aesthetic content on which individual creativity is founded. In a scientific discipline, these might include concepts, facts, theories, laws, hypotheses, formulas, principles, techniques, methods, problems, questions, goals, etc. Third and last is the *field* consisting of the set of individual creators who are active in the same discipline; this component recognizes the social aspect (colleagues, collaborators, competitors, editors, referees, etc.). Of course, the specific nature of individual, domain, and field will vary from discipline to discipline. In the arts, for example, some portion of the field might include a contingent of aficionados, patrons, connoisseurs, and critics who evaluate contributions without producing contributions. Similarly, the domain in artistic disciplines often incorporates ideas from outside the domain per se, as when plays, novels, or films include references to current events or concerns (e.g., [175]). For present purposes, these disciplinary contrasts in domain and field composition will be ignored.

The individual, domain, and field operate to produce a creativity cycle [27]. The individual takes domain-specific ideas and transforms them into new products that contain original ideas. The field then determines which of these ideas can count as useful and hence creative contributions to the domain (e.g., peer review and citations in science). Once receiving validation from the field, the new ideas are added to the domain, and the cycle continues. Through a series of iterations involving all individuals making up the field, the domain transforms and, if cumulative, expands.

3. Specifications

By integrating the foregoing definitions with Campbell's [15] basic BVSR framework, it is possible to derive a set of empirically consequential implications. This integration requires the development of a generic combinatorial model that can be then extended to or elaborated into specific models. In particular, we need to specify individual domain samples, variable field size, and ideational combination and disciplinary communication.

3.1. Individual domain samples

Presumably, each individual member of the field obtained, during the course of education and training, a personal sample of the ideas defining his or her chosen domain. Because few if any individuals can master all of the ideas constituting the domain, each sample constitutes a subset. That is, if I_D represents the total number of domain-specific ideas, and I_i represents the number of such ideas mastered by individual i, then $I_i < I_D$. Not only will each individual possess a mere subset, but also those subsets will be heterogeneous rather than homogeneous. In academic disciplines, for example, the samples will be heterogeneous insofar as each student takes a different set of courses, in different years, from different instructors, at different colleges or universities, using different textbooks or textbook editions, and so forth. In disciplines that also exhibit low consensus regarding essential domain content, such as holds in the social sciences and humanities [183], it is even possible to assume that the individual samples are drawn practically at random from the larger domain. In such disciplines, the separate samples may only overlap regarding a few core ideas shared by all members of a particular field (e.g., what is taught in required courses), but diverge regarding all of the more peripheral ideas (e.g., what is taught in elective courses). Nonetheless, it can be supposed that the union set of all individual domain subsets would closely approximate the entire set of ideas defining the domain. Without at least one member of a field including a particular domain-specific idea, that idea would eventually become extinct (i.e., no longer appear in curricula, textbooks, lectures, reference lists, etc.). Examples might include obsolete notational schemes or conceptual terms that are no longer in contemporary usage (e.g., phlogiston in chemistry).

Individual samples differ not only with respect to their contents but also with regard to their size. Although the smallest sample size would have to satisfy some threshold level of competence (i.e., $I_i > \theta$ for all i), certain field members will still have extracted more domain-specific ideas – learned more knowledge and mastered more technique – than others in the same field (i.e., $I_i \neq I_j$ for most if not all $i \neq j$). Given the probable existence of substantial individual differences in these sample sizes, the question arises regarding their cross-sectional distribution. There are two main possibilities. The most obvious is to assume that the sample sizes are normally distributed in the field (i.e., according to the bell-shaped or Gaussian curve). This would be the expected distribution if the size of an individual's sample were a function of a large number of independent abilities, interests, and values that exert an additive influence on expertise acquisition. As Galton [43] was the first to show, the scores received on achievement tests tend to be normally distributed. The same holds true for the subject tests of the Graduate Record Examinations administered by ETS [36]. The second possibility is that the sample is highly skewed in some manner, such as a lognormal distribution. For instance, the size of an individual's domain-specific sample might be determined by traits that operate via a multiplicative rather than additive function [169]. For reasons that will become more evident later, the first distribution provides the more conservative assumption.

For the sake of completeness, it should be admitted that some individuals might sample from more than one domain [173]. Often this cross-domain sampling occurs, for instance, when someone switches disciplines, first acquiring expertise in one domain before entering another [81]. However, because such individuals are relatively rare and introduce special (even if very interesting) complications, this possibility will be ignored in the current review article.

3.2. Variable field size

Let N be the number of individuals making up a given field. This number will vary greatly across disciplines. Some fields may involve only a half dozen active individuals, whereas other fields may include hundreds, perhaps thousands of participants. Needless to say, this parameter is not necessarily stable for any discipline. Sometimes it may decrease over time, as a discipline declines and even becomes obsolete (e.g., alchemy). Other times the figure may increase (e.g., string theory in modern physics). Nonetheless, there is often a limit on field growth, especially in the sciences [121]. Once a discipline reaches a maximal size, it often fragments into two or more subdisciplines (e.g., physical and organic chemistry) or even specialties (e.g., purine chemistry). When that fragmentation happens, the fields will similarly split along with corresponding subsets of the original ideational domain. Members of one derived field will no longer view themselves as colleagues of those belonging to the other derived fields, with predictable consequences for peer review and citation behavior. Although it was long held that $N \leqslant 100$ for scientific specialties [121], a more recent estimate puts that figure at somewhere between 250 and 600 scientists [197].

Theoretically at least, it could be possible that $N = 1$. This minimal field size would occur if an individual somehow managed to carve out a new domain that was not shared with any other individuals. Such creator would exemplify a "lone wolf" in which the field is reduced to a single individual and the domain to a unique set of ideas [173]. Even so, because such creators do not have colleagues to validate their original ideas, it may be said that those ideas are not creative until they become validated later after those ideas have become integrated into a regular discipline with a larger field. Such ideas can be called historically premature [189]. If they never become incorporated into a recognized domain, such ideas provide no more than examples of ordinary creativity. Hence, we will normally assume that $N > 1$.

3.3. Ideational combination and disciplinary communication

In line with Campbell's [15] BVSR model, we now posit that individuals subject the ideas in their respective domain samples to some blind combinatorial process. As suggested by Poincaré [118], at any one time the combinatorial process would be normally applied to a subset of the individual sample and most often to those ideas "from which we might reasonably expect the desired solution" (p. 389), albeit additional ideas may be elicited in associations with ideas already in the combinatorial mechanism. Because the procedure is presumed blind, the ideational combinations for any one individual at any one time will differ greatly respect to their originality and utility. That is, the individual lacks the foresight to pick out the best combinations before the worst combinations. Furthermore, it can be safely assumed that the largest proportion will not even be worthy of publication, performance, or presentation, and thus be aborted. Even among those ideas that satisfy the minimal standards necessary for evaluation by the field will vary tremendously in quality. In all likelihood, the most creative ideas will be extremely rare in comparison to less creative ideas even though the latter will be much rarer than those ideational combinations that are left unpublished in notebooks or sketchbooks.

In any case, once a product passes the selection criteria imposed by the field, it becomes communicated to the larger field. As such, the creative ideas contained in that product provide new elements in the disciplinary domain. Accordingly, the new ideas can become part of the domain samples of subsequent creators within that discipline. Nevertheless, the rate at which creative ideas feed back into the domain varies immensely from discipline to discipline. More specifically, this assimilation rate depends on such factors as disciplinary gate-keeping procedures (e.g., editorial policies, peer review), communication practices (e.g., least-publishable units, such as articles versus books), and eventual diffusion to such secondary sources as introductory and advanced texts used in undergraduate and graduate education. Not only will the assimilation rate vary across disciplines, but also across time for any given discipline.

4. Implications

The above specifications provide the basis for several important inferences regarding how exceptional creativity operates with respect to the individual, domain, and field. Although these three systems will be discussed separately below, it will soon become clear that certain phenomena cannot be explicated without considering at least two systems simultaneously.

4.1. Individual system

An individual's creative ideas are communicated to the field in the form of specific products. Not only do individuals vary in the number of products they contribute, but also each individual usually contributes their products over the course of an extended career.

4.1.1. Individual variation

If one examines the lifetime output of all N individuals in a given field, one obtains a cross-sectional distribution that is highly skewed, with a very long upper tail [59,139,141]. As a result, a very small proportion of the creators will be credited with a disproportionate amount of the products. In particular, it is not uncommon for the upper 10% in total output to contribute about 50% of all of the work, whereas colleagues below the median of the distribution will total only about 15% of the field's collective output [32]. This skewed cross-sectional distribution has been replicated so many times that it has been described according to the following pair of laws (using the notation in [173]):

1. The Lotka Law holds that number of individuals producing T products is inversely proportional to T^2, that is, $f(T) = k/T^2$, where k is a constant that depends on the particular field [61,87]. If both sides of this equation are subjected to a logarithmic transformation, we obtain $\log f(T) = \log k - 2 \log T$, which shows that if the distribution were graphed on a log–log plot, we should expect a linear function with a negative slope. This expectation holds very well, at least as a first approximation [121,191].

2. The Price Law characterizes the skewed distribution in a different manner ([121]; cf. [3]). If N is the size of the disciplinary field, then the law predicts that 50% of all the contributions to the domain will produced by an elite consisting of just $N^{1/2}$ individuals. Thus, if $N = 100$, then 10 will have made half of the contributions. A repercussion of the Price Law is that the cross-sectional distribution becomes more skewed as the field size increases. For example, if N increases from 100 to 1000, then the productive elite is predicted to decrease from 10% to 3% (cf. [198]).

Unfortunately, there is no dearth of plausible theoretical explanations for the skewed distribution (e.g., [2,59,139,141,169]). Even so, a reasonable first approximation can be derived directly from a very simple combinatorial model [166]. If the individual domain samples I_i are normally distributed, and if these samples are each subjected to a combinatorial process, then we may consider a new variable m_i that represents the maximum number of combinations that can be generated by individual i. Assuming that this m_i is roughly an exponential function of I_i, then m_i should approximate a lognormal distribution [159,166]. Finally, because the total output of products would be proportional to the total number of combinations (i.e., $T_i \propto m_i$ albeit $T_i \ll m_i$), then the same distribution would hold for contributions. Of course, if we are willing to assume that I_i itself has a highly skewed distribution even prior to the implementation of the combinatorial procedure, then the result would become even more skewed. Yet the assumption that I_i is normally distributed offers a more parsimonious explanation.

Although the above implication is not particularly distinctive relative to the many alternative accounts, another inference has a better claim to predictive uniqueness. We have assumed that the ideational combinations show considerable variation in both originality and utility. As a consequence, the resulting products that contain these combinations will also vary appreciably in creativity and thus disciplinary impact. In the sciences, to illustrate, almost half of all published articles are never cited in subsequent publications [125]. If self citations are omitted, this percentage increases even more, and an appreciably smaller minority would constitute high-impact articles.

To simplify discussion, let us separate out from an individual's total output T_i that subset of works that actually has an influence on the field, and identify this number H_i as the creator's lifetime count of "hits" (whether artistic masterworks or scientific breakthroughs). Because both H_i and T_i are ratio scaled variables with bona fide zero minima, we can then propose that $H_i = \rho_c T_i$, where ρ_c is the cross-sectional "hit rate" for members of a given field. This linear equation has been called the "equal-odds baseline" [182]. This baseline is consistent with the empirical research showing that the number of high-impact contributions is a positive function of the total number of contributions [30,116,117,153,195]. In short, quality is a linear function of quantity.

Nevertheless, this association between H_i and T_i is statistical rather than deterministic, meaning that individual cases will scatter around the baseline [23,38]. Given a particular total output, some individuals who have fewer hits than expected whereas others will have more hits than expected. This error variance can be formally recognized by altering the linear function to $H_i = \rho_c T_i + u_i$, where the new term is a random variable that has a roughly lognormal distribution, and where $0 \leqslant u_i \leqslant T_i(1 - \rho_c)$ so that $H_i \leqslant T_i$ still holds. If u_i is close to zero, the individual will have a very low proportion of hits relative to total output (e.g., "mass producers"), but if u_i is very large, then individual i will have a high proportion of hits relative to total output (e.g., "perfectionists"). It is conceivable that the actual size of this disturbance term depends on whether a particular individual obtained an optimal or suboptimal sample from the domain set of ideas. Some creators may have an unlucky draw, having a set of ideas that generate few if any "good combinations".

It must be emphasized that $H_i = \rho_c T_i + u_i$ is most likely to be valid when two conditions are met. First, the individual domain samples $I_i < I_D$ are randomly chosen from the domain. Second, the ideas composing each individual sample are subjected to truly blind variations. Therefore, if the quality–quantity relation in a particular discipline departs from the relationship predicted by the combinatorial model, it would suggest some departure from one or both of these assumptions.

4.1.2. Longitudinal change

Total lifetime productivity is seldom concentrated in a single year but rather is distributed over virtually the entire course of the career. This fact raises the question of how output quality and quantity – both H_i and T_i – are distributed across the career. The issue is most easily answered with respect to total lifetime output. Recent investigations have established two empirical facts for all creators making at least one contribution to their chosen field [57,58,60–63]. First, annual productivity seems to be randomly distributed over the career: There do not appear any conspicuous "runs" at the beginning, middle, or end of the interval. Second, the annual distribution of output is best predicted using the highly skewed Poisson distribution. To be more precise, the probability of making j contributions in a certain year is given by $P(j) = \mu^j e^{-\mu}/j!$, where μ is the mean and variance of the distribution.

Both outcomes are what would be expected given the basic combinatorial model outlined earlier [173]. If each individual generates ideational combinations according to a blind combinatorial process, and if the combinations so generated vary immensely in originality and utility, then creative ideas should be more or less randomly spread across the career. The difficulty of producing a creative idea in year t is only magnified by the need for the idea to be sufficiently original and useful to meet the minimum standards for presentation to one's colleagues. Moreover, given that the production of a single publishable idea represents a rare achievement for any given year, conceiving two in the same year should be rarer still, and arriving at three in a given year must be even more improbable. For this reason, the modal output in a single year should be 0, the next most 1, the third most 2, and so on. This distribution is best approximated by the Poisson, the distribution typical of rare events. The events have such low probabilities that they can only occur because there are so many ideational trials. "The greatest practical inventions [are] so much dependent upon chance", said Bain [7], that "the only hope of success is to multiply the chances by multiplying the experiments" (p. 597).

The same two expectations should apply not just to quantity of output but also to quality of output. Because highly creative ideas are a subset of all publishable ideas, and because the ideas generated by the combinatorial process should be rather uneven in originality and utility, we can propose another equal-odds baseline for the generation of "hits" for the ith individual in his or her career year t: $H_{it} = \rho_l T_{it}$. Here ρ_l is the longitudinal hit rate, that is, the proportion of hits relative to total annual attempts and T_{it} is the total count of contributions in year t. As previously, the actual number of hits per attempts will fluctuate around this baseline, necessitating the addition of a stochastic term. The corrected equation then becomes $H_{it} = \rho_l T_{it} + u_{it}$, where once more $0 \leqslant u_{it} \leqslant T_{it}(1 - \rho_l)$ so that $H_{it} \leqslant T_{it}$. This theoretical explanation is supported by several empirical studies (e.g., [24,106–108,145,153,166]; but see [79]). Finally, when this expectation is combined with the annual distribution of total products, we can infer that (a) high-impact contributions will be randomly distributed across consecutive years of the career and (b) the annual output of those high-impact contributions will also be Poisson distributed (but with a much smaller μ).

It cannot be stressed too much that the above expectations function only on average, across a large number of individuals representing a disciplinary field. Any singular realization may depart from those expectations (see, e.g., [54]). This possibility is analogous to what happens when someone conducts multiple experiments where an unbiased coin is flipped a dozen times. Although the probability of getting heads is unchanged in consecutive tosses, in any given experiment the heads might be concentrated in the first half or the second half of the series. But in the aggregate, across many different careers, these departures would average out to produce the longitudinal version of the equal-odds baseline.

Even more important is the fact that sometimes certain basic assumptions are violated so that the expectations are undermined even at the individual level. Consider the following two examples:

First, the conclusions drawn in this section assume that the creativity cycle is not contaminated by other processes that override the combinational model. For example, the longitudinal baseline $H_{it} = \rho_l T_{it} + u_{it}$ assumes that the random shock term u_{it} is stable across time. Yet it could very well happen that under certain conditions the expected value of u_{it} might tend to increase or decrease over time. Such a secular trend would contradict the equal-odds baseline. To illustrate, the magnitude of this shock might be a function of some cumulative advantage process whereby the "rich get richer and the poor get poorer" [97]. In this case, the expected value of u_{it} might be a positive even if probabilistic function of H_{it-1} (i.e., the number of hits in the previous career period).

Second, the inferred implications assume that there is no fundamental change in the unit of publication over the course of a career. If the unit changes so that it can encompass a larger number of creative ideas, then this can alter expectations regarding longitudinal trajectory. For instance, a composer might gradually advance from smaller forms, such as songs and piano pieces, to larger forms, such as symphonies and operas. Because the latter contain more total creative ideas, they have a higher likelihood of having enhanced impact [149]. This career-wise transformation may explain why the best evidence for the baseline $H_{it} = \rho_l T_{it} + u_{it}$ comes from scientists who tend to depend on the same publication unit throughout their careers, namely the article in a professional journal [173]. Even the book chapter in an edited volume may differ relatively little from an article, at least not if the increased word count in chapters is offset by a decrease in the creativity of the ideas presented in chapters.

Taken together, the longitudinal version of the equal-odds rule is probably more tenuous than the cross-sectional version. Any discrepancies imply that processes are operating other than the pure BVSR presumed to underlie creative thought per se. These extra processes may be either psychological or sociological.

4.1.3. Individual-longitudinal integration

We will now introduce a more complex combinatorial model, one that deals with both individual-differences and cross-discipline contrasts in creative careers. This integrative model begins by imposing a qualification on the earlier conclusions that output is randomly distributed across the individual's career. That random distribution is only valid when we investigate annual output at the individual level for all N persons making up the field. Because the modal number of contributions by the ith person is just unity [32], and the mean number of contributions per creator may only be a very small integer multiple of that figure (e.g., between 3 and 4 [197]), the picture tends to be dominated by the majority who contribute little rather than the minority who contribute a great deal. Additionally, because the time-series units were single years, the reliability of the longitudinal assessment is considerably reduced in comparison to using longer units, such as decades or half decades [1]. In the latter case, the diverse idiosyncrasies of publication or presentation lags across vehicles or venues can average out. Hence, a very different picture may emerge if we impose two types of data aggregation simultaneously [173]. In the first place, the data can be aggregated across individuals who exhibit extreme variation in lifetime output, from one-idea creators to the most prolific creators in the field. Second, the output counts across the career can be aggregated into larger time-series units, such as consecutive 5- or 10-year intervals (e.g., [33,85]).

This doubled time-wise and cross-sectional aggregation provides a very different view of the longitudinal changes in creative output: Creative productivity then becomes a curvilinear, single-peaked function of age [157,166]. More specifically, output rises rapidly to a career maximum and then slowly declines, attaining the zero output rate asymptotically. Both the specific location of the peak as well as the slope of the post-peak decline are contingent on the discipline [33,85,161]. In disciplines such as mathematics and poetry, the peak comes early in the career and the decline is relatively steep, whereas in disciplines such as philosophy and history, the peak appears much later and the post-peak decrement is far more gradual.

These aggregate results can be explained by introducing a somewhat more elaborate model of what holds at the individual level [166]. The model starts with the earlier assumption that each individual begins with a domain-specific sample, or I_i. The latter again determines m_i, the maximum number of ideational combinations that can be theoretically generated in an unlimited lifespan. This individual-difference parameter can be termed the person's *creative potential*. However, because the individual begins the career with I_i rather than with m_i, the former must be converted into the latter via the *ideation* process that produces the raw combinations. That constitutes only the first step. In the second step, the combinations generated in the first step are subjected to an *elaboration* process to convert and package the ideas thus obtained into a form suitable for performance, publication, or presentation to the field. Given this two-step process, we can then derive an equation that predicts output per time unit as a function of *career age*, that is, the number of years that have elapsed since the individual began subjecting his or her domain sample to the presumed combinatorial process. That equation normally assumes the form of

$$C_{it} = abm_i(b-a)^{-1}\left(e^{-at} - e^{-bt}\right), \tag{1}$$

where C_{it} is output of individual i at career age t, a is the typical ideation rate for the domain ($0 < a < 1$), and b is the typical elaboration rate for the domain ($0 < b < 1$; but when $a = b$, then $C_{it} = a^2 m_i t e^{-at}$). The total number of contributions that individual i makes at time t, T_{it}, is assumed to be directly proportional to C_{it}, where the proportionality constant depends on the "least-publishable unit" typical of the discipline in which the creator is active. If T_{it} is summed across all years that delineate a creator's career, we get T_i, the person's total lifetime output of contributions.

When fitting the prediction to the aggregated data, so that individual differences can be ignored, Eq. (1) can be simplified to

$$T_t = c\left(e^{-at} - e^{-bt}\right), \tag{2}$$

where c is a constant (that incorporates a, b, m_i, and the discipline-specific proportionality constant indicating that $T_t \propto C_t$). The curve generated by this equation normally correlates in the upper .90s with aggregate tabulations drawn from a diversity of data sets [151,166]. Just as importantly, by adjusting the ideation and elaboration rates (i.e., a and b), the combinatorial model can accommodates cross-disciplinary contrasts in the career trajectories [160]. For example, the parameters for chemists are .042 and .057 whereas those for geologists are .024 and .036, indicating that ideation and elaboration takes place much faster in the former discipline. Likewise, the parameters for poetry are .045 and .055 whereas those for novel writing are .034 and .040. Differences in these two parameters have substantial consequences in the location of the career peak as well as the size of the post-peak decline. To illustrate, mathematicians peak at career age 26.5 whereas geologists do so 8.3 years later (cf. [161]); similarly, poets peak at career age 20.1 whereas novelists do so 14.7 years later (cf. [178]). These age gaps are by no means trivial in magnitude.

If attention is confined to a specific discipline, then Eq. (2) can be used to characterize contrary career trajectories for members of the same field. Because the ideation and elaboration rates (plus the proportionality constant) are identical for all individuals working with ideas from the same domain, the constant c entirely represents individual differences in creative potential (i.e., $c \propto m_i$). Hence, it is possible to distinguish between individuals with high creative potential (large-c) and those with low creative potential (small-c). Given that the constant c in Eq. (2) patently determines the amplitude of the function, then the former group will display the higher rate of output throughout the career course [161,166]. Eq. (2) then yields two empirical predictions, both of which have been confirmed [124,161,162,166,176]. First, the career peak, as determined by ideation and elaboration rates, will appear at the same career age regardless of individual differences in creative potential. The same must generally hold for the creator's single best contribution to the domain (see also [196]). Second, individual differences in output in consecutive career intervals, when correlated across all career periods, should exhibit a pattern of correlations more consistent with a single-factor model (where the single latent variable is creative potential) than with a cumulative-advantage or autoregressive model (e.g., a simplex or quasi-simplex matrix). No alternative model of creative productivity makes these two empirically confirmed predictions.

At the same time, it is useful to recognize another individual-difference parameter that is implicit in Eq. (2): age at career onset [161,166]. Because output is defined in terms of career age, individuals can be differentiated into two types, namely, early bloomers who are relatively young at the start of their career and late bloomers who are relatively old at their career onset (e.g., chronological ages $\leqslant 25$ versus $\geqslant 30$, respectively). The former group will have their career peak shifted to an earlier chronological age while the later group will have their peak shifted to a later chronological age. Considering that age at career onset is demonstrably orthogonal to creative potential, the two individual-difference variables can be combined to generate a fourfold typology of career trajectories: high-creative early bloomers, low-creative early bloomers, high-creative late bloomers, and low-creative late bloomers [161,166].

Admittedly, these four types represent the extreme points in a two-dimensional space, with most individuals situated near the middle of that space, but the differentiation permits a set of distinctive predictions, particularly with respect to the location of an individual's career landmarks [161]. These landmarks are the age at first hit, the age at best hit, and the age at last hit (cf. [124,199]). For instance, the model predicts that the correlation between the first age and the last age after holding the middle age constant will become negative [166]. So far, this and other unique predictions have been confirmed in empirical research on both scientific and artistic creativity [161,162,164,176].

4.2. Domain system

The domain is not a static entity. Creative individuals use their respective domain samples to generate new creative ideas that, if approved and recognized by the field, serve to update the domain by changing the set of ideas that define the domain. Although some ideas may then become obsolete, and thus vanish from the domain, it is likely that the number of ideas tends to increase rather than decrease. Because of this net gain, domains may reach the size where they can no longer support a coherent discipline. As mentioned earlier, the discipline then splits into subdisciplines or specialties. Yet before that disciplinary divergence takes place, the domain will often experience an "information explosion", expanding at an exponential rate [41,84,121,123,148]. This explosion emerges not just from the increase in I_D but also from a corresponding increase in N, the size of the field (e.g., [142,158,163]). That is, the interaction of the domain and field together accelerate growth in the domain.

This acceleration has been explicated in terms of an unambiguously combinatorial model [41]. The model begins with the assumption that "the rate of growth in the number of ideas is proportional jointly to the number of ideas in hand and the number of minds to consider them" [41, p. 18]. Using imagery reminiscent of Poincaré's introspective report [118], the model assumes that discovery requires a "random creative collision process" in which ideas are "the result of a 'collision' between minds and ideas" (p. 15). This process can be described by the differential equation $\mathrm{d}I_D/\mathrm{d}t = \gamma I_D N$, where γ is a constant that is presumably contingent on the discipline. Stated qualitatively, the rate at which new ideas are added to the domain is directly proportional to the product of the size of the domain and the size of the field. This model provides an excellent fit to the rate that new ideas have been accumulating in the domain of physics [41]. There would be little reason to deny that the same model would probably apply equally well to any domain that involves field expansion in combination with the accumulation of knowledge and technique.

This intensification may bear some relation to the Price Law [173]. As noted earlier, as N increases, the proportion of the field that accounts for half of the total contributions decreases. The growth of the productive elite may be partly responsible for the accelerated growth rate the domain size I_D. That enhancement may occur because the most prolific creators have a larger supply of colleagues with whom to exchange ideas. There is some indirect evidence that this synergistic relation operates in both the arts and the sciences [150,165]. Rather than being social isolates, highly creative individuals are usually enmeshed in a rich network of discipline-specific collaborators, associates, correspondents, competitors, and friends. Consequently, the greatest creative geniuses in any given domain tend to appear in the same generations as less well-known figures in the field [142,158]. The luminaries and also-rans together comprise the discipline's Golden Age, such as Italian Renaissance Art or the Scientific Revolution.

4.3. Field system

It was suggested earlier that disciplines differ substantially regarding the field's consensus regarding the composition of the domain. In fact, empirical research indicates that major disciplines can be placed in the following order: physics, chemistry, biology, psychology, sociology, the humanities, and the arts [183]. Expressed in Kuhnian terms [81], the natural sciences are more paradigmatic than the social sciences, which in their turn are more paradigmatic than the humanities and the arts. One special ramification of these differences is that the individual domain samples I_i in highly paradigmatic disciplines will be far more homogeneous across the N members of the field (i.e., $I_i \approx I_D$

for all i). Accordingly, creative individuals in high-consensus disciplines will be applying the hypothesized combinatorial procedure to largely the same set of domain-specific ideas. This ideational overlap then produces a distinctive event in the sciences that has no exact counterpart in other disciplines: the phenomenon of multiples [82]. Multiples take place when two or more scientists come up with the same creative idea in complete independence of each other [99]. Because verified cases of these multiples run into the hundreds [156], the event is traditionally adopted as strong evidence on behalf of sociocultural determinism [99]. At a specific instant in history, a particular discovery becomes inevitable, as if the idea was some ripe fruit ready for the picking. Although this interpretation may appear plausible on first blush, additional scrutiny reveals that the multiples phenomenon can be explicated better using combinatorial models of scientific creativity [172]. In particular, combinatorial models can explain the empirical findings with respect to the distribution of multiple grades, the temporal separation of multiple discoveries, the degree of multiple congruence, and individual differences respecting the participation in multiples.

4.3.1. Multiple grades

Multiples vary greatly in the number of scientists independently making the same contribution. This variable has been named the multiple's *grade* [99]. Hence, the invention of calculus was a grade 2 multiple (doublet), the law of conservation of energy a grade 3 multiple (triplet), the periodic law of the elements a grade 4 multiple (quadruplet), and so forth. If the sociocultural determinists are correct, and discoveries are inevitable, then high-grade multiples should have higher frequencies than low-grade multiples; moreover, multiples in general should have higher frequencies than "singletons" (i.e., those discoveries that have only a single creator [99]). Yet empirical data reveal the opposite frequency distribution: The higher the multiple grade, the fewer the number of substantiated instances, and singletons outnumber multiples by a very large margin. In fact, the frequency distribution looks very similar to the distribution of annual productivity within individual careers. Empirical tests show that the frequencies are indeed governed by the same Poisson distribution, with $\mu \approx 1$, as in the case of individual annual output [146,147]. This outcome is precisely what can be predicted by a combinatorial model [173]. Given a field consisting of scientists subjecting relatively homogeneous domain samples to blind combinations, then the likelihood is very high that at least two individuals will happen upon similar if not identical ideational combinations. That said, singletons still would have a higher probability than multiples, and low-grade multiples would have a higher probability than high-grade multiples.

Because there is nothing deterministic about this explanation, the main role of disciplinary zeitgeist is merely to provide the ideas that define the original domain from which scientists drew their individual samples. In other words, the domain provides the necessary but not sufficient conditions for discoveries within the domain, whereas the combinatorial process taking place at the individual level produces the actual discoveries. Because the combinatorial process is presumed blind, it is even conceivable that none of the individuals making up the field manage to generate a potential discovery. The result is then a "nullton", an idea somehow overlooked by the scientific community [146]. Although it might seem that these events are only hypothetical, they in effect occur whenever someone makes a discovery that could have just as well been made decades earlier because all of the ideational components were already in place long before (e.g., paper chromatography and the heliocentric model of planetary motion). If the civilization associated with our planet ever encounters an alien civilization on another planet, genuine nulltons might become even more conspicuous, particularly if one civilization is far more advanced than the other.

4.3.2. Temporal separation

Whereas some multiples may be separated by decades or even centuries, other multiples can be practically simultaneous [99]. Although sociocultural determinists infer that simultaneity proves discovery inevitability, this inference proves invalid. A combinatorial model can be readily constructed that incorporates a negative contagion process that recognizes that a finite amount of time is required for a new idea to enter the domain [13,155]. Once a discovery becomes part of future domain samples, then it can no longer add new claimants. Given this conception, the distribution of temporal separation closely approximates that observed for multiple grades: fewer years correspond to fewer duplicates. Most independent discoveries will take place within a single year, next most frequently within two years, and so on, in a negative monotonic function. Multiples that require a decade or more to appear will be extremely infrequent. The latter events imply inefficiencies in the communication of scientific discoveries (i.e., a slow individual-field-domain creativity cycle).

Because the diffusion of scientific knowledge has become more effective over historical time, the combinatorial model predicts that recent multiples should exhibit even greater simultaneity. Similarly, those scientific disciplines with more efficient modes of information dissemination will also feature more simultaneous multiples. Both of these predictions have been confirmed in empirical research [14]. In the former case, as an example, the average time interval between duplicates declined from around 86 years in the 16th century to a little more than 2 years in the 20th century. Furthermore, if multiples must emerge during more restricted time intervals, the opportunity for high-grade multiples is also reduced, an expectation that is also confirmed [14]. With the advent of modern electronic communication, multiples beyond grade 2 have become rather unusual and have to appear within a year or two if they are to appear at all.

4.3.3. Multiple congruence

In making up their lists of multiples, sociocultural determinists will often overlook the fact that the separate contributions claimed to represent a single multiple are usually far from identical [25,110,137]. In fact, when the ideas first appeared they might not have been even viewed as the same discovery. But much later historians will assign some generic category to encompass what might be better considered to represent distinct ideas. A combinatorial model provides a way to interpret the degree of multiple congruence [173]. Because scientists subject their individual domain samples to blind combinatorial processes, the odds are small that two creators will arrive at identical combinations. Rather, the combination will converge on some ideas and diverge regarding other ideas. This explanation then predicts that the magnitude of congruence should exhibit a telltale distribution, namely a distribution echoing that seen for grades and temporal separation. Most discoveries will be singletons sharing virtually no novel ideational content with other discoveries. The next most common frequency would be multiples that have just one major domain-specific novelty in common. The greater the degree of ideational convergence the rarer would be the multiple. Disputes over patent infractions imply that this expectation has empirical validity [137]. Most disputes are based on a small number of overlapping claims. Truly identical multiples virtually never happen.

4.3.4. Individual differences

It is a significant fact that multiples are not randomly distributed across individual scientists. Instead, some scientists tend to be involved in more multiples than do other scientists. This cross-sectional variation can be explained using a combinatorial model [173]. There are two central explanatory variables.

First, disciplinary domains exhibit variation in N, the size of their respective fields. At one extreme, a field may consist of numerous investigators all generating ideational combinations from highly overlapping samples (e.g., the “hot” topics), whereas a domain at the other extreme may have only two or three investigators using samples drawn from the same domain (e.g., new areas of research). Just by chance, those working in popular areas with numerous colleagues will produce more multiples than those working in unpopular areas with few colleagues. Of course, a lone wolf exploring new territory would be the least likely to particulate in multiples.

Second, because individuals vary in their domain-specific samples, they also vary in the total number of ideational combinations that they can conceive during their careers. In addition, the larger a scientist’s individual sample, the more that sample would have to overlap with the samples drawn by others in the same field. It immediately follows that scientists who create more combinations are more prone to generate combinations containing ideas that coincide with the combinations of colleagues active in the same domain. These statements lead to the following prediction: The most prolific scientists will tend, on the average, to participate in more multiple discoveries. In contrast, one-idea scientists would have the lowest probability of involvement in multiples (see also [98]). To do so would require really bad luck.

Although more research could certainly be conducted on this subject, both of the above expectations have received tentative empirical support [52,147].

5. Substantiations

It should be noted that this review has so far studiously avoided any references to the combinatorial process being random or stochastic. Rather, the generated combinations were merely said to be blind. This is because the latter adjective constitutes the more inclusive qualifying term. Campbell [15] was emphatic that blind variations need not be restricted to random variations. He gave the simple example of radar sweeps: The radar’s scan of the horizon is blind but also completely deterministic. This example may be considered a minimal case of a *systematic* combinatorial process, that is, the radar systematically searches all possible polar coordinates to the horizon. Nevertheless, the radar scan could have been designed to operate according to a *stochastic* combinatorial process, blindly drawing all directional angles out of an urn (without replacement until exhaustion). Theoretically, the search effectiveness would be indistinguishable for the two alternative mechanisms; the two search strategies would have precisely the same likelihood of spotting a distant object approaching from an unforeseen direction. So it is the blindness of the variations that is most critical, not whether the combinatorial procedure is systematic or stochastic.

The above conclusion can be illustrated using two alternative approaches to computer simulations of creativity or discovery. On the one hand are the evolutionary algorithms that emulate the BVSR process in organic evolution by introducing computerized analogs of genetic recombination and mutation [45,56]. In these programs, the combinatorial processes are strictly random. On the other hand are the discovery programs that implement some form of systematic heuristic search through a defined problem space [12,83,140]. These latter programs do not rely on any random input but rather function through a series of if–then propositions that produce a predictable set of generate-and-test operations. Despite the contrast between these two types of programs, both independently discovered Kepler's Third Law of planetary motion, namely, $P^2 \propto D^3$, where P is planet's period of rotation around the sun and D is the planet's maximum distance from the sun. The evolutionary algorithm (genetic programming [76]) did so using a stochastic combinatorial search, whereas the discovery program (BACON [83]) accomplished the same feat using a systematic combinatorial search. Because the former search relied on necessarily blind randomness, whereas the latter search was systematic but blind, both can count as BVSR procedures, the striking contrast in implementation notwithstanding [168].

Although methodical (but blind) combinatorial processes are theoretically equivalent to random (and perforce blind) combinatorial processes, in practice computer programs that simulate creativity are far more likely to operate according to the second mechanism. After scrutinizing the procedures of several highly creative programs, one reviewer affirmed, "what is useful for creativity in minds and evolution is useful for creative computers too. A convincing computer model of creativity would need some capacity for making random associations and/or transformations", a requirement that would often be met "by reference to lists of random numbers" [11, p. 226]. Indeed, although the discovery programs mentioned earlier have managed to make rediscoveries, only the evolutionary algorithms have consistently demonstrated the capacity to offer original solutions to problems (e.g., [56,77,78]). Perhaps this differential performance should come as no surprise. Systematic combinatorial procedures require an *a priori* specification of the possibilities, and that specification may inadvertently exclude viable options. In contrast, stochastic combinatorial procedures, because they often lack explicit boundaries, may more likely enable the computer to "think outside the box." To be sure, the latter mechanisms cannot completely open up the floodgates to all possibilities, for then a "combinatorial explosion" would effectively shutdown the process [37]. That is why it was earlier assumed that each creator at any one time only subjects a subset of I_i to the combinatorial procedure. Yet, the evolutionary computer programs are often so designed that the horizon of the combinatorial search can be blindly but tentatively expanded via analogues of mutation.

Thus, the optimal interpretation may be to infer that creativity requires some variety of constrained stochastic process [172]. Creative thought imposes sufficient constraints that it avoids unbridled and unwieldy randomness, but is not so structured that it violates the essential requirement of blind variation, as defined earlier in this review (see also [105]). This in mind, below I will briefly examine the cognitive processes, personality traits, developmental factors, and social contexts that might sustain this delicate balance.

5.1. Cognitive processes

It is critical to recognize that there is no such thing as a single "creative process" [184]. Rather, a large number of distinguishable processes have been identified that have proven instrumental in creative problem solving. Any one problem may be solved by using a subset of the available processes, and more than one subset will often lead to a solution. This process multiplicity itself lends support to a blind variation model. Unless it can be demonstrated that the specific process subset was predetermined precisely because it was known in advance that particular subset would have the best chance of producing a solution, it seems safe to infer that the choice was blind to the likelihood that those particular processes would produce a solution. Apart from this implication, many of the processes that might enter into the specific set would be expected to have a considerable blind component.

This last point can be illustrated using the Newell–Simon problem-solving tradition in cognitive psychology [104]. Although algorithmic (strong) methods provide dependable solutions to routine problems, exceptional creativity must rely on (weak) heuristic methods in which a solution is no longer guaranteed [72,73]. The heuristics include hill climbing (steepest ascent), working backwards, means-end analysis, analogy, and trial-and-error. The last heuristic explicitly entails blind ideational variations; if otherwise, there would be no errors, just a single successful trial. When trials are sighted, the first trial must have the highest probability of both generation and successful test (i.e., the highest *a priori* fitness). Nonetheless, the other heuristics are most frequently blind in operation as well. For example, although the analogy heuristic frequently proves useful in creative problem solving, the creator must often engage in some trial-and-error before finding an optimal analogy and identifying the best correspondences between the analog and the target (cf. [44]). Likewise, although hill climbing appears straightforward in application, solving problems via this heuristic often must confront the problem of "local maxima", and the only maneuver around that obstacle is to implement a blind search for the genuine "global maximum" in the "fitness landscape" (cf. [113]). Furthermore, problems requiring exceptional creativity are often poorly defined with respect to goals and means, a conceptual ambiguity that often makes it difficult to decide on the optimal heuristic approach. As a consequence, the creator must often activate what has been labeled as the trial-and-error meta-heuristic [173]. That is, the solution depends on the capacity to generate and test two or more heuristics.

The heuristic searches just described rely on conscious and deliberate information processing. Yet creativity probably has an even stronger reliance on unconscious and undirected processes as well [184]. This dependence is especially conspicuous during the incubation phase of problem solving when the creator has given up working on the problem and has instead turned to other tasks, including the business of everyday life [11]. During this phase, the preparatory work on the problem will continue in the form of spreading activation, an associative process that can pursue two or more pathways, one of which may eventually produce the solution (see, e.g., [90]). The blindness of this implicit search is reinforced by two additional cognitive realities.

First, the associations to any given initial stimulus can adopt many forms, including remote associations [95], rare associations [47], divergent thinking [50], primordial cognition [92], Janusian associations [131], allusive or overinclusive thought [37], and even clang associations [51]. Hence, the elicited associative chains can pursue two or more distinct directions.

Second, during the incubation phase the creator frequently lapses into defocused attention [6,37,96], as indicated by reduced latent inhibition and negative priming [19,144]. Such extraneous stimulation can deflect the spreading activation into new associative directions, one of which may yield the insight necessary for solution (cf. [138]). The blindness of this superfluous sensory influx becomes even more conspicuous when the stimuli come from mundane activities, such as taking a bath in the case of Archimedes' famous Eureka experience.

Interestingly, even though blind ideational variations do not have to be random, it is telling that creativity tends to be enhanced when a person is exposed to irregular, novel, or incongruous stimuli [40,122,130,186,193]. Such haphazard sensory priming redirects associations toward solutions that might otherwise be overlooked. In a sense, each stimulus and its corresponding associative sequence represents a single ideational variant. Because these largely unconscious variants are blind regarding the outcome, most will go nowhere. It is partly for this reason that incubation periods often have to last so long, especially for highly creative solutions to difficult problems. The larger the hiatus between problem and solution, the more the creator must be exposed to stimuli that have no obvious connection to the goal.

To anticipate later points, the creative processes participating in scientific creativity are not identical to those involved in artistic creativity [168]. Scientists most often rely on conscious, objective, and deliberate processes whereas artists more often depend on unconscious, subjective, and involuntary processes. Even so, this difference is quantitative rather than qualitative, the less paradigmatic sciences being more similar to the arts and the more formal arts more similar to the sciences [183].

5.2. *Personality traits*

Most of the associative and attentional processes mentioned in the previous section are linked to individual-difference variables. In other words, certain persons are more likely to engage in these processes than others are, and this individual variation corresponds to differences in the likelihood of exceptional creativity. For instance, both enhanced divergent thinking and reduced latent inhibition are positively related to openness to experience [93,114,115]. Not surprisingly, scores on openness are also positively associated with both assessed creativity and creative achievement [20,53,114]. Because openness is connected with having wide interests and diverse hobbies (see also [48]), these correlations imply that creative individuals are more prone during the incubation period to expose themselves to a more heterogeneous range of environmental stimuli, and thereby increase the odds that the associative process will eventually be primed toward a more fruitful direction. To provide a concrete illustration, high-impact scientists are not only likely to have artistic avocations as adults [129], but the higher the scientific impact, the larger the probability of such adulthood avocations [128].

The above findings raise an interesting paradox that provides indirect support for the argument that creativity is contingent on blind variation. It is difficult to see how broad interests and hobbies might contribute to adulthood creativity if the latter depended solely on sightedness. It would seem that a creative individual would be far better served acquiring increased domain-specific expertise. Given the fact that each individual only has so much time to devote to various activities during the day, such avocations would appear as distractions rather than occasions beneficial to creative achievement. Yet the contrary holds, implying that exceptional creativity requires the intermittant infusion of seemingly irrelevant stimulation that can provide the basis for blind variations, particularly during the incubation phase of creative thought.

Even more paradoxical is the positive relation between creativity and psychopathology [120]. This is not to say that creative genius must be mad, but rather that exceptional creators share certain dispositional attributes with individuals suffering psychopathological symptoms [100,134]. For example, the reduced capacity to filter out extraneous stimuli is associated with both creativity and psychopathology [37]. It is partly for this reason that creative individuals tend to score higher than the norm with respect to psychoticism and schizotypy [46,100,112,133]. The creative and psychopathological individuals also show a distinct tendency to share a common genetic basis. It has long been known that both creativity and psychopathology tend to concentrate in the same family lineages [4,67,94,126], but more recently research has begun to tease out the shared genetic bases [70]. Naturally, research has also isolated other variables that can prevent any proclivities toward psychopathology from resulting in that cognitive disability. Examples include higher intelligence, ego-strength and self-sufficiency [8,19,22]. So long as the individual maintains enough meta-cognitive control, a moderate cognitive proclivity toward psychopathology makes a positive contribution toward the capacity for generating blind variations.

The last assertion must be qualified by an observation made much earlier in this review: Disciplines vary greatly in the degree to which they are paradigmatic (i.e., exhibit a high field consensus and domain precision). The more paradigmatic the discipline, the lower would be its dependence on blind variation [181]. That is, a larger proportion of the ideational content of any publication, performance, or presentation will be dictated by domain-specific expertise. Accordingly, creators in the arts should display higher rates of psychopathological symptoms than would creators in the sciences, an expectation that has been confirmed empirically [39,88,103,119]. The "mad genius" is far less likely to appear in the sciences than in the arts, with poets having an especially high susceptibility to mental illness [65,68,69,185]. Nevertheless, the same principle that distinguishes artistic disciplines from scientific disciplines can also make differentiations within disciplines [89,183]. A particularly interesting case is what happens to paradigmatic sciences when they undergo a scientific revolution: Although eminent scientists who work within a given paradigm display low proclivities toward psychopathology, scientific revolutionaries who strive to overthrow the old paradigm exhibit higher tendencies toward psychopathology [74]. Presumably, the latter are also more dependent on the need to generate blind thought trials. Many paths can lead away from a rejected paradigm, but only one of these may yield a valid paradigmatic replacement.

5.3. Developmental factors

Because almost all personality traits associated with exceptional creativity have reasonably large heritability coefficients [180], this capacity has some genetic basis, albeit the specific developmental operation of genetic inheritance can become quite complex [169]. Nonetheless, environmental influences cannot be overlooked: Creative ability is a function of both nature and nurture. Of special interest are those developmental influences that might be expected to enhance a creator's capacity for blind ideational variations. For example, Campbell [15] maintained that "persons who have been uprooted from traditional cultures, or who have been thoroughly exposed to two or more cultures, seem to have the advantage in the range of hypotheses they are apt to consider, and through this means, in the frequency of creative innovation" (p. 391). His conjecture has empirical support (e.g., [86]), as does the closely related proposition that creative potential has a positive association with bilingualism [179]. Because languages are never isomorphic in lexicon and syntax, persons fluent in two or more languages will tend to have ideas cognitively coded in multiple ways and thereby increase the associative richness – such as remote and rare associations – that they can bring to bear upon problem solving.

In more general terms, creative development is enhanced by childhood and adolescent exposure to unconventional, heterogeneous, and enriching experiences both at home and in school [173]. Such experiential input facilitates the growth of both the personality traits and cognitive processes that contribute to creative problem solving. Even so, once again we need to distinguish disciplines according the degree to which they rely on BVSR [181]. As an illustration, adolescents who display scientific talent are more disposed to grow up in stable homes where their parents pursued commonplace hobbies and interests, whereas artistically talented adolescents are more prone to develop in bohemian homes that exhibited substantial diversity regarding geographic origins (e.g., foreign born), economic mobility, and extensive travels both domestic and foreign [136]. A parallel pattern holds for education and training: Whereas scientific creators tend to be excellent students who attain high levels of formal education, artistic creators tend to be more mediocre students who fail to advance very far in higher education (e.g., [124,143,152,154]).

These art-versus-scientist developmental contrasts are seen even at the level of Nobel laureates [9]. Recipients in the sciences, when compared to recipients in literature, are far more likely to have had fathers who were academic professionals. In contrast, the literary laureates are far more likely to have lost one or both parents through death or desertion, or to have experienced the family's impoverishment or bankruptcy. Of all Nobel laureates, the physicists, who create in the most paradigmatic science, have the highest likelihood of growing up in stable and conventional home environments (see also [127]).

5.4. *Social contexts*

Although the systems perspective obliges that creativity be examined in the context of the field and domain, creativity often occurs in social settings that go beyond such purely disciplinary concerns. In some disciplines, in particular, creativity may emerge from collaborative groups rather than just individuals [111,135]. This collaboration is most conspicuous in scientific disciplines where much of the creative ideas come out of large research laboratories [35]. Yet creative collaborations can also take place in certain artistic disciplines, such as architecture, video games, cinema, theatre, and dance [135,174,194]. A critical question in such situations is how to assemble a collaborative group to make it maximally creative. One obvious inference is that the group members should not have identical individual samples from the domain, but rather each should bring some unique portion so that the whole group enjoys a larger domain-specific sample than any given member.

This last assertion has been confirmed in studies of scientific collaborations. Thus, as one investigator concluded from a study of productive research laboratories in the biomedical sciences, "members of a research group should have different but overlapping research backgrounds" [35, p. 391]. Another empirical study examined more than a thousand research units in a half-dozen European countries [5]. Each research unit was measured on several indicators of group diversity, including discipline, specialty area, funding source, professional role, and research projects. These indicators of group heterogeneity were positively associated with two distinct creativity assessments, namely, subjectively rated effectiveness and objectively assessed productive output.

The positive consequences group diversity may extend beyond just the size of the collective domain sample. Earlier we saw that creativity was increased for individuals who had multicultural experiences, who were bilingual, and who had broad interests venturing outside their specific domain. In an analogous fashion, collaborative groups can benefit from extraneous sources of diversity and dissent [101,102]. These sources can include age, gender, ethnicity, language, profession or occupation, socioeconomic background, and geographical origins (see also [109]). Although many explanations can be offered for this fascinating group effect, one interpretation is predicated on the mutual stimulation that occurs as members interact during group problem solving [173]. In a sense, each group member is providing serendipitous stimuli that can prime new associative pathways that would not be evoked if everybody in the group thought and acted alike. This explanation has the advantage that it can account for why this effect may dissipate if the collaboration continues too long (e.g., [21]). With repeated interaction, the collaborators eventually become habituated to each other as sources of serendipitous stimulation. It then becomes time to change the membership of the work group, thereby mixing up the broth.

If the foregoing interpretation is correct, then an individual should demonstrate more creativity just living in a sociocultural milieu that is similarly diverse. Interaction within a group environment is not necessarily required. The empirical evidence endorses this expectation [171]. It is partly for this reason that highly creative individuals are more likely to be located in metropolitan areas where the populace is exceedingly heterogeneous with respect to occupation, language, culture, religion, and ideology. In such a diverse environment, any creator incubating some hitherto intransigent problem will receive incessantly diverse stimulation just taking the subway or walking a few blocks. Major universities situated in college towns can provide a comparably mixed and unpredictable sensory influx in otherwise provincial environment.

Previous discussion has often taken special note of how disciplines can differ greatly regarding the degree to which they are paradigmatically constrained. These disciplinary differences apply to social context as well [181]. In the main, scientific creativity is associated with sociocultural milieus that are politically stable and culturally homogeneous, whereas artistic creativity is related to those conditions that are more unstable and heterogeneous (e.g., [18, 142,144,167]). These contrasts almost exactly parallel those witnessed for psychopathology and family instability or unconventionality.

6. Conclusion

This review has provided an updated argument on behalf of Campbell's [15] thesis that creativity depends on some variety of blind-variation and selective-retention process. The argument began by defining the key concepts, with special emphasis on what it means for an ideational variant to be blind rather than sighted. These definitions were used to specify a basic combinatorial model of creativity built on a systems perspective that partitioned the discipline into individual, domain, and field. This abstract model yielded empirical implications with respect to some key phenomena, such as individual productivity, the information explosion, and multiple discoveries. From there, the discussion advanced to substantiations of the model via current empirical results regarding creative processes, personality traits, developmental factors, and social contexts.

The half-century of research thus reviewed indicates that some progress has been made toward resolving major theoretical and empirical issues. Still, the BVSR view of creativity has substantial latitude for additional development. The following three potential areas of growth are perhaps the most important:

First, much more needs to be done to translate the theory into precise, comprehensive, and predictive models. In this review, this translation took the form of combinatorial models. As is often the case, these models were based on certain "simplifying assumptions" that help render the mathematics more tractable. Yet these suppositions are, strictly speaking, false. Most conspicuous is the recurrent assumption that individuals launch their careers with a fixed domain sample I_i that is then "used up" as their careers progress. Although it is possible to remove this unrealistic assumption, to do so requires the addition of parameters that render the models less empirically testable [166,167]. The greater the number of parameters the more the model can fit almost any data set. Nevertheless, this problem might be remedied by turning to explicit computer simulations of BVSR creativity. Although evolutionary algorithms operate according BVSR principles, the operations mimic biological evolution rather than human creativity, such as relying on simultaneous rather than successive selection.

Second, empirical research should be directed more specifically at the psychological processes deemed to support BVSR creativity. With few exceptions, advocates have been largely content to marshal past empirical research on the theory's behalf rather than design new empirical tests of particular predictions (e.g., [168]). Future research can certainly benefit from current developments in cognitive neuroscience, and investigators have already begun to examine insight and problem solving using brain imaging techniques (e.g., [75]). Yet it is equally important to consider data sources from outside the laboratory. Because BVSR theory is probably most applicable to exceptional creativity, investigators should consider using relevant archival materials concerning genius-grade creators. Examples include biographical data regarding the careers of eminent scientific or artistic creators (e.g., [79,161,162]) as well as the notebooks or sketchbooks recording their ideational development with respect to specific problems (e.g., [49,177,192]). If the tenets of BVSR theory are fundamentally correct, the empirical results emerging from these diverse methodological approaches should triangulate on the same conclusion: Creative thought is contingent on blind ideational variations.

Third and last, considerable room remains for the complete development of universal selection theory in general and the BVSR theory of creativity in particular. For this development to be successful, the various parties to the debate must reach a consensus on major definitions and questions. Too often critics of BVSR largely ignore the impressive advances that have been made in the core theory [71,105]. A case in point is Kronfeldner's [80] recent attempt to show that scientific hypothesis formation cannot possibly be blind. Although her essay is often insightful and well informed, she completely ignored Kantorovich [66] and gave short-shift to Nickles [105] even though these two publications offer among the most complete expositions of BVSR theory. Psychologists critical of BVSR are even less likely to be appraised of these relevant discussions (e.g., [42]). The controversy cannot be resolved without first attaining a consensus on the terms of the debate.

To offer an illustration, much space has been wasted debating whether BVSR can provide a valid theory of creativity given the manifest disanalogies between biological evolution and creative thought (e.g., [34,80,190]). Besides differences in selection (sequential versus simultaneous and internal versus external), creative thought is held to be guided or directed whereas only biological evolution can be deemed genuinely blind. Even some BVSR proponents will accept this contradiction and thus attempt to show that biological evolution is also guided or directed like creativity (e.g., [188]). Yet this supposed problem vanishes once it is recognized that BVSR is not predicated on an analogy. As seen earlier, a proto-BVSR theory was advocated by Bain prior to Darwin's *Origins*. In addition, Campbell [15] conceived BVSR as the generic process, with evolution, perception, learning, and creativity as special cases, with each case having its own peculiar mode of operation (see also [28,31]).

Indeed, it can be argued that creative thought is not just different from biological evolution but also better: Creativity is the superior generator of adaptive originality (cf. [31]). This superiority stems largely from the fact that the BVSR process most frequently incorporates internal rather than external selection. That is, thought trials are often first generated and tested against internal representations of the external world, which then renders the subsequent thoughts or behaviors more guided, more intelligent. In fact, this internal selection procedure can be used to provide constraints on the available ideational variants, constraints that, as Campbell [15] noted, often represent prior inductive achievements acquired through past BVSR episodes. Yet so long as this guided selection still produces at least two variants that satisfy the conditions of blindness specified earlier, then BVSR still comes into play.

But what occurs when the pre-selection narrows the possible ideational variants down to just one? In particular, what happens if out of variants X and Y, it is determined that $p(X) = 1$ and $p(Y) = 0$ on logical or factual grounds? To respond, suppose both options are still tested and it is found that $w(X) = 1$ and $w(Y) = 0$, thus perfectly confirming our expectation. The question then becomes whether this outcome can be considered creative: Does the result exhibit both novelty and utility? Many proponents of BVSR creativity would answer in the negative (e.g., [159]). This situation represents routine rather than creative thinking, the expectations of prior expertise receiving a straightforward confirmation. Instead, it should be evident that we only obtain an original outcome if the prediction is disconfirmed, that is, $w(X) = 0$ and $w(Y) = 1$. The resulting novelty can be styled an *anomaly* (cf. [81]). Better yet, if the anomaly is not just novel but also useful, we can identify the outcome as a *serendipitous discovery*. Ironically, serendipitous results must then be considered blind [66]. The blindness comes from the fact that the variant probabilities $p(X) = 1$ and $p(Y) = 0$ are unquestionably decoupled from the variant fitness values $w(X) = 0$ and $w(Y) = 1$. Because serendipity can be classed as another form of creativity, we have to conclude that completely guided variations can only be creative if they are blind to the extent that they are proved wrong! Only then does the creator learn something unknown before.

To sum up, it is hoped that this review will inspire other investigators to engage in more theoretical and empirical research on Campbell's [15] BVSR theory of creativity. The geneticist and evolutionary biologist Theodosius Dobzhansky is often quoted as saying that "nothing in biology can be understood except in the light of evolution" (e.g., [187, p. 36]). Something similar may eventually be said of creativity: Nothing about creativity can be comprehended except in the light of blind-variation and selective-retention. Adaptive originality requires blind variations no matter it takes the form of ideas or species. Even so, it took evolutionary biologists more than a century since the publication of *Origins* before Dobzhansky could make that claim. Hence, Campbell's own theory should be granted at least another 50 years to attain the same status.

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