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The Optimal Age to Start a Revolution

ABSTRACT

Previous research on the relationship between age and creativity has shown that career age, rather than chronological age, correlates best with longitudinal changes in creative productivity. Recently, Dietrich (2004) proposed a new theoretical framework that integrates cognitive neuroscience with the findings of creativity research. By identifying distinct neural mechanisms that might underlie different types of creative mentation, this framework makes empirically testable predictions regarding the relationship between age and creativity. In this paper, we report the results of such a test and question the concept that creativity is a function of career age for a special, but crucial instance. In the case of revolutionary science or significant innovative discoveries, as opposed to paradigmatic science, discoveries are almost exclusively made by individuals who are young, both in terms of career *and* chronological age. These results remain robust even when taking into account the proportion of young scientists in the population of scientists. Neuroscientific data shows that a decline in prefrontal cortex function due to aging causes perseveration, the antithesis of creativity. Consequently, we interpret our findings that *paradigm-busting ideas* occur overwhelmingly to people in their 20's and early 30's, as indication that a nimble prefrontal cortex and thus chronological age is a critical factor.

INTRODUCTION

Simonton (1997) has shown that "creative productivity is a function of career age, not chronological age" (p.70). Although career age and chronological age are highly correlated, latecomers to a discipline show the same career trajectories and landmarks, making career age the better measure (Simonton, 1997, 2003). This finding is in contrast to the often made observation that revolutionary science, as opposed to paradigmatic or normal science (Kuhn, 1970), is overwhelmingly made by individuals in their 20's and early 30's. To exemplify, the mean age at which Newton, Darwin, and Einstein had the fundamental insight that led to the respective scientific revolution was 25.33! This curiosity has led to the hypothesis that younger scientists are more likely to produce innovative discoveries. This is also related to the Planck hypothesis, which states that younger scientists are more receptive to innovation (e.g., Hull, Tessner, & Diamond, 1978). Equally curious is the observation that scientists who made a revolutionary contribution early in their career hardly ever make a second one of equal impact at an advanced career age, suggesting that chronological age rather than individual differences is the responsible variable (Dietrich, 2004).

It is arguable which factor accounts for more progress in science, a single revolutionary discovery or the thousands of scientific discoveries that precede and follow a so-called paradigm shift. However, it is clear that society places a different value on scientists whose creative thinking caused revolutions and the qualitative difference between a major work that busts an entire paradigm and one that stays within the bounds of the currently accepted thinking patterns is widely recognized. The Planck hypothesis suggests further that this qualitative difference is not independent of chronological age.

A new theoretical framework that outlines the possible brain mechanisms underlying creative thinking has recently been proposed (for details see Dietrich, 2004). Briefly, creativity results from the factorial combination of 4 kinds of brain mechanisms. Neural computation that generates novelty can occur during two modes of thought (deliberate and spontaneous) and for two types of information (emotional and cognitive). Regardless of how novelty is generated initially, circuits in the prefrontal cortex perform the computation that transforms the novelty into creative behavior. To that end, the role of the prefrontal cortex in the creative process is threefold. As a first step, one has to become conscious of a novel computation. Given the view that the working memory buffer of the prefrontal cortex holds the content of consciousness (Cowen, 2001; Dietrich, 2003), a novel thought can be said to become a conscious insight when it is represented in working memory. Second, once an insight occurs, the prefrontal cortex can bring to bear its full arsenal of higher cognitive functions to the problem, including central executive processes such as directing and sustaining attention, retrieving memories as well as buffering that information and ordering it in space-time. These cognitive functions lay the foundation for abstract thinking and the ability to consider the appropriateness of the novel thought. Third, the prefrontal cortex must implement the expression of the insight. The prefrontal cortex orchestrates action in accordance with internal goals (Miller & Cohen, 2001), such as aesthetic or scientific goals. In everyday problem-solving, planning and executing concurrent subgoals while keeping in mind the main goal are critically dependent on prefrontal activation (Channon & Crawford, 1999; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). Thus, prefrontal circuits are involved in making novelty fully conscious, evaluating its appropriateness, and ultimately implementing its creative expression.

According to this framework, insights can occur during two modes of processing, deliberate and spontaneous. Deliberate searches for insights are instigated by circuits in the prefrontal cortex and thus tend to be structured, rational, and conforming to internalized values and belief systems. Spontaneous insights occur when the frontal attentional system does not actively select the content of consciousness, allowing unconscious thoughts that are more random, unfiltered, and bizarre to be represented in working memory. Several lines of evidence corroborate the notion that deliberate insights are different from spontaneous insights. For instance, the prefrontal cortex is recruited in long-term memory retrieval (for reviews, see Cabeza & Nyberg, 2000; Hasegawa, Hayashi, & Miyashita, 1999) and thus can be said to have a search engine that can "pull" task-relevant information from long-term storage in the posterior cortices, momentarily representing it in the working memory buffer. Once online, the prefrontal cortex can use its capacity for cognitive flexibility to superimpose the retrieved information to form new ideas.

Since perception and cognition are strongly determined by a person's mindset (Gazzaniga, Ivry, & Mangun, 2003; Snyder, 1998), both processes are inherently structured, that is, the search engine and the recombination of stored items operate under a number of constraints. For instance, deliberate problem solving is characterized by formal logic (e.g., A causes B), assumptions about meaningfulness, and, for efficiency, excludes *a priori* remote associations or counterintuitive paths. This is substantiated by data showing that past knowledge or conscious thinking about a problem can be detrimental to solving it (DeBono, 1968; Frensch & Steinberg, 1989; Guilford, 1950; Koestler; 1964; Schooler & Melcher, 1995), suggesting that solutions that would violate what is known about the world are not readily considered in deliberate creativity. Moreover, the prefrontal cortex houses a person's cultural values and belief system (Damasio, 1994). Thus, the processes of effortful retrieval and recombination of knowledge yield results that are highly consistent with a person's world view and past experiences (see Dietrich, 2004).

Another critical limitation of the deliberate processing mode is due to the fact that any information that is retrieved deliberately and is thus explicitly available for conscious manipulation is subject to the capacity limit of working memory. This capacity limit is roughly 4 independent chunks of information but only if the chunks are part of a coherent scene (Cowan, 2001). If two chunks are logical inconsistent or mutually exclusive to common sense, such as the Necker cube, the capacity limit is even more narrow (Baars, 1989; Cowan, 2001). In those circumstances humans appear to be able to process only one single item. Thus, in addition to the limited solution space, the bottleneck of consciousness further restricts the creative potential of the deliberate processing mode by putting a severe constraint on the number of possible ideational combinations that can occur concurrently.

In contrast, the spontaneous processing mode produces insights that are different qualitatively because they are not initiated by prefrontal database searches that are limited to preconceived mental paradigms as well as quantitatively because information is not subject to the capacity limit of working memory. During the inevitable times when the frontal attentional system is downregulated, for instance in daydreaming, thoughts that are unguided by societal norms and unfiltered by conventional rationality become represented in working memory (Dietrich, 2003). In such a mental state, conscious thinking is characterized by unsystematic drifting, and the sequence of thoughts manifesting itself in consciousness is more chaotic, permitting more loosely connected associations to emerge. Prefrontal areas are also activated by surprise violations of learned associations (Fletcher, Anderson, Shanks, Honey, Carpenter, & Donovan et al., 2001), suggesting that novel combinations of information that contradict conventional wisdom might have a lower threshold to enter conscious awareness.

Conscious thoughts that are unguided by prefrontal activity are by no means random. There is a consensus in cognitive science that memory is stored in associative networks (e.g., Anderson & Bower, 1973; Collins & Loftus, 1975; Gabrieli, 1998). In addition, people with frontal lobe lesions often perform normally on intelligence tests (Hebb, 1939), suggesting that knowledge can be acquired and manipulated without prefrontal integration. Thus, spontaneous insights are unlikely to be irrational and the spreading activation through a knowledge-based network alone can yield a new, sophisticated Gestalt. Thus, new ideas can be assembled unconsciously and then represented in working memory in their finished form.

Finally, evidence that prefrontal activation provides the basis for the qualitative difference between the two modes of processing comes from altered states of consciousness. REM sleep is a mental state that is marked by prefrontal inactivity (Braun, Balkin, Wesensten, Gwadry, Carson, & Varga et al., 1997), and is characterized by mentation that is largely void of prefrontal-dependent cognition (Hobson, Pace-Schott, & Stickhold, 2000). Not surprisingly, dreams rarely conform to societal values and conventional wisdom. Yet, more often than not, a coherent story line emerges due to the associative nature of subsequent activation. Thus, dreaming might be regarded as the most extreme form of the spontaneous processing mode and can give rise to insights that are difficult to come by during normal consciousness.

By identifying neural mechanisms that might underlie different types of creativity, this framework makes empirically testable predictions regarding the chronological age at which a creator in a given domain will show optimal capacity for unconventional *and* useful ideational combinations. In particular, if the prefrontal cortex is, as proposed in this framework, the pivotal neural structure mediating creative behavior, creativity ought to be closely related to prefrontal cortex development across the life span.

The prefrontal cortex is the last structure to develop phylogenically and ontogenically (Fuster, 2000, 2002). In humans, it is not fully matured until the early 20's, which is likely the reason why the creativity of children is less structured and appropriate. Likewise, evidence suggests that prefrontal functions are among the first to deteriorate with age. Data from humans and other animals show that aging individuals are less able to inhibit well-learned rules and have less independence from immediate environmental cues or long-term memories (e.g., Axelrod, Jiron, & Henry, 1993; Means & Holstein, 1992). This tendency to adhere to outdated rules might be compounded by the fact that mental states that enable the spontaneous processing mode, such as REM sleep or daydreaming, go dramatically down with age (Hobson et al., 2000; Singer, 1975). Thus, in addition to perseveration, the deliberate processing mode, which favors solutions that tend to be consistent with a person's belief system, becomes the more dominant problem solving mode of thought in the elderly.

Given that the ability to break conventional or obvious patterns of thinking and adopt new and/or higher-order rules is at the heart of any theory of creativity (Guilford, 1950, 1967), we must predict on empirical and theoretical grounds that creative insights differ in quality as a function of chronological age. According to Simonton (1997), creativity is a function of career age because latecomers show the same career path as do scientists with traditional careers. But if we differentiate between revolutionary science or significant innovative discoveries, which requires cognitive flexibility of the highest degree, and paradigmatic science, which can be characterized as a logical extension or refinement of an existing scheme of thinking, a different pattern might emerge. The above outlined framework suggests that older scientists, regardless of whether or not they are latecomers, are past their biological peak for cognitive flexibility, and are thus less likely to have insights that break existing paradigms in favor of new directions. Thus, we predict that latecomers do differ from other scientists, not in overall career pattern, but in the height of the peak of their best contribution, that is, they do not reach the level of creative achievement of the most extraordinary type, scientific revolutions. This type of creativity is predicted to be primarily a function of chronological age and might thus represent an exception to the otherwise valid concept of career age.

METHODS

In testing this hypothesis, the single biggest challenge was to settle on an operational definition of what constitutes a scientific revolution or a significant discovery. There are perhaps a number of ways to list or rank paradigm-shifting ideas for each scientific discipline and subfield but we decided, for simplicity sake, to consider the scientific Nobel Prizes as the best approximation. Naturally, it is arguable whether or not the Nobel Prize is a valid measure of great achievements or revolutions, as there are numerous factors, such as national biases, that determines to whom the prize is eventually awarded (Crawford, 2001). Moreover, not all achievements that were judged to be worthy of the Nobel prize constitute a scientific revolution or an innovative discovery.

Nevertheless, using the Nobel Prize as an operational definition has a number of advantages. First, it is a putative indicator of truly outstanding achievement that is universally recognized as the hallmark of creative genius. Since the work leading to the award signifies a disproportional leap forward in our knowledge, and "creative thinking by definition goes beyond knowledge" (Weisberg, 1999, p. 226), a Nobel Prize is a good measure of the extent to which a creative idea advances our knowledge and thus might be considered revolutionary. Second, for the scientific awards, the Nobel Prize is given not for lifetime achievement but for a single discovery (Nobel Foundation, www.nobel.se). This fact makes it relatively simple to determine the date, and thus the laureate's career and chronological age, at which a particular creative idea occurred. Finally, the Nobel list comprises hundreds of scientists so that normal science is more likely to be included rather than the fairly rare revolutionary science excluded. Consequently, any resulting age distribution emerging from our study is unlikely to favor our hypothesis.

Since our hypothesis specifies that revolutionary *ideas* occur predominantly to young scientists, we recorded the age at which the basic insight occurred that won a scientist the Nobel Prize. This emphasis on the first conscious realization of a groundbreaking idea, rather than the date of publication, is justified on two accounts. First, from a neuroscientific viewpoint, there is a critical distinction between creative insights, which are conscious realizations that occur in working memory, and creative expression, which is the implementation of that insight (Dietrich, 2004). According to the above framework, only the creative insight is critically dependent on a nimble prefrontal cortex. The creativity that transforms an insight into a finished product is typically paradigmatic in type and relies on well-learned methodologies, particularly in science. Second, there appears to be no empirical or historical evidence to suggest that older scientists have difficulty implementing their insights. It is the taking shape of a revolutionary idea in the first place that appears to cease in aging.

We determined the chronological and career age for all scientists who won the Nobel Prize in physics, chemistry, and physiology/medicine between 1901 and 2003. Every effort was made to ascertain the age at which the creative thought first came to mind. Fortunately, this was a straightforward task in most cases, as the scientists themselves often reported this information in either their Nobel lecture or in autobiographies. Some information was also gathered from the Nobel Foundation (www.nobel.se) or related websites (e.g., www.almaz.com), which publishes a biography for each laureate. In those cases where the date could not be determined precisely, we used the date the idea first appeared in print. Again, as the publication date represents, by definition, a date later in time than the date of the insight, which in some cases amounted to quite a significant time delay, the data would not err in favor of our hypothesis. Finally, in those cases where the Nobel-prize winning work was published as a series of papers and/or over a number of years, the date of the first publication was used.

Career age was determined by either the highest degree, which was a doctorate (Ph.D. or M.D.) in the vast majority of cases or the date of the scientist's first ever publication. Both measures are common markers of career start (Simonton, 1997). The use of these markers and the fact that we determined the age at which the idea occurred allowed for the possibility of a negative career age. There are a number of prominent examples, such as Marie Curie, Guglielmo Marconi, Albert Einstein, or Charles Sherrington for whom the Nobel-prize winning idea became the Ph.D. and/or first ever publication, and thus preceded the date of the Ph.D. or first publication. In those cases, we set the career age as 0.

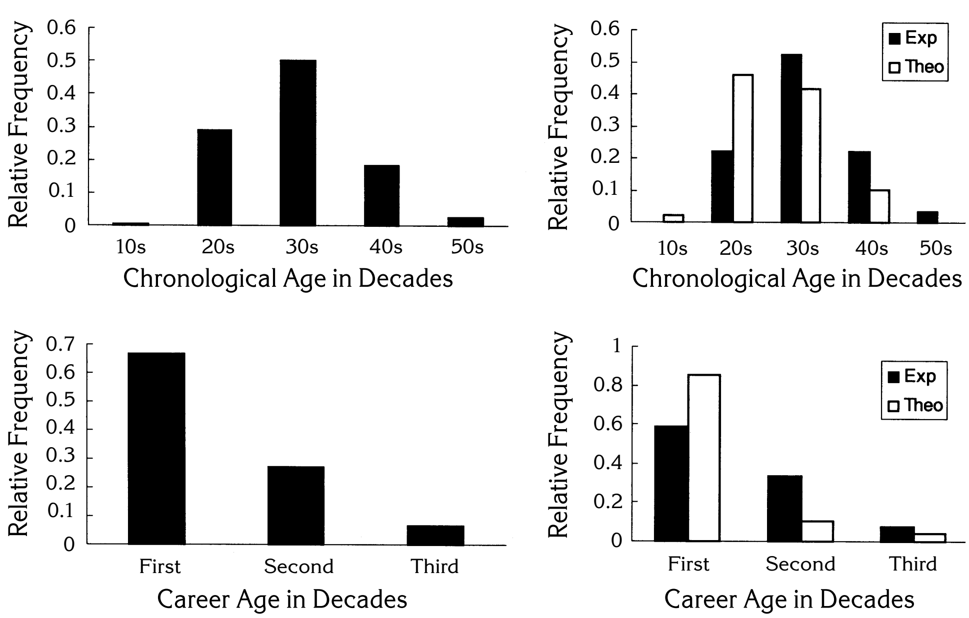
We should also mention that some scientists represented special cases and/or were difficult to classify in a straightforward manner. For instance, military service often disrupted a scientist's career. In those cases, we still set career age as the age in which the Ph.D. was received or the first publication appeared. For a few scientists, the exact date of the initial insight could not be pinpointed. We resolved such cases by taken the mean of a range of years, which we were able determine in all instances. Finally, there was also the special case of three individuals who received two science Nobel prizes. Since the award was given for work done in the same domain in all three cases, we recorded the same career age each time.

In addition to obtaining distributions of nobel prize winning ideas as a function of chronological and career ages, we also examined whether or not any conclusions based on those distributions are affected by the base rate fallacy (Wray, 2003). We computed the percentage of people who made revolutionary discoveries in a particular age group (PRD) for all three disciplines and compared them with the results obtained by Wray (2003).

RESULTS

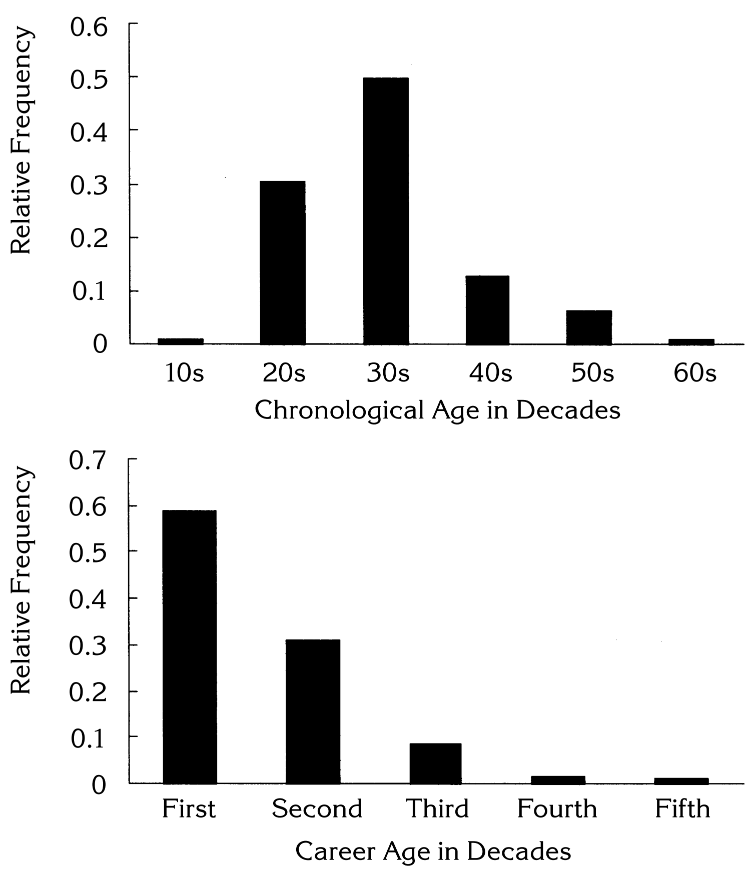
All 493 scientists who received the scientific Nobel prizes between the years 1901 and 2003 were examined. The resulting distribution showed a chronological age with a peak at 34.39 ± 7.43 (mean ± SD) and a career age with a peak at 8.50 ± 7.43. Remarkably, 49 scientists (physics, 15; chemistry, 19; physiology/medicine, 15) recorded a negative career age. Equally remarkable, the distribution marks the age of 49.25 as two standard deviations above the mean. Indeed, a mere 19 laureates (physics, 4; chemistry, 9; physiology/medicine, 6) or 3.8% of the sample were 50 years of age or older at the time of their discovery. The distribution for each of the three disciplines of physics (170 laureates), chemistry (143), and physiology/medicine (180) closely resembled each other as well as the overall distribution.

FIGURE 1. Physics. Relative frequency in chronological (upper panels) and career (lower panels) age expressed in decades for Nobel laureates in physics. Panels on the right side show the data divided into experimental and theoretical contributions.



For physics, chronological age peaked at 34.06 ± 7.15 and career age peaked at 8.14 ± 6.96. *Fig 1* shows relative frequency as a function of age expressed in decades. In terms of chronological age, the overwhelming majority of scientists fell, as might be expected, into the decades of the 20's (29%), 30's (50%), and 40's (18%). Only 4 scientists, all of whom were experimental physicists, Röntgen (50), W. H. Bragg (51), Cohen-Tannoud (51), and Koshiba (54), were in their 50's (2%). The data is strongest for theoretical physics (top right panel of *Fig 1*), which shows that 90% of all theoretical contributions

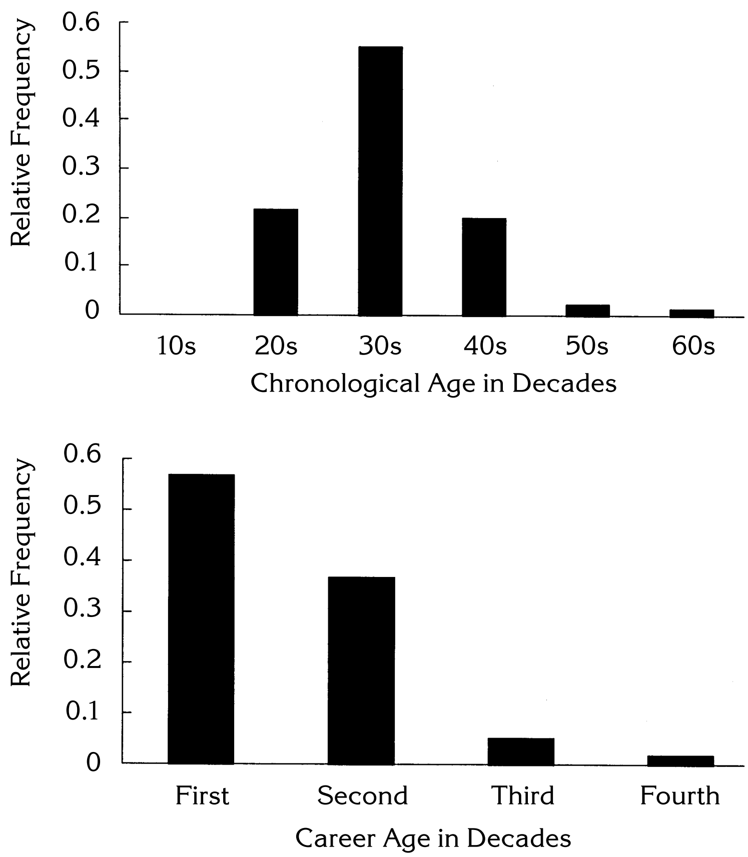
FIGURE 2. Chemistry. Relative frequency in chronological (upper panels) and career (lower panels) age expressed in decades for Nobel laureates in chemistry.



occurred *before the age of 40* and that no theoretician over the age of 50 had ever had an idea that was deemed worthy of the Nobel prize. In terms of career age, all insights occurred in the first 3 decades of career start. Two-thirds of all insights occurred in the first decade (67%), with sharp declines in the second (27%), and the third (6%) decade.

For chemistry, chronological age peaked at 34.23 ± 8.26 and career age peaked at 8.99 ± 8.47. *Fig 2* shows that the overwhelming majority of scientists fell again into the decades of the 20's (30%), 30's (50%), and 40's (13%). One scientists,

FIGURE 3. Physiology/Medicine. Relative frequency in chronological (upper panels) and career (lower panels) age expressed in decades for Nobel laureates in physiology/medicine.



Theodore Richards, was a teenagers (1%), while 9 chemists were over the age of 50 (6%), including one, John Fenn, who was over 60. In other words, 94% of all contributions in chemistry occurred before the scientist reached the age of 50. In terms of career age, most insights occurred again in the first decade (59%), with sharp declines in the second (31%), the third (8%), and the fourth (1%) decade.

For physiology/medicine, chronological age peaked at 34.92 ± 7.0 and career age peaked at 8.52 ± 6.88. Solidifying the above result, *Fig 3* shows that the overwhelming majority of scientists fell again into the decades of the 20's (22%), 30's (55%), and 40's (20%). Thus, 97% of all ideas that led to the Nobel prize in physiology/medicine were made by scientists before they reached the age of 50. Only 6 scientists were over the age of 50 (3%), which included two in their 60's, Robert Furchgott (62) and the developer of the frontal lobotomy, Egas Moniz (61), a dubious choice for the award indeed. In terms of career age, most insights again occurred in the first decade (57%), with sharp declines in the second (37%), the third (5%), and the fourth (1%) decade.

Wray (2003) computed the percentage of people who made revolutionary discoveries in a particular age group (PRD). Based on that analysis, he claimed that the 36-45 age group is responsible for most significant discoveries. We performed a similar analysis, the results of which are shown in *Table 1* along with the results from Wray (2003) for comparison. In our sample, slightly more than 60% of discoveries were made by people aged below 35 and around 30% were made by people aged between 35 and 45.

TABLE 1. Distribution of Scientists by Age Group.

Age	Percentage	PRD from Wray (2003)	PRD (Physics)	PRD (Chemistry)	PRD (Physiology & Medicine)
Below 35*	45%	46.4%	62.94%	62.94%	58.33%
36-45	27.6%	39.3%	29.41%	27.27%	35%
46-55	17%	14.3%	7.65%	7.69%	5.56%
56-65	10.5%	0%	0%	2.1%	1.11%

* The below 35 age category ranges between 25 and 35 in Wray's analysis, but does not include a lower limit in our sample.

DISCUSSION

Our data support the observation that truly groundbreaking work is done by young scientists. The near total absence of older scientists in the Nobel population calls into question the concept that scientific creativity is solely a function of career age. If this were the case, one would expect the countless scientists who start their careers later in life or switch fields in mid-career to be represented among Nobel laureates. We interpret our finding that scientists above the age of 50 are a rarity in the Nobel prize list and that latecomers, scientists who are young in terms of career age but advanced in terms of chronological age, are completely absent, on the basis of the distinction between revolutionary and normal science. Career age remains the best descriptor of productivity in science in general, but a limitation of this concept becomes apparent if we isolate achievements of the highest quality. Revolutionary science is a special type of science that requires the utmost cognitive flexibility, which in turn depends on a nimble prefrontal cortex. Given the data that prefrontal function declines with age, chronological age must be regarded as a limiting factor to career age for the special but important case of revolutionary science or innovative discoveries. Accordingly, our data suggests that paradigm-shifting ideas in science occur to a mind that is young, both in terms of career *and* chronological age.

An additional argument against the sole use of career age is the fact that only 3 scientists received two Nobel prizes, Marie Curie (chronological age: 31 and 31), John Bardeen (39/49), and Frederick Sanger (25/52). Bearing these 3 cases, it is striking that no Nobel-prize winning scientist had ever had a second idea that was deemed worthy of the award. To put this into the form of a provocative question, if Nobel laureates are brilliant why are they brilliant *at this level* only once, and why only when they are young?

Our data on Nobel laureates suggests the following broad generalizations about the career path of scientists: (1) the window of opportunity to produce revolutionary science is during the first two decades of career age *if this age does not exceed the chronological age of 50* and (2) irrespective of whether or not a revolutionary idea occurred before the age of 50, contributions beyond the age 50, regardless of career age, are paradigmatic in type. For the sake of illustration, Einstein can perhaps serve as an instructive example. Einstein received is Ph.D. in 1905, at the age of 26, the same year in which he published his paper on the photoelectric effect that won him the Nobel prize. In 1905, he also published the first paper on special relativity. In the following 10 years, he worked further on relativity culminating in the general theory of relativity in 1915 at the age of 36. Einstein died in 1955 at the age of 76 with a total of 248 publications (Simonton, 2003), yet none of is later work remotely matched in creativity and originality anything he did until 1915. Moreover, as early as in his mid-forties, Einstein had considerable trouble reconciling the emerging data in quantum physics with the worldview he himself shaped, an unmistakable sign of perseveration.

Distributions of creative discoveries based on age are susceptible to the base rate fallacy. To guard against this pitfall, Wray (2003; 2004) computed the percentage of scientists in certain age groups and, based on this analysis, claimed that middle-aged scientists (between the ages of 35 and 45) are responsible for most innovative discoveries. We analyzed our data in the same manner. The results, shown in *Table 1*, demonstrate clearly that even when taking into account the larger number of younger scientists in the population, most Nobel Prize winning discoveries were made by people below the age of 35. Thus, not only is the most significant portion of the discoveries made by people below the age of 35 but the ratio of the percentage of revolutionary discoveries to the percentage of the total population of scientists is also higher for the below 35 age group. This shows that our results based on Nobel Prize winners do not suffer from the base rate fallacy. If neither our nor Wray's (2003; 2004) results suffer from the base rate fallacy what could explain the different distributions? There are several critical methodological differences between these studies. One such difference that might explain why Wray's distributions peak at a higher chronological age relates to the issue of publication dates. Wray counted the date a discovery was made public, which is, by definition, always a date later than the one for the original idea. We focus on creative cognition and do not include the time it takes to bring them to paper. The second difference relates to sample size and selection. Wray used a rather limited sample of scientists (28), who made revolutionary contributions. This data set is much smaller compared to our study (493). Moreover, the sample selection is not as objective as using Nobel Prizes, which are arguably the single most respected measure of assessing the scientific value of a contribution. Finally, Wray's sample spans a period of more than 500 years, whereas the data in our study span a little more than 100 years.

Kanazawa (2003) obtained distributions similar to those shown in our study. However, he explained the phenomena that significant revolutionary discoveries are made by younger scientists by focusing on similarities between crime and scientific research. According to him, the concept of competition plays a key contributory role in the differences of creative productivity as a function of age. This link between competition, youth and creativity is an interesting hypothesis but lacks substantial empirical support. In contrast, our proposal that this phenomenon is linked to the development and degeneration of prefrontal regions is build on a solid body of empirical evidence from psychology and neuroscience. The prefrontal cortex undergoes structural and functional age-related changes, and it has become clear that those changes affect cognitive processes such as executive functions and cognitive flexibility (Fuster 2000, 2002) and, by extension, creative ideas and innovative discoveries.

According to the longitudinal model (Lehman, 1953; Simonton, 1997), creative output is a single peak function. Empirical data has shown that creative output over the course of the career first rises sharply to a single peak and then gradually declines to about half the rate of the peak (Dennis, 1966; Lehman, 1953; Simonton, 1988). Since we did not collect longitudinal data, the present results are not inconsistent with these findings. Longitudinal research on the relationship between age and creativity has also led to the formulation of the equal-odds rule, which states that the ratio between major and minor works for any unit of time in a creator's life remains approximately constant (Simonton, 1997). Creative people show no evidence for "runs" or periods of time in which their work produces a higher hit rate. In other words, the age curves for quality and quantity are similar, making overall productivity the best indicator of eminence. An extensive amount of data can be recruited to substantiate the equal-odds rule (Over, 1982; Simonton, 2000; Weisberg, 1993), irrespective of the operational definition used to measure quality or the field of endeavor (Simonton, 1988). Again, since we did not collect longitudinal data, we have no evidence to dispute the equal-odds rule. However, our data suggest that the equal-odds rule may not hold if we introduce an operational definition that differentiates between revolutionary and normal science. The general principle that quality is a probabilistic function of quantity would still apply but the period of revolutionary *ideas* may be special in that it preceeds the period of peak productivity.

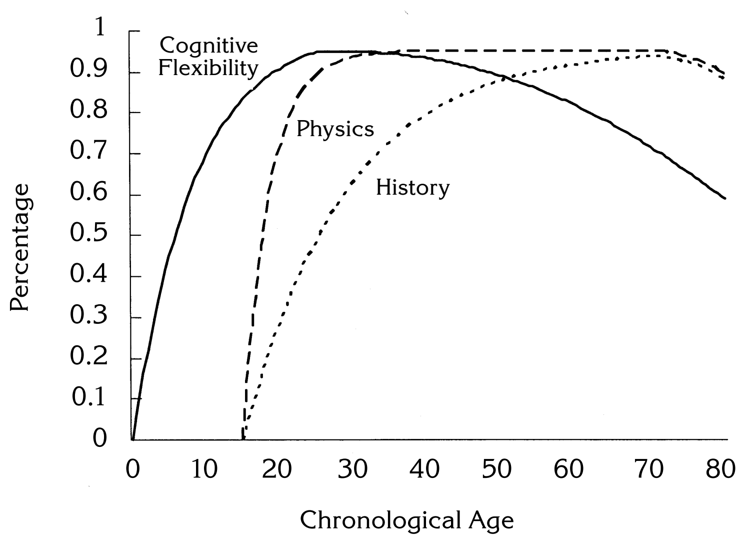
The observation that the quality of scientific output changes with age is already inherent in the fact that creative productivity is a single peak function. But again, we do not suggest that creativity in science is best understood in terms of chronological age. Indeed, Simonton (1997) has made a convincing case for the use of career age. We simply propose that for the special case of groundbreaking advances in science chronological age is a limiting factor to career age.

Two difficult questions rise from this analysis: (1) why does chronological age seems to matter for paradigm-shifting creativity and (2) why do the age curves for the sciences differ from those in other domains, such as history or philosophy. The theoretical framework proposed by Dietrich (2004) associates distinct neurocognitive processes with different types of creativity and thus permits for the first time to attempt a mechanistic explanation to these questions.

To that end, it is imperative to recognize that knowledge stored in long-term memory and the creative recombination of that knowledge recruit different brain circuits. While knowledge is stored in temporal, occipital and parietal cortices (TOP), creativity is enabled by the cognitive flexibility provided primarily by the prefrontal cortex. Accordingly, we propose that the answer to the first question is directly related the development of the prefrontal cortex across the life span, while the second question is best addressed by considering the nature of the knowledge in various domains and the rate at which it can be acquired.

Primarily as a visual aid, *Fig 4* depicts a hypothetical model that portrays the time course of prefrontal cortex development as well as the rate of knowledge acquisition by TOP cortices for two domains with large differences in creative output, physics and history. Admittedly crude, the slope of the prefrontal curve was based on data showing that prefrontal-dependent cognition is not fully matured until the early 20's and is among the first to deteriorate with age (Fuster, 2002). For instance, the curve takes into account that performance on the Wisconsin Card Sorting Task is fairly stable in mid-life and then declines as a function of age in a linear fashion, particularly the ability to adapt to changing rules (Axelrod, Jiron, & Henry, 1993). Aging rats in a repeated reversal paradigm that tests for cognitive flexibility and working memory show comparable perseveration to old information (Means & Holstein, 1992). On that criterion alone, one would expect creative achievement to peak, regardless of discipline, in early to mid-life, at the height of prefrontal capacity.

FIGURE 4. General Model. This hypothetical model shows the time course of prefrontal cortex development as well as the rate of knowledge acquisition by TOP cortices for two domains with large differences in the peak of creative output, physics and history. Functional capacity is expressed in percentage and plotted as a function of chronological age. The slope of the prefrontal curve (solid line) takes into account that prefrontal-dependent cognition is not fully matured until the early 20's and is among the first to deteriorate with age. The slope of the curve for physics (stripped line) and for history (dotted line) are drawn to intersect the prefrontal curve in order to fit the historiometric observation that physicists peak in the early 30's, while historians peak in the early 50's (see text for details).



However, there are factors other than mental flexibility influencing creative ability. Creative insights in a knowledge-based domain depend on the number of domain-specific items stored in TOP areas. The more knowledge is readily available in memory, the more relevant items can be superimposed in working memory to form new combinations (Dietrich, 2004). Thus, the quality of an insight in a cognitive domain depends on expertise (Weisberg, 1993). But the rate of acquisition of this expertise differs among domains. Physics or chemistry, for instance, are reductionistic domains, in which the knowledge base can be compacted into a manageable set of equations and concepts that can be acquired at a fast rate. This is not the case for history or philosophy, which are domains with multifactorial and incondensable topics that undoubtedly need additional time to be committed to memory. We tried to reflect this in our model by drawing different time courses for physics and history. The slopes of these curves are drawn to intersect the prefrontal curve in order to fit the historiometric observation that physicists peak in the early 30's, while historians peak in the early 50's (Dennis, 1966; Lehman, 1953; Simonton, 1988).

The accelerated speed at which expertise can be acquired in physics also results in a more rapidly growing knowledge base as compared to history. As a consequence, physics requires constant adaptation to a new set of rules, which means that previously successful responses have to be modified constantly to fit new paradigms. It is exactly this ability which depends critically on prefrontal cortex functioning. For instance, the elderly have little trouble adapting to the first sorting rule in the WCST but do not seem to be able to inhibit knowledge of this rule when it changes (Axelrod, Jiron, & Henry, 1993). They even report to be aware that the old rule no longer applies but continue to emit habitual behavior nonetheless. In contrast, historians do not have to adjust to such a neck-breaking pace and the cognitive inflexibility that is the inevitable result of an aging brain might not become as evident. Thus, the decline of cognitive flexibility might affect scientists more readily than historians, who can continue to operate creatively on the first set of rules they acquired. Of course, physicists and historians can produce creative work until old age, but historians have the advantage that the quality of their work does not suffer because history moves at a slower pace and requires less shifting of their cognitive mindsets.

Thus, we propose that creativity in a knowledge-based domain can be explained by the interaction of two broad neurocognitive processes, cognitive flexibility enabled by the prefrontal cortex and the differential rate of knowledge acquisition for various domains by TOP areas. Although this explanation is speculative at present, it represents the first attempt to provide a mechanistic explanation for the data that revolutionary science is the realm of the young and the historiometric data that the age peak for creative productivity differs among domains.

To illustrate, suppose an individual starts a career in physics in his 40's. Although he would achieve the same mastery of the subject than his colleagues who started in their 20's, he would hit the peak of his expertise at a time his prefrontal cortex is past the prime. However, to break established patterns a scientist needs the utmost cognitive flexibility, which is more likely during the height of prefrontal capacity. Thus, although career landmarks and trajectory are likely to be unaffected by the late start, our scientist would miss the window of opportunity to produce innovative discoveries. It is for this reason that we propose that chronological age must be considered a constraint when plotting creativity as a function of career age. In other words, extraordinary creative acts in a cognitive domain become increasingly likely the closer full mastery of the subject matter coincides with maximum prefrontal power.

This scenario is more likely for physics than it is for history, a subject matter that lends itself less to data compression. It is perhaps for this reason that new concepts in modern physics so often violate common-sense, whereas, history tends to be characterized by the steady and conservative progression of logical analysis. In history, a radical reconceptualization of the available data is as rare as a 26-year old savant historian.

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