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Characteristics and Problems of the Gifted: neural propagation depth and flow motivation as a model of intelligence and creativity

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ABSTRACT. Giftedness, the potential for exceptional achievement, is characterized by high intelligence and creativity. Gifted people exhibit a complex of cognitive, perceptual, emotional, motivational and social traits. Extending neurophysiological hypotheses about the general intelligence (*g*) factor, a construct is proposed to explain these traits: neural propagation depth. The hypothesis is that in more intelligent brains, activation propagates farther, reaching less directly associated concepts. This facilitates problem-solving, reasoning, divergent thinking and the discovery of connections. It also explains rapid learning, perceptual and emotional sensitivity, and vivid imagination. Flow motivation is defined as the universal desire to balance skills and challenges. Gifted people, being more cognitively skilled, will seek out more difficult challenges. This explains their ambition, curiosity and perfectionism. Balance is difficult to achieve in interaction with non-gifted peers, though, explaining the gifted's autonomy, non-conformism and feeling of alienation. Together with the difficulty to find fitting challenges this constitutes a major obstacle to realizing the gifted's potential. The appendix sketches a simulation using word association networks to test the propagation depth model by answering IQ-test-like questions.

KEYWORDS: *g*-factor, creativity, giftedness, neural networks, flow motivation

Modern society has always been fascinated by creative genius [Simonton, 2001; Ochse, 1990; Eysenck, 1995; Terman, 1925], by the great thinkers, scientists, and artists, such as Einstein, Shakespeare or da Vinci, who have laid the foundations for our present knowledge and culture. Genius is generally viewed as very valuable, but rare. Therefore, it is worth investigating how we can optimally exploit this scarce resource, and, if possible, make it more abundant. This means that we must try to understand at the deepest level the characteristics that distinguish an exceptionally creative mind from an ordinary one. Moreover, we should try to understand the processes that produce these characteristics—whether at the biological, psychological, social or cultural level. This will allow us to see how we can foster such processes, and which obstacles we must remove in order to maximally reap the benefits from a gifted mind.

That there are plenty of such obstacles becomes obvious once we note how unevenly distributed genius is: most well-known examples, such as the ones above, are European or American men, from a middle or upper class background. That world-changing creativity requires a minimum level of health, wealth, education and supporting infrastructure seems obvious, explaining why top intellectual achievements are rare in developing countries. However, it is much less obvious why such an exceedingly small number of women have reached the highest levels of eminence. None of the standard tests of intelligence and creativity find significant differences in potential achievement between men and women. The sociological observations of an "old boys networks" or "glass ceiling" in part explain this discrimination, but we need to move to a deeper, psychological level to fully understand the mechanisms that hold back women and other classes of gifted people from achieving their true potential. For that, we need to better understand what giftedness is.

Defining Giftedness

Up to now, we have used the terms "genius", "creativity", "intelligence" and "giftedness" more or less interchangeably. So let us propose more precise definitions. "Genius" typically refers to an exceptional intellectual achievement, such as the Theory of Relativity, Hamlet or the Mona Lisa. As such, it is recognized after the fact, sometimes well after the death of its author. This makes "genius" a far too subjective and unreliable concept to categorize people here and now, and the term has therefore been all but abandoned in the psychological literature. Creativity, while referring to a more common type of achievement [see e.g. Sternberg, 1998; Heilman et al., 2003; Getzels & Jackson, 1962], suffers to some degree from the same problem: who is to judge which intellectual product is sufficiently novel or important to be deemed "creative"?

"Intelligence" at first sight seems easier to determine. If we define it as "problem-solving ability", then we can develop an objective measure simply by counting how many problems from a list a certain person can solve. This is the basic idea behind IQ tests: the number of correct answers to a standard questionnaire is normalized so that the average score for the population is 100 and the standard deviation 15. The following labels are commonly used for the IQ scores that we would associate with the highest levels of achievement: *gifted* - 130 and above, *highly gifted* - 145 and above,

exceptionally gifted -160 and above. Thus, giftedness could be defined quantitatively as ability more than 2 standard deviations above the average, and what used to be called "genius" as 4 or more standard deviations.

But intelligence too is a problematic concept [Neisser et al., 1996]. This is seen nowhere more clearly than in artificial intelligence, the research domain that aims to develop computer programs exhibiting a human-level intelligence. After half a century of failed attempts to achieve this lofty goal, the main lesson learned is that intelligence is highly contextual. First, intelligence requires extensive knowledge, and depending on the kind of knowledge available, problems may be trivial or impossible to solve. Second, intelligence cannot exist purely in an abstract realm of ideas: real-world problem-solving requires interaction with the environment [Clark, 1999]. Practically, this means that problem-solving ability strongly depends on the available cognitive resources (knowledge, heuristics, experience, specialized processing modules...), physical resources (tools, sensors, books, maps, ...) and social resources (other people to consult, institutions to coordinate problem-solving activities...).

IQ tests try to circumvent these requirements by selecting problems that are as general and abstract as possible, requiring not more than pen and paper, and a minimum of knowledge. For example, a classical test type probes the breadth of the subject's vocabulary by asking her to choose the closest synonym from a list for a variety of terms. Since we can assume that any adult, native speaker of a language has had a wide opportunity to encounter various words, this test should make little distinction between specialized forms of expertise. But this still requires an upbringing within a particular language community. More "culture-free" tests, such as Raven's Progressive Matrices, avoid any reference to learned knowledge by asking subjects to recognize regularities in abstract patterns. But even those assume specialized visual analysis skills, a specific logic about which elements of the pattern form a coherent whole, and familiarity with the idea of taking tests by marking answers on a questionnaire.

Observations such as these have led to a theory of "multiple intelligences" [Gardner, 1993], which claims that people have different abilities in different problem domains, such as spatial, verbal, emotional or practical. Recent advances have indeed shown that the brain is a complex organ, with specialized modules for domains such as language or spatial manipulation. Therefore it is to be expected that some of these abilities are more developed in some people than in others. Yet, large-scale statistical analysis of all the different tests of mental ability, from Raven's Matrices to general knowledge, academic achievement and technical skills, shows that their results are all positively correlated. This implies that there is at least one basic factor they have in common, the so-called *general* or *g-factor* [Jensen, 1998; Chabris, 2006]. Surprisingly, this factor appears to have little to do with advanced, knowledge-based problem-solving, as it is most strongly correlated with the simplest possible test results—such as inspection times—which do not require anything that we would conventionally call knowledge or intelligence.

In fact, the more advanced the type of test and the person taking it, the lower the mutual correlations between different tests and test items, making the measurement of IQs above 160 essentially unreliable [Jensen, 1998]. This can be understood by the fact that ordinary tests are standardized on large populations by eliminating all items that do

not correlate well with the overall results because they require too specific skills. In the highest IQ ranges, though, the available population is far too small to achieve reliable standardization, and for the "difficult" problems used to differentiate the most advanced subjects there may not be any generally accepted way of attaining the solution. The true creativity that we could expect in this range may show itself precisely in the fact that different people see problems and their solutions differently (and differently from the experimenter who designed the questionnaire!).

In conclusion, high scores on an IQ test merely give a strong indication of giftedness, but certainly do not define—and even less explain—the trait. The famous longitudinal study of Terman [1925; Terman & Oden, 1947, 1959] followed an extended group of individuals with IQs over 140 from their teens until their nineties. Only a fraction of those achieved the eminence that could be expected from their apparent level of intelligence. This could mean that IQ tests are not a reliable measure of high-level giftedness, or that society throws up too many obstacles for gifted people to achieve their full potential. Most likely, both explanations apply to some extent. On the other hand, the fact that a disproportionately high section of Terman's group did achieve eminence, while hardly any of the not-selected did (ironically, these did include the only one to get a Nobel Prize, William Shockley), indicates that a minimally high IQ of about 140 seems like a necessary, albeit not sufficient, condition for exceptional achievement [Jensen, 1998].

This brings us back to the definition of what constitutes giftedness. To avoid the need for after-the-fact assessment of achievement, we will define it as *potential for exceptional achievement*. This potential will be realized only if the environment provides sufficient support. To recognize this potential, we must go beyond IQ tests, and look at a variety of personality traits that include not only problem-solving and cognition, but perception, emotion, motivation, and social relations. As we will see in the next section, giftedness is typically accompanied by a specific complex of such traits. Thus, a simple questionnaire probing into feelings, sensitivities, interests, sense of humor, and relations with peers and authorities may already provide a reliable indication that an individual is gifted, and likely to score high on an IQ test [Silverman, 1990]. To understand giftedness, we need to analyze this whole complex of interrelated traits, and not just the problem-solving or creative abilities.

The present paper proposes a simple model to explain these traits and their relations. First, we will summarize the basic traits defining the "giftedness syndrome". After reviewing the literature on the physiological basis of the *g*-factor, we will propose a hypothesis of neural propagation depth that will help us to understand the cognitive, perceptual and emotional traits. We will then extend Csikszentmihalyi's [1990] theory of *flow* to infer the individual and social motives that drive gifted individuals. Finally, this theory will help us to understand the often difficult relations gifted individuals—and gifted women in particular—have with their environment, and how this may prevent their potential from being realized.

Basic traits of the gifted

Several authors have compiled lists of traits or characteristics that, in addition to high IQ, distinguish gifted individuals [see e.g. Silverman, 1990; Tuttle & Becker, 1980; Rogers, 1986; Roeper, 1991; Clark, 2006; Jacobsen, 2000; Sak, 2004]. An Internet search allowed me to collect about twenty such lists, which I have compiled further by putting similar traits together in one category, and then selecting the categories that have entries from at least two independent lists. Let us now summarize these traits, not piecemeal as most lists do, but in the form of a coherent personality description of a typical Gifted Person (GP)—starting with cognition, moving to perception, emotion, motivation and finally social behavior. (Of course, since each individual is unique, some of these characteristics will be more developed in the one than in the other).

Cognition

As already implied by high IQ, gifted persons (GPs) excel at *reasoning* and *problem-solving* [Davidson, 1986; Keating & Bobbitt, 1978; Sternberg, 1986]. But they show more than a propensity at tackling puzzles: they are able to generalize from specific cases, seeing the deeper patterns to *connect seemingly unrelated phenomena*. They quickly grasp complex and *abstract concepts*, such as in mathematics or science, and their general comprehension is far advanced. Their thinking is deep, broad and at a high level of abstraction.

Yet, they do more than reason abstractly and logically: they have a very rich and *vivid imagination* [Piechowski, Silverman & Falk, 1985]. Together with their capacity to connect and integrate, this gives them a remarkable *creativity*. Perhaps most noticeable is their constant production of original, *unusual ideas*, coming up with things that other people would never have thought of, or seen the relevance of. Their mind seems constantly busy, moving very quickly, and often on multiple tracks at the same time.

Not just their thinking, but their *learning* seems to run in a higher gear [Bloom, 1982; Hollingworth, 1942; Robinson, Roedell & Jackson, 1979; Terman & Oden, 1947]. They quickly and eagerly assimilate new knowledge, and they have an *excellent memory* for the things they have learned [Freeman, 1985; Guilford, Scheuerle, & Schonburn, 1981]. This is perhaps most noticeable in their *extensive vocabulary* [Borkowski & Peck, 1986; Terman & Oden, 1947] and facility with words and language in general.

Perception and emotion

Gifted people are very *perceptive* [Sak, 2004], showing an excellent sense of observation. They notice things that others are not aware of, and their overall perception of the world seems quite different, in the sense of richness and detail, from the one of ordinary people. Thus, what someone else may see as just a chair or a stone, a GP may see as a subtle play of light, texture and perspective, the way a professional artist may

have been trained to perceive it. They are often *sensitive* to small changes in the environment, such as temperature differences, or an itchy label in the collar of a shirt.

This high sensitivity [Mendaglio, 1995; Clark, 2006; Piechowski, 1991; Tuttle & Becker, 1980] is not just sensory but affective: GPs tend to undergo intense feelings and experiences, which may be elicited by situations to which others hardly react. This brings us to a peculiar weakness or vulnerability typical of many gifted people, which Dabrowski [1972; Dabrowski & Piechowski, 1977; Piechowski & Cunningham, 1985; Gallagher, 1985] has called *overexcitability*. This can be defined as an excessive response to stimuli, and may occur in different domains: psychomotor, sensual, emotional, imaginational, and intellectual. GPs in general can become easily excited or passionate about an idea, a feeling or something they imagine. This unusual strength of feeling is sometimes called (emotional) *intensity* [Piechowski, 1991; Piechowski & Colangelo, 1984; Silverman & Ellsworth, 1980; Whitmore, 1980].

Their rich sense of observation and multitasking mind allow them to see simultaneously many sides to any situation, and consider problems from different viewpoints. In general, we may say that they have a high *tolerance for ambiguity* and complexity [Piechowski, 1991; Roeper, 1991], i.e. they feel little need to reduce their perception to a simple black-or-white categorization. Their ease with ambiguity and paradox also shows in their excellent, but unusual *sense of humor* [Getzels & Jackson, 1962; Shade, 1991; Terman, 1925], in which they often relativize a situation by looking at it from an unorthodox angle.

Motivation and drive

Together with strong passions, GPs also have a high *drive* [Winner, 2000] and great deal of energy. This shows itself in their capacity to sustain their concentration on the topics that interest them. Once they get interested, they can be very *persistent* [Feldhusen, 1986; Tuttle & Becker, 1980] and have a *long attention span* [Rogers, 1986; Witty, 1958]. The downside is that they can sometimes work themselves to exhaustion. Their high level of activity may make it difficult to relax, as they cannot stop thinking [Roeper, 1991].

Whatever their specific interests, they are all driven by intense *curiosity*, by an overwhelming desire to know and understand [Bloom, 1982; Cox, 1977; Freeman, 1985]. From an early age they are typically avid readers [Cox, 1977; Gross, 1993; Robinson, Roedell, & Jackson, 1979], who will absorb information of all kinds. They have a very *broad range of interests*, but may be overwhelmed by the diversity, not knowing what to investigate first. As such they may seem to lack focus, apparently getting bored as soon as they have a rough understanding of a domain, and moving on to the next one. Yet, at a deeper level, they continue looking for connecting patterns, for meaning and understanding. Thus, they are seekers for ultimate truths, for the meaning of life [Lovecky, 1994].

A GP typically develops a far and wide *vision* of how things might be or ought to be, and a sense of destiny or mission [Lovecky, 1992], as the one who is to realize these visions. The goals they set for themselves are typically very *ambitious* [Winner, 1996],

and may look unrealistic or unattainable to others. They enjoy difficult *challenges*, and have a penchant for *taking risks*, that is, explore situations where the outcome is everything but predictable. This may get them in serious troubles of a kind that other people find difficult to imagine. Another downside of their ambition is that they can be too *perfectionist* [Clark, 2006; Whitmore, 1980], setting such high standards for themselves and others that they are in practice disappointed. The fear of failing to achieve these standards may also keep them from finishing a concrete piece of work, such as writing a book or thesis, as their preparation for it never really seems good enough.

Social relations

Their intrinsic motivation makes them less dependent on rewards and punishments, praise and criticism given by others. This characteristic of being driven by their own goals rather than by those imposed by society has been called "entelechy" [Lovecky, 1992]. It makes them very independent or *autonomous*. It also makes them *question rules and authorities* [Schetky, 1981; Sebring, 1983; Whitmore, 1980]. They are particularly prone to find the gaps and inconsistencies in the conventional view. They often ask embarrassing questions, to which people do not know what to answer. They love ardent discussion and the play of question and answer, argument and counterargument. They are generally *non-conformist*, preferring to reach their own understanding of an issue rather than to accept the view of the majority or of a higher authority such as church, government, or intellectual establishment.

The downside of this non-conformism is alienation. Gifted people usually *feel different* [Roedel, 1986], and out of step with the rest of society. Other people, although they may look up to them for leadership, do not really understand them, and generally do not appreciate their intensity, perfectionism, questioning, and being "too smart". As a result, GPs have a sense of being alone in the world. Yet, they do not try to compensate for their intrinsic loneliness by desperately seeking company. They rather have a *need for solitude*, and for periods of contemplation in which they are not disturbed by others [Csikszentmihalyi, Rathunde, & Whalen, 1993; Ochse, 1990]. As such, most GPs are categorized as *introverted*.

The above may have suggested a picture of rather egocentric individuals who do not care much about others. However, the opposite is true: GPs tend to be very *compassionate* and have great *empathy* for other people [Lovecky, 1994]. They can feel along with others, and help them understand themselves in the process. They have a strong *sense of fairness*, and clear moral convictions [Gross, 1993; Hollingworth, 1942; Silverman & Ellsworth, 1980; Terman, 1925]. They tend to be outraged at injustice [Rogers, 1986; Silverman & Ellsworth, 1980], and try to work for a better society. They strongly value integrity and *honesty*.

1.	Good problem solving/reasoning abilities
2.	Rapid learning ability
3.	Extensive vocabulary
4.	Excellent memory
5.	Long attention span
6.	Personal sensitivity
7.	Compassion for others
8.	Perfectionism
9.	Intensity
10.	Moral sensitivity
11.	Unusual curiosity
12.	Perseverant when interested
13.	High degree of energy
14.	Preference for older companions
15.	Wide range of interests
16.	Great sense of humor
17.	Early or avid reading ability
18.	Concerned with justice, fairness
19.	At times, judgment seems mature for age
20.	Keen powers of observation
21.	Vivid imagination
22.	High degree of creativity
23.	Tends to question authority
24.	Shows ability with numbers
25.	Good at jigsaw puzzles

Table 1: *Silverman's [1990] Characteristics of Giftedness scale, proposing typical traits used to identify gifted children.*

Conclusion

Giftedness is characterized by a complex of traits extending far beyond aptitude for IQ tests. A typical summary of these traits can be found in Silverman's [1990] Characteristics of Giftedness scale, which has been shown to reliably distinguish gifted from non-gifted children (see Table 1).

Most of these traits clearly support the potential for exceptional achievement. For example, to succeed in difficult enterprises you need ambition, passion and perseverance; you need to be able to imagine or envision things beyond the ordinary; you need to be sufficiently independent to overcome skepticism and resistance; you need to be able to see how different elements fit together to form a novel whole.

Yet, giftedness is more than the sum of traits necessary to succeed: it is a coherent "Gestalt", or personality type, including traits that appear indifferent or even

detrimental to the chances for success. For example, while intellectual non-conformism may be necessary for true innovation, social non-conformism may make it more difficult, as you always need the help of others to succeed. Sensitivity, overexcitability and isolation make the gifted more vulnerable, while their compassion and sense of humor seems at best irrelevant to exceptional achievement (one might rather assume that selfishness and seriousness would make it easier to achieve one's ambitions).

We will now argue that all these traits can be inferred from a single underlying characteristic, to be called *neural propagation depth* which, extended by Csiksentmihalyi's concept of *flow*, provides a simple and coherent explanation for the Gestalt.

Neural mechanisms of giftedness

Much research has been done to determine the fundamental factors underlying intelligence and giftedness. A first basic observation is that the results of different tests measuring either intelligence in general or certain aspects of it (e.g. verbal, spatial, musical, ...) are all correlated, implying that there is a common factor in what they are measuring. The existence of this so-called *g*-factor (for "general intelligence") has been demonstrated by multiple statistical analyses [Jensen, 1998; Chabris, 2006]. Research trying to pinpoint biological or psychological mechanisms underlying this factor has come up with several non-trivial correlations. First, *g*-factor intelligence seems to have a clear genetic component, in that relatively little of the variations between individuals can be accounted for by normal environmental variation. Second, *g* is positively correlated with basic biological factors such as size of the brain and speed of transmission in nerves. It is also correlated with elementary cognitive capacities such as size of working memory and reaction speed (positively), or inspection time (negatively) [Jensen, 1998; Chabris, 2006].

This has led to various speculations as to the underlying mechanisms causing differences in *g*-intelligence, under the general assumption that *g* somehow reflects the *efficiency of information-processing in the brain*. Intuitively, we may compare the brain with a computer, and then *g* could be a measure of the processor speed or perhaps the amount of RAM (working memory) that is available for performing operations. But brains and computers function very differently, and therefore we should be careful in using such analogies. A better model of the brain can be found in neural network simulations, which have been shown to adequately replicate a broad range of cognitive processes [McLeod, Plunkett and Rolls, 1998]. Such neural networks will function better or worse depending on a whole range of parameters, such as number of nodes, number of connections, amount of experience, learning constants, etc.—but simple processor speed is not one of them.

An obviously crucial factor for intelligent behavior is the amount and quality of the *knowledge* that is stored in a neural network: without any knowledge, the network is simply incapable of solving any problem. But the knowledge factor cannot be the whole, or even the main, story as people who have undergone a similar amount of education still vary strongly in their general intelligence. A well-known way to

conceptualize the difference between knowledge-dependent and general factors is Cattell's [1987] distinction between "fluid" and "crystallized" intelligence. *Crystallized intelligence* is the result of the accumulated knowledge and experience that we bring to tackle problems. It typically increases unrestrictedly with age. *Fluid intelligence* is the quickness and versatility of thinking that is needed to solve the most abstract, highly *g*-loaded IQ tests such as Raven's Progressive Matrices. Fluid intelligence increases during childhood, but reaches a plateau by the end of puberty (around 16 years) and tends to decrease with older age [Horn, 1982; Jensen, 1998].

A neural model of fluid intelligence cannot depend just on the amount or type of knowledge acquired. The proposed mechanisms can be ordered in two classes, depending on whether they focus on the immediate processing of information, or on the changes in network structure that underly learning. Processing accounts [e.g. Jensen, 1998] tend to focus on the speed of transmission of signals between neurons, on the intensity of the signal, or on the amount of noise or dissipation that disturb the signal. Learning accounts [e.g. Garlick, 2002] tend to focus on the ease with which neurons develop new connections to other neurons. Given what we know about the brain, there is plenty of room for variation in the different physiological parameters that determine the efficiency of these processes.

The structural building blocks of the process are neurons and the synapses that connect them. A neuron builds up an electrical potential as it is stimulated by other neurons via its incoming synapses. If the total stimulation crosses a certain threshold, the neuron will "fire", propagating the action potential across its long axon to its outgoing synapses. These will in turn stimulate the neurons they are connected to by the diffusion of neurotransmitters across the synaptic cleft. This may result in a new firing, and thus a transmission of the activation to one or more further neurons. The whole process is very energy intensive (the brain uses some 20% of total calories while it only takes up 2% of body mass [Raichle & Gusnard, 2002]) and subject to several constraints and possible problems.

For example, to efficiently propagate the electrical signal along the axon, this "wire" needs to be electrically insulated. This is achieved via *myelin*, a fatty substance surrounding the axon. One of the more plausible hypotheses therefore proposes that more intelligent brains are characterized by higher myelination [Miller, 1994], so that impulses can be carried with less loss. Another constraint is that the generation and regeneration of these electrical impulses requires constant input of energy in the form of glucose. This is brought to the neurons via the blood vessels that criss-cross the brain, and the glial cells that surround and support the neurons. Again, a plausible hypothesis is that more intelligent brains are characterized by more glial support tissue. This is confirmed by at least one observation, that Einstein's brain apparently had more glial tissue than normal in certain areas [Heilman, Nadeau & Beversdorf, 2003]. Both hypotheses may explain the correlation between intelligence and brain size [Jensen, 1998], as glia and myelin occupy a sizeable fraction of the brain volume.

A somewhat more down-to-earth hypothesis might propose that more intelligent brains simply have better blood circulation, e.g. because they have more, wider or more flexible capillaries. This might explain why fluid intelligence tends to decrease in old age, as it is well-known that age-induced atherosclerosis makes blood circulation more

difficult. Related hypotheses may focus on the energy production by the mitochondria within the cells, a process that produces a lot of toxic free radical byproducts, which must be efficiently mopped-up by antioxidant defenses in order not to disturb the cell's functioning. This may explain why many "smart drugs" [Dean et al., 1991], such as Ginkgo-extract [Stough et al., 2001] or Acetyl-L-Carnitine, which have been shown to improve cognitive processing in certain circumstances, have an antioxidant and/or circulation-improving effect. Other hypotheses might focus on the permeability of cell membranes for chemical signals, where e.g. the concentration of Omega-3 fatty acids has been shown to affect cognitive development [Willats et al., 1998], or on the neurotransmitters that are produced by the neurons to carry activation across the synaptic cleft [Heilman et al., 2003].

All these approaches consider factors that either facilitate or obstruct the propagation of activation across connections between neurons. The learning-based approaches, on the other hand, focus on the creation of these connections in the first place. According to the *neural plasticity hypothesis* proposed by Garlick [2002], during the critical maturation period between birth and 16 years of age, intelligent brains more easily form connections via the growing of axons. The effect is that for the same level of education and experience, the more intelligent brain will have developed a larger and more efficient network of long-range connections, thus facilitating the processing of complex information. Other learning-based hypotheses may focus on the short-range changes in the conductivity of existing synapses via the process of long-term potentiation (LTP), positing that such adaptation occurs more easily in the more intelligent brain. Such a hypothesis might be supported by the observation that mice genetically enhanced to have higher synaptic plasticity not only seemed to have better memory but to behave more intelligently [Tang et al., 1999]. Both types of hypotheses may find support in neural network simulations, where the speed of adaptation depends on a learning parameter that controls how much the weight of a connection changes after a new experience [Garlick, 2002].

Neural propagation depth

In the present paper, I do not want to argue for or against any of these specific hypotheses—whether they are focusing on processing or on learning. I would rather propose a model that is compatible with all of them, and which I will call *neural propagation depth*. The core idea is that intelligent processing requires the parallel propagation of activation across a complex network of nodes connected by variable-strength links. The efficiency of this propagation will depend on the dynamics of signal transmission across individual nodes (neurons) and links (synapses), but also on the architecture of the network, as a signal may need to follow either a circuitous route to get from A to Z, or a shortcut bypassing most of the intervening connections.

The basic assumption is that every crossing of a connection is problematic: it requires energy that may be scarce or unavailable and it is accompanied by *dissipation* of the available energy, potential transmission *errors*, and the intrusion of *noise,* in the sense of random perturbations coming from elsewhere. All these "entropic" factors reduce the signal-to-noise ratio, so that the probability of the correct signal being

transmitted diminishes with every step (crossing) of the process. We may generally assume that after a certain number of steps, the remaining signal will have become too weak to be distinguishable from the background noise, resulting in the stopping of the propagation process.

In a simple neural net model, we may assume that a given amount A(t) of activation is transmitted at each time step t. Without external stimulation generating more activation, activation will diminish at every step because of the general dissipation processes sketched above. This can be modelled by an exponential decay of the form:

$$A(t) = c.A(t-1) = c^t A(0) \text{ with } 0 < c < 1$$

c is here a decay constant characteristic of the specific brain physiology, and A(0) is the initial amount of activation that started the process. We can moreover assume that neurons are characterized by a threshold B that incoming activation must surpass for the neuron to become activated as a whole. Therefore, activation will no longer be transmitted after a certain number of steps D, determined by the condition:

$$A(D) = c^D A(0) < B$$

This means that propagation processes will have a typical maximum length of :

$$D = \text{int}\,(\log(B/A(0)) / \log c)$$

where *int* represents the function that keeps the largest integer number, but erases the fraction after the decimal point. We will call D the *propagation depth* of the network, since it represents the maximum number of coherent steps a process of information propagation can undergo before it stops. "Coherence" refers here to a process that is not interrupted or interfered with by outside stimuli—which may focus attention in a direction different from where the initial "train of thought" was heading.

In practice, of course, thinking or processing will never stop, because there will always be stimuli to grab the attention and refocus the process. Even in the absence of outside stimuli (e.g. in situations of sensory deprivation or REM sleep) the brain will generate its own stimuli by amplifying noise and chance fluctuations, so as to generate a continuous pattern (e.g. a hallucination or dream), albeit one that wanders without constraint across a field of associations. The actual number of steps in any train of thought will of course vary, as local conditions (strength of synaptic connections, amount of initial activation, random fluctuations, ...) will affect how much activation remains after each propagation step. But the core idea is that different brains will be characterized by different "typical" or "average" propagation depths. Our proposed theory of giftedness then states that *more intelligent brains are characterized by higher average propagation depths.*

Let us look at some concrete numbers to see how the decay factor c affects the propagation depth D. Assume that B/A(0) = 0.1, i.e. the signal is no longer transmitted if it goes below 10% of its initial activation strength. Let us now consider two decay factors: c = 90% and c' = 80%. The corresponding propagation depths are D = int(log

0.1/log 0.9) = 21, and D' = 10. This means that if 10% more activation is lost at each transmission step, the total length of the propagation decreases with more than half, from 21 steps to a mere 10. Let us now consider a much smaller variation in decay factor: suppose c" = 89%, then D" = 19. In other words, a reduction in decay factor with a mere 1% already leads to a decrease in propagation depth of more than 10%! For a more detailed view of the relation between c and D, check Fig. 1.

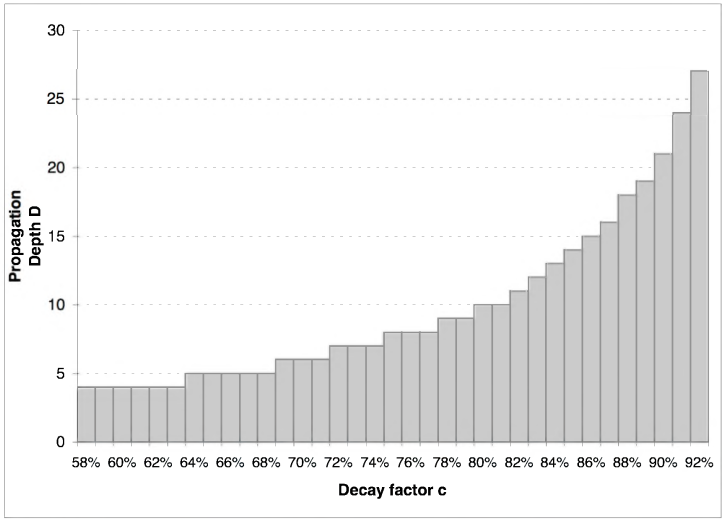

Figure 1: a plot of the relationship between propagation depth D and decay factor c (changing with values of 1%), representing the formula: D = int (log 0.1 / log c)

Given the variability and potential for error in the physiological mechanisms sketched above, we can expect a substantial variation in typical decay factors between individuals, depending on such factors like genetic differences, ontogenetic brain development (e.g. growth of myelin and glia), and overall health, nutrition and energy level. According to the model proposed, this will lead to an even more substantial variation in propagation depth. We now need to examine the implications for cognitive processing of such differences in propagation depth.

Propagation depth and intelligence

In the most general terms, intelligence can be conceptualized as the ability to solve problems. A problem here means any difference between the actual, perceived state of

affairs and a potential, preferred or desired state of affairs. This can refer to a concrete physical problem, such as hunger or a car breaking down, or an abstract, intellectual problem, such as the desire to prove a mathematical theorem, or to produce a work of art. While concrete problems eventually need to be tackled through action, the preparation of the action is typically an internal, mental process where different possible routes for action and their implications are conceived, explored and compared. This cognitive process starts with the conceptualization of the initial state of affairs. This includes the definition of what is the problem, i.e. in what respect the state needs to be changed. From this initial state, different associated states are explored, until one or more new conceptual states are discovered that appear to solve the problem. To implement this solution, the sequence of steps leading from the initial to the final states must be formulated explicitly and memorized, producing a *plan*. As we will argue in more detail, the maximum length of this sequence will strongly affect the maximum complexity of the problem that can be tackled.

While this description of problem-solving may have been inspired by the classical, "symbolic" approach to cognition [Newell and Simon, 1972], the present formulation is abstract enough to be applicable to more recent connectionist [McLeod & Plunkett, 1998] and embodied [Clark, 1999] approaches to cognition. Indeed, even low-level sensory-motor activities—such as catching a ball—require a cognitive transformation from perceived to desired states, as the visual impression of a ball approaching needs to be translated by the brain into an estimated trajectory and a planned sequence of movements to intersect with that trajectory. The main difference with the older symbolic approaches is that this implicit analysis of the situation and planning of action happens at a less conscious, subsymbolic level, where it is strongly influenced by the sensory-motor feedback from the senses and the muscles. Although it is in this case no longer possible to strictly separate internal processing from external interaction, the internal processing still needs to follow a complex path of "reasoning" or "inference" across different intermediate states in order to come to a viable solution.

This conception of problem-solving is also general enough to cover both "convergent" and "divergent" thinking [Guilford, 1967]. The former applies to problems, such as a complex calculation, where there is a unique solution that can only be found by being very selective, determining the "right" next state at each step of the problem. The latter refers to problems, such as brainstorming or producing a work of art, where the number of acceptable solutions is a priori unlimited, but where there still is an explicit or implicit criterion for distinguishing better ones from worse ones.

Finally, we must note that our problem-solving model covers sequential as well as parallel processes. To find a solution, you can explore intermediate states one by one (e.g. depth-first search), or you can explore many states simultaneously, considering a complex combination of several of them as a possible solution. Traditionally, symbolic and convergent approaches tend to be modelled as sequential processes, whereas subsymbolic and divergent approaches tend to be seen as parallel, but we hope to have shown that this is not logically necessary.

A network model of problem-solving

Let us now formulate our problem-solving model in more detail so that we can examine the role of propagation depth. We will call the elements that mental processes work with *concepts*. Concepts are the categories or distinctions that we use to carve up the continuous, infinitely extended world of experience into discrete, manageable "chunks" and that allow us to identify meaningful classes of objects or features. Examples of concepts are "car", "inflation", "large", and "blue". Concepts can be explicit and conscious, as in the symbolic processes supported by language, or implicit and subconscious, as in the distributed pattern-recognition processes that underlie perceptual experience, or somewhere in between. The initial situation that defines the problem can now be conceptualized as a particular combination of concepts, e.g. the "large" "car" is "out of gas"; "inflation" and "unemployment" are "high"; or the "canvas" is "empty". This initial state needs to be transformed into a final state characterized by a different combination of concepts, e.g. the "car" "drives", or the "canvas" contains a "painting" of a "woman" with a "child".

In contrast to the traditional symbolic approach, I will assume that problem-solving *cannot* be achieved by systematically investigating all combinations of the available concepts aided by heuristic rules, until an acceptable one is found. The failure of symbolic AI to come up with workable simulations of intelligent behavior except for very restricted, artificial domains is sufficient evidence for this assumption. Furthermore, it is worth noting that the real world is simply too complex to be carved up into a small set of independent categories. To offset the combinatorial explosion engendered by a large set of concepts, together with the fact that concepts are never really independent, we need something more than heuristic rules: we need a complex tissue of associations weaving the concepts together into a network [Heylighen, 2001a,b]. These associations will guide the processes that search for problem-solutions.

This brings us to the essence of the connectionist approach: cognitive processes take place by the propagation of activation across a network of connected "units", where the connection weight represents the degree of association that exists between the units. There are two basic "flavors" of connectionism, *localist* and *distributed*. In localist representations, one unit corresponds to one concept, i.e. a separate element of meaning. In distributed representations, concepts are defined as patterns of activation extending over several units, while individual units partake in the representation of several concepts. From the little we know about brain functioning, it seems that networks of real neurons are neither purely localist (e.g. it seems unlikely that there would be a single neuron for the concept of "grand-mother" [Gross, 2002]), nor purely distributed (individual neurons appear to be specialized to respond to a particular category of stimulus, e.g. a specific individual [Quian Quiroga et al., 2005]). It seems most likely at the moment that concepts are implemented as small assemblies or clusters of similar, but not quite identical, neurons.

For our present purposes, the exact implementation of concepts at the neural level is not so important. What counts is the way concepts are associated in such a way that the activation of one concept may trigger the activation of other concepts. All connectionist models agree that the weights of connections develop by reinforcement:

the more often a connection is (successfully) used, the stronger it will become. The simplest learning algorithm, which is reflected in the actual dynamics of synapses, is the Hebbian rule, which states that a connection between units is strengthened each time both units are co-activated. This means basically that concepts will develop an association whenever the one is encountered simultaneously with, or shortly after, the other one. The corresponding process for neurons is the long-term potentiation of the connecting synapses. For example, regularly seeing a baby in a cradle, will create a strong association between the concepts "baby" and "cradle". Conversely, concepts that are rarely or never encountered together will not develop any associations. Thus, few people would associate the concepts "baby" and "fish".

This means that the problem-situation where a place is to be found for a "baby" to "sleep" will almost automatically trigger the idea of obtaining a "cradle" as potential solution. The association is so immediate that few people would think of a such a one-step inference, baby & sleep -> cradle, as a form of problem-solving. But many situations require a more complex process.

For example, if the problem is that the "baby" regularly "cries" this may trigger the inference that the baby is "ill", which may in turn suggest "allergy" as a potential illness, and "food" as a possible cause of such an allergy. Finally, of the possible foods, "fish" may be chosen as the most likely cause of allergy, resulting in the potential solution of removing fish from the diet. This brings us to the 5-step association path: baby crying -> illness -> allergy -> food -> fish -> fishless diet (see Fig. 2).

At first sight, it should be easy to propagate activation over a mere 6 concepts, and 5 intervening links. On second sight, however, each step is chosen among several other possibilities. For example, crying may indicate besides illness also hunger, loneliness, tiredness, anxiety, or physical discomfort, while fish is just one of several food types that may be allergenic. This means that the total number of possibilities to be explored grows exponentially with the number of steps. Assuming that there are on average 10 possibilities for each step, the total number of possibilities to be explored would be 10^5 = 100 000, which seems wholly unrealistic for unaided cognition.

In practice, of course, possibilities are not explored sequentially, one by one. Spreading activation is an automatic, parallel process, that will follow several of the strongest associations simultaneously, focusing on those concepts that gather most activation overall [Heylighen, 2001a,b]. This focus depends on two factors:

1) the existing general *knowledge*, which determines the weight of the different associations. For example, somebody who does not know that food can be a cause of allergy is unlikely to conclude that eating fish may be a cause of the baby crying;

2) the specific *context* that primes the network with low level activation or the temporary facilitation of certain associations. For example, the memory that the baby recently ate a food containing fish may prime the network so as to facilitate the flow of activation into the "fish" concept.

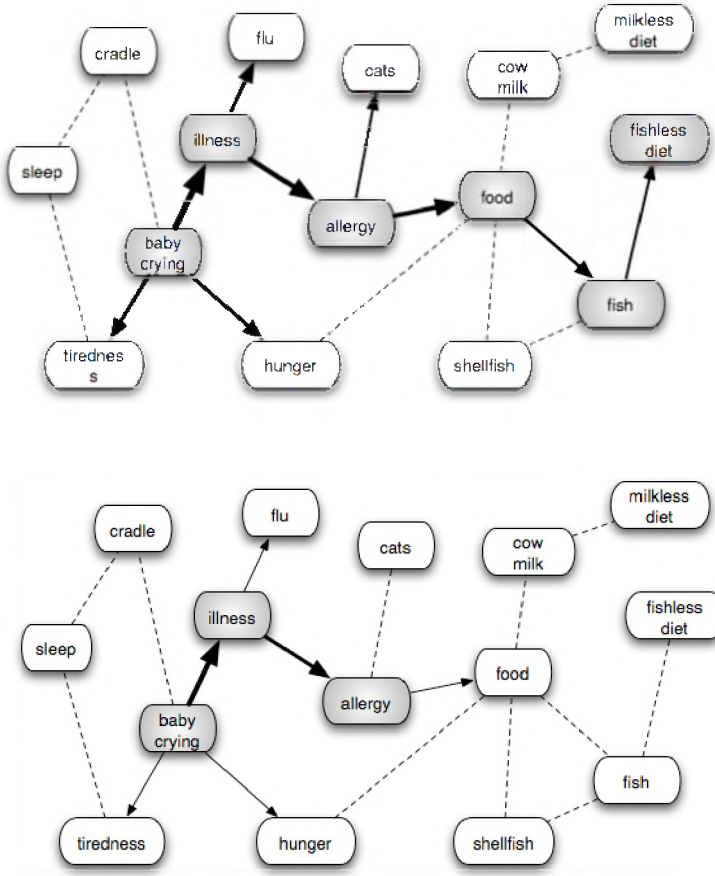

Figure 2: illustration of problem-solving via activation spreading over a network of associated concepts. Highlighted nodes represent activated concepts, dotted lines represent associations, and solid arrows represent the amount of activation propagated over an association (thicker arrows = more activation). Because of decay, activation decreases with subsequent steps in the propagation process. The diagram above represents a network with relatively high propagation depth, where six concepts in sequence get activated. In the diagram below, there is much more decay so that activation stops propagating after three steps. (Note that this representation is of course very simplified, including only a few representative concepts and associations, and not marking the strength, orientation or valence (reinforcing or inhibitory) of the associations.)

The role of propagation depth

Generally, we can conclude that the competence in problem-solving will depend at least on the following factors: number of concepts explored (sequentially and/or in parallel), available knowledge, and context-sensitivity. We will now show that all of these depend directly or indirectly on propagation depth.

This is most obvious for the number of concepts explored. For a full problem solution, *all* steps of the inference sequence or action plan need to be kept in mind. Just remembering the initial "baby cries", the second step "illness" and the fourth step "fish" is insufficient to tackle the problem, because it does not suggest an unambiguous action plan to remedy the situation. Leaving out the "allergy" step may lead one to conclude that the baby is ill because the fish it ate was spoilt, thus incorrectly concluding that the baby should be treated for poisoning. The point is not only for activation to propagate along associations that are stably stored in long-term memory, but to keep the intermediate stages simultaneously activated, thus temporarily maintaining a trace of the reasoning process.

If we assume as before that activation decays at each propagation step, then activation may never reach the desired end-point ("fishless diet") because it dips below the threshold at an earlier stage (e.g. "food") (see Fig. 2). If the process is reactivated along the way by an independent stimulus (e.g. seeing the remains of fish in the plate that the baby ate), the endpoint may be reached, but with the intermediate stages lost through decay in the meantime. The strength of the decay will determine how many steps in the problem-solving sequence can be simultaneously kept in mind. This number can be interpreted as the size of *working memory*. Brains with a lower decay factor will have greater propagation depth and working memory size, allowing them to explore a much larger *range* of potentially relevant concepts, and to discover more complex, less commonplace sequences of solution steps.

For example, assume that the same reasoning about baby crying is made by someone with the same knowledge, but a greater propagation depth. Instead of stopping after 5 steps, that person may continue the reasoning while keeping 6 or 7 steps in minds. That person may make the additional inference that while pure fish allergy is rare in babies, shellfish allergy is common, but that the baby did not eat any shellfish. The conclusion may be that another food allergy is likely to be involved, leading the reasoning to backtrack from "fish" to "food", and from there to "cow milk", coming up with a perhaps better explanation of the baby crying (see Fig. 2). A truly gifted individual, by considering all the factors directly and indirectly associated with baby crying, may even come up with a revolutionary hypothesis which, if confirmed by further observations, may result in the identification of a new syndrome and thus in the saving of thousands of infant lives...

Reducing decay factors also positively affects the knowledge and the context-sensitivity. First, contextual information, i.e. information that is not part of the explicit problem definition but that is still kept in short-term memory (e.g. that the baby recently ate fish) will affect the spread of activation, albeit more weakly than the concepts in focus (e.g. that the baby is crying once again). Therefore, its effects will quickly dissipate, unless the decay factor is weak enough to keep contextual activation going.

Knowledge, as noted, is the result of the creation and reinforcement of links between units that are regularly co-activated. Less decay means higher (co-)activation and higher propagation depth, i.e. a larger maximum distance between the units co-activated by the same process. Therefore, it will lead to more efficient reinforcement of used links (increased conductivity of the synapses), and to the creation of links between units that are initially farther apart while still being associated. It is the latter process that Garlick [2002] calls "neural plasticity" and proposes as the basis of intelligence differences. Variations in propagation depth may thus explain variations in neural plasticity or, more generally, in learning ability, and the resulting variations in problem-solving competence.

Vice-versa, it is worth noting that intrinsically higher neural plasticity or learning ability may indirectly cause higher propagation depth, albeit not via the intervening decay factor. Indeed, if a brain is more adept at creating meaningful shortcuts between spatially remote neurons during development, then such a brain will also be able to explore a wider range of approaches, as it will need to perform fewer reasoning steps to connect the initial problem statement to a solution state. In network terms, such a brain will be more of a "small-world network", i.e. the average path length between its neurons will be smaller. E.g. in our baby-crying example, someone may have learned to immediately associate such crying with food allergies, thus bypassing the "illness" and "allergy" steps. This would allow reaching the potential solution "fishless diet" after a mere 3 steps rather than 5, leaving sufficient activation for two additional steps of exploration beyond "fish" (e.g. from "shellfish" back to "food allergy" and from there to "cow milk").

The present paper does not intend to take position about the precise underlying neurophysiologic causes of differences in propagation depth. The proposed model is compatible with accounts focusing on efficiency of signal transduction between neurons (e.g. myelination), with approaches focusing on the efficiency of learning (e.g. neural plasticity), or with some combination of both. Discriminating between these mechanisms will require much more fine-grained observations which we will not undertake here, although we can suggest some possible avenues for exploring the implications of the different modelling strategies. For this, we will introduce a concrete simulation model of propagation depth and how it may affect IQ measures in the appendix.

Propagation depth as a physiological model of g

We have shown how both neural efficiency and neural plasticity theories of intelligence can be seen as special cases of the more encompassing construct of neural propagation depth, and how this construct directly explains intelligence in the sense of problem-solving capability.

The same cannot be said for the simpler theories. For example, the hypothesis that more intelligent brains are characterized by faster signal transduction across nerves [Jensen, 1998] does not in se explain why they are more intelligent: a computer with a faster processor may need less time to solve a given problem, but will not be able to

solve any problem that a slower processor cannot solve. Since most IQ tests are untimed, speed is not central to the definition of intelligence. Similarly, the hypothesis that neural connections in more intelligent brains are better insulated by myelin [Miller, 1994] may explain their faster speed and reduced need for energy, but does not explain higher intelligence functions. Even the more sophisticated neural plasticity hypothesis [Garlick, 2002], which states that more intelligent brains more easily produce long-range connections between neurons, does not guarantee that these connections will be useful in complex problem-solving: that is only likely to happen if these connections are created as traces of successful problem-solving experiences, implying that there should already have been a minimum form of advanced intelligence during the process of connection formation.

Another strength of the propagation depth model is that it is compatible with a variety of elementary cognitive and neurological correlates of intelligence or *g* [Jensen, 1998; Chabris, 2006]. The shorter reaction and inspection times characterizing high *g* individuals may be explained by the fact that longer propagation is likely to have created shortcuts for multiple step neural pathways. Moreover, the underlying assumption of lower dissipation or decay of the activation implies that there is less chance for errors or noise perturbing the process and thus requiring a time-consuming new focusing of activation. This may explain in particular the strong negative correlation found between *g* and the variability of reaction times while repeating the same task [Jensen, 1998]: the more "noisy" the propagation process, the higher the chance that a reaction time longer than strictly needed would occur.

The correlation between *g* and the size of working memory follows rather straightforwardly from our assumptions if we view working memory as the collection of concepts that remain simultaneously activated during the problem-solving (propagation) process: the lower the decay factor, the larger the number of such active concepts. The fact that more intelligent people use less energy to perform a given task, as measured by glucose metabolism in the active brain region [Haier, 1993], also fits in with the model: if less activation is lost through decay or dissipation, less input of energy is required to "renew" or "sustain" the level of activation sufficiently to solve the problem. Finally, the (weaker) correlation between *g* and the capacity for sensory discrimination [Jensen, 1998] also follows from the propagation depth model: while there is no special reason to assume that more intelligent people have more efficient sensory organs, their higher propagation depth makes it more likely that weak signals from these organs would accurately reach the higher cognitive regions where awareness of differences occurs.

The flow model of motivation

After examining the role of propagation depth in problem-solving skills, we need one more theoretical construct before we are ready to explain the "gifted personality Gestalt", namely a simple concept of *intrinsic motivation*. Whereas most theories of motivation focus on external factors that are considered to be rewarding or punishing, such as getting food when you are hungry or company when you feel lonely, a number

of, mostly humanistic, psychologists have proposed intrinsically motivating factors, i.e. activities that are rewarding in their own right, independently of the external changes they bring about. For example, making a walk in the park, performing a hobby or sport, or developing your painting skills are pleasurable even though they bring no obvious improvement in your situation with respect to the outside world. Maslow [1970] has proposed to distinguish "deficiency needs", which require an outside reward to be satisfied, such as food, attention, or a financial bonus, from "growth needs", which are directed at personal development. While there is some discussion over whether intrinsic and extrinsic needs and motivations can really be separated, the only thing we need for the present discussion is a concept of motivation that depends only on the skills of the individual, and not on any specific environmental characteristics, as these will differ from one gifted individual to another.

Possibly the most concrete concept of intrinsic motivation can be derived from Csikszentmihalyi's [1990; Csikszentmihalyi & Nakamura, 2002] theory of *flow*. Flow is an intrinsically rewarding state of activity that people will try to attain, while they will feel unhappy, dissatisfied or stressed in its absence. The flow state was conceptualized by Csikszentmihalyi by finding common patterns in those activities during which people typically reported the highest level of pleasurable feelings, as measured by the method of experience sampling. Examples of such activities are rock climbing, performing music, playing a challenging game such as chess, or, more generally, being engaged in a complex, attention-demanding task in which one is particularly skilled. During flow, activity is focused, continuous and goal-directed, with constant feedback telling the individual how well he or she is doing with respect to the goals. But most importantly, the results are such that the individual feels *in control*, able to achieve the goal, although the goal itself may still be far away and never actually be reached. The essence is that during a flow activity, *the skills match the challenges*, i.e. however high or low the demands of the situation, the individual feels able to do what is necessary, even though this may require investing most or all of her/his attention and effort.

Flow can fail to be achieved for two opposite reasons (see Fig. 3):

1) the challenges are higher than the skills. In this case, the individual loses control over the situation, and feels anxious, having good reason to expect failure;

2) the challenges are lower than the skills. In this case, the individual feels bored or indifferent, lacking the stimulation to truly focus on the task.

In either case, the individual will be motivated to get out of this unpleasant state and regain flow, by raising the difficulty of the task in the case of boredom, by trying to lower it in the case of anxiety. For example, a chess player will look for a more experienced opponent if winning a game is too easy, and a less experienced one if winning is almost impossible.

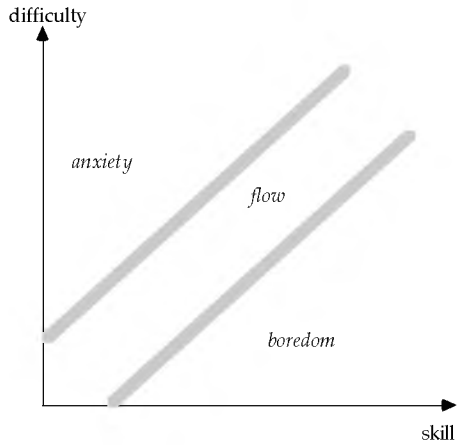

Figure 3: flow can occur when the challenge or difficulty of a problem roughly matches the skill brought to bear on it. Individuals will normally try to stay in the "flow channel" around the diagonal in this difficulty vs. skill diagram, avoiding both the anxiety zone in the upper left and the boredom zone in the lower right.

Generally, we can assume that for an unchanging task the skill levels will increase as the individual becomes more experienced at that task. Thus, activities that initially were challenging tend to become boring, and therefore people tend to gradually increase the difficulty of the problems they set for themselves. For example, alpinists will try to climb increasingly high and difficult mountains, while managers will try to get responsibility over ever larger groups of employees or companies.

Independently of Csikszentmihalyi's more elaborate (and in a number of respects more vague) theory of flow, the present simple model of intrinsic motivation makes sense from an evolutionary perspective. Organisms are obviously selected to remain in control as much as possible: losing control because the problem is more difficult than what your skills are able to cope with may cost you your life! Therefore, we can safely assume that our brains are programmed to as much as possible avoid the "anxiety zone" in Fig. 3.

The need to avoid the "boredom zone" is less evident, but can be explained as follows. In the boredom zone, existing skills are not used; therefore they do not get the chance to develop further by experience, and may even be forgotten in the longer term. Yet, in evolution you cannot afford to stand still. There is a constant competition between individuals and species. Whenever one manages to get the upper hand via some small advance, the others will have to follow suit, or be eliminated by natural selection. Rather than wait until a new challenge is externally raised, such as a competitor becoming more skilled, the wisest strategy is to try to develop one's skills whenever possible. If necessary, the opportunity can be created, by engaging in self-

chosen "problems"—such as climbing a rock or winning a game of chess—that in themselves provide little survival value, but that offer a relatively safe and controlled environment in which to test and extend one's skills. This "challenge-seeking instinct" can be recognized in the play and exploration behavior shown by higher animals.

Applying the model to giftedness traits

Armed with the concepts of propagation depth and flow motivation, we are now ready to explain all the different traits that make up the gifted personality, as reviewed earlier. We will start by assuming that gifted people have a neural propagation depth much higher than the average person, but the same basic motivation to balance skills and challenges.

Cognition

We have already demonstrated how a higher propagation depth leads to better problem-solving and reasoning skills (Fig. 1). Also the fact that a gifted mind seems to work in a higher gear follows directly: as less activation is lost to dissipation, reasoning can move faster and farther, requiring less effort and "time out" for rest or refocusing in between activities. More importantly, farther propagation of activation will allow a GP to discover connections and analogies between concepts that to normal people appear unrelated—because activation spreading from the one concept will have decayed well before it has found a path connecting it to the other concept. This allows the GP to discover the deeper, more general patterns or systems in which these concepts fit. As such, they will be quicker to comprehend abstract—e.g. mathematical or scientific—ideas and theories, which typically apply to a much wider range of phenomena than common-sense rules.

The GP's imagination and creativity too are direct consequences of better propagation. Imagination, in the concrete sense of *imagery*, can be understood as a flowing back of activation from more abstract concepts being reflected upon to the neural circuits that normally represent sensory (e.g. visual) input, where they trigger memories of concrete stimuli associated with these abstract thoughts [Kosslyn et al., 1995]. Trying to imagine in detail what a phenomenon that is not presently available looks like is a notoriously difficult task, that requires the controlled activation of typically vague memories. Therefore, most people will merely experience a very coarse representation of the imagined situation, e.g. without the normally experienced colors, textures, feels, or level of detail. The assumption that GPs have a better memory for experiences, as we will immediately motivate, and that they have more efficient means to let activation spread between memories (both perceptual and conceptual), thus creating novel combinations of experiences, seems sufficient to explain why they have a more vivid imagination.

Imagination, in the more abstract sense of *creativity* or the generation of original ideas, too follows straightforwardly from better propagation: as connections are created and maintained between concepts that are farther apart in the network of associations, a

much larger variety of combinations, and especially unusual or unexpected combinations, becomes available for consideration. A common test for creativity is divergent thinking ability [Guilford, 1967]. This can be measured by the number of distinct answers to questions such as "Name as many possible uses for a brick as you can think of". Answering such questions requires activation of the focal concepts (e.g. "brick" and "use") and the spread of this activation as far and as wide as possible in order to retrieve associated concepts. This is obviously facilitated by a high propagation depth.

We have already argued that better propagation produces better learning and memory, because it is easier for meaningful combinations of concepts to become and remain co-activated, thus facilitating the creation and strengthening of synaptic links between these concepts. From flow motivation, we may moreover deduce that gifted people will also be more driven to learn, advance, and generally improve themselves: as their skills in any cognitive domain increase more quickly than other people's, they need to increase their challenge level more quickly as well in order to maintain flow.

An extensive vocabulary is one of the most easy to observe results of this process (and as such one of the most commonly tested skills in IQ tests). New words are typically learned not by studying dictionaries, but by experiencing them in a context of already known words, so that associations with these words are created and the meaning can be inferred [Heylighen, 2001b]. This is something that better propagation will typically facilitate. Moreover, flow will motivate GPs to read much more than other people, without shying away from more complex or technical discourse. Thus, they will both encounter more words and be quicker to grasp their meaning.

Perception and emotion

During perception, activation propagates in several steps from sensory stimuli to the more abstract concepts in which these sensations can be categorized. Given the limited capacity of the brain to sustain spreading activation, only the most salient features of the perceived phenomenon are likely to survive this process. For GPs, we may assume that the capacity of the "propagation channel" is intrinsically larger, and therefore more sensory details are likely to reach the higher, more abstract and conscious processing levels. The disadvantage is that GPs may be "too sensitive", reacting strongly to stimuli that others hardly notice. More generally, GPs may be more vulnerable to sensory and information overload, as their intrinsic perceptiveness coupled with their motivation to always learn more may bombard them with more stimuli than even their highly efficient minds can handle. This sensitivity is not only perceptual or cognitive, but affective, as the activation produced by subtle stimuli, thoughts, or imaginations can propagate far and wide, eliciting powerful, intense feelings and emotions.

In spite of this strength or feeling, the present model does not make any a priori assumptions about GPs being more neurotic or emotionally unstable than others. According to an entrenched cliché, genius and madness are closely related [cf. Simonton, 2001; Eysenck, 1995]. This is illustrated by many accounts of exceptionally gifted people, such as Newton, Van Gogh or Mozart, who also had exceptional

emotional problems. On the other hand, Maslow's [1970] study of self-actualizing personalities, who are supposed to be the epitome of mental health and emotional stability, included many renowned GPs, such as Einstein and Eleanor Roosevelt. A review of the empirical literature [Neihart, 1999] confirms this inconsistent picture: most studies of gifted children find that they are somewhat better adjusted than their peers, while a few point to particular problems of alienation characteristic especially of the exceptionally gifted; some studies of creative artists, on the other hand, find a higher than normal level of neuroses.

The apparent paradox may be resolved by noting that GPs simply react more intensely to the situation they experience. If this is a situation they cannot master, their feelings of anger, sorrow, or despair may reach higher levels than those of average people, and moreover be expressed in ways that others may not even be able to imagine (such as theatrical, literary or artistic representation). On the other hand, as long as they are confronted with intrinsically manageable problems, their perceptiveness and problem-solving competence will help them to achieve better control and therefore a sense of self-confidence, composure and peace of mind [Heylighen, 1992]. Moreover, as noted they are more motivated to overcome problems and maximally develop their potential, resulting in what Maslow [1970] calls "self-actualization". In such happier circumstances, they are likely to exhibit more intensely positive emotions, such as pleasure, pride, awe, love, or compassion.

Motivation and drive

We have already argued on the basis of the flow model that GPs will be strongly motivated to absorb knowledge of all kinds. This explains their intense curiosity and very wide range of interests. The downside is an apparent lack of focus, as becoming specialized in a single field at whatever level of expertise may seem not enough of a challenge, leaving their superior learning and information processing skills underutilized. This already points to one of the most common misconceptions about GPs.

The typical image that the public has of outstanding intelligence is that of the expert who is so advanced in an intellectual domain reputed to be difficult, such as chess or mathematics, that others simply have to bow down in deference. In practice, a GP is more likely to be skilled in a wide variety of fields, many of which may not be specifically associated with intellectual achievement, such as acting or painting, without necessarily reaching the level of the true experts. One reason is that if you have convinced yourself that you can reach the expert level by sustained study, then actually reaching that level is not so much of a challenge anymore, while proving that you can also reach expert level in a different domain may be more stimulating. Moreover, once you reach the rarefied domain of advanced knowledge in a restricted discipline, the number of new concepts and stimuli that you encounter diminishes, simply because there are not enough other experts, cases, or observations around to generate many new insights. When for a given speed of skill increase, the challenge increase slows down, the flow level is reduced, and therefore the motivation to advance further along this

path. This makes such a domain intrinsically less attractive to the intensely curious and novelty-seeking GPs. We might even argue that very specialized disciplines attract the opposite personality type, namely people who like to see everything under the tight control of rigidly defined rules. In the most extreme version, this attitude can be illustrated by the phenomenon of idiot savants, who are extremely expert in one very limited intellectual domain, such as making complicated calculations without pen and paper, but cognitively impaired in other domains. The advantage of the GP's lack of specialization is precisely their potential for creativity and the making of novel connections that cut across the conventionally defined disciplines.

Some examples of these multiple talents and cross-disciplinary achievements exhibited by the truly gifted are Leonardo Da Vinci, who was both a most imaginative engineer and an artist, and closer to us, the 20th century scientists John von Neumann (1903-1957) [Macramé, 2000] and Herbert Simon (1915-2001) [Simon, 1991]. The mathematician von Neumann was not only one of the founders of the modern computing paradigm, but also laid the groundwork for the physical theories of quantum mechanics, quantum logic and ergodic theory, the economic theory of games, and the recently fashionable modelling paradigm of cellular automata. Among colleagues, he was notorious for the fact that you could ask him about *any* complex mathematical problem that you had unsuccessfully been struggling with, and within an hour or so he would come up with a solution. Simon received a Nobel price in economics for his concept of bounded rationality and equivalent honors in computer science as one of the founders of artificial intelligence and in psychology for his investigation of human problem-solving. In addition he made various revolutionary contributions to the theory of organizations, complexity, and philosophy of science. Note that although Simon and von Neumann were arguably more talented than Albert Einstein, they have not reached anything comparable to Einstein's level of recognition, probably because their contributions cannot be pinholed to a recognized domain of expertise, such as theoretical physics, but rather opened up a slew of new problem areas in between the disciplines.

The goals or "missions" that GPs choose for themselves will typically be very ambitious, as the insurmountable difficulties that other people would expect when tackling these problems appear manageable to them. This is another common area for misunderstanding, as these goals, if expressed to other people, would seem wholly unrealistic and unachievable. Of course, like everybody, GPs will sometimes misjudge the difficulty of a task, and the risks they take may sometimes get them into serious trouble. Yet, GPs will generally be quite self-confident when starting out on their "mission", having learned from previous experiences how much farther they can get than others with a little bit of sustained effort, and knowing that even if their main enterprise fails, they will quickly find an acceptable alternative. For example, a gifted engineer may be more likely to give up a stable, well-paid job, and take the risk of starting a new company to develop an innovative technology. Although the chances of the company actually succeeding may be slim, the GP generally has plenty of other ideas in reserve for what to do in case this enterprise fails, and therefore won't be afraid to give up a secure position.

Since GPs, like everybody, normally choose challenges that match their perceived level of skill, they will be able to sustain flow states characterized by great concentration, drive and persistent activity when involved in activities that to others seem so complex and abstract that they would not know where to start. This level of concentration is facilitated by their efficient neural functioning, which can sustain high levels of activation for long times without getting tired or needing external stimulation. This shows itself in their ability to remain focused on an intellectual task, such as tackling a scientific problem, planning a new company or conceptualizing a book or work of art, without being distracted.

The danger of this tendency to set very high challenges while working mostly on their own is the hang for *perfectionism*: demanding such high standards from the finished work that it may never get realized. Because GPs are so adept at working in isolation from the outside world, they may forget that this outside world also imposes constraints, such as requiring recognizable, concrete achievements within a relatively short term. While the GP may be confident that the work is moving ahead fast, the provisional results may appear too abstract or far-fetched to satisfy outside observers, while not being sufficiently advanced yet to satisfy the GP. The result may be grand projects, such as books, movies or scientific theories, that are announced year after year, and that either never seem to materialize, or suddenly appear when no one was expecting them anymore. An example of this pattern can be seen in the later career of the great film director Stanley Kubrick, when the interval between subsequent movies seemed to grow from years until over a decade.

The problem may be exacerbated by the fact that GPs tend to have unrealistic appraisals of other people, expecting them to understand or tackle problems that they themselves would have little difficulty with, but that are simply above the head of the average person. Therefore, they will tend to underestimate the difficulty of projects that involve others, even when they have a realistic estimate of their own capabilities. This brings us to the most problematic area of gifted psychology: their relations with others.

Social relations

We already noted that GPs are largely intrinsically motivated, as they find flow in difficult challenges without needing external reinforcement. Therefore, they are very autonomous, having little dependence on the advice, support or stimulation of others. Their intellectual self-confidence means that they will rarely defer to an outside authority or expert, preferring to investigate an issue on their own. If their conclusions run counter to the accepted wisdom or voice of authority, they will generally not be shy to express their reasoning, hoping to convince others by their logic—or be convinced by them in case they have overlooked some important fact. But the other side may not understand or even want to acknowledge their advanced form of reasoning. This may get the GP in serious conflict, resulting in the most extreme case in the "heretic" being burned on the stake, as happened with the renaissance cosmologist Giordano Bruno. But the truly gifted are usually smart enough to step back when things really get out of

hand, making a compromise with the authorities while privately keeping to their own opinion, as Galileo did in circumstances similar to Bruno's.

The source of tensions between GPs and others runs more deeply than hostile reactions to non-conformity, though. To explain this, we need to extend the flow model to a two-person interaction. We can assume that both GPs and non-GPs will seek a situation where skills and challenges are balanced. When they are each on their own, this poses no specific difficulty. However, when the two parties meet, as in a collaboration or discussion, it will be very difficult to find a level of challenge that satisfies both. Assume that the GP is conversing with a non-GP about a subject that neither party has any specific expertise in. Every sentence said by the one will trigger a cognitive process in the other, to interpret it within the wider context of the conversation, and formulate an appropriate rejoinder. According to the propagation depth model, the process in the GP will extend much farther, drawing more advanced inferences, making more unusual associations, and generally be several steps ahead of the process in the non-GP. As a result, the reply made by the GP will only be partially understood by the other conversation partner.

Such an interaction is intrinsically unsatisfactory for either party. Given the GP's substantially higher level of cognitive skills for the same conversational challenges, there won't be any overlap between the "flow channels" (see Fig. 3) of the two parties. As a result, the GP will tend to remain in the boredom zone, anticipating most of what the other is going to say without learning much new, while the non-GP remains in the anxiety zone, being unable to comprehend much of what is being said, and wondering what the other party is up to. Insofar that the GP is aware of this danger of misunderstanding, s/he may consciously try to simplify the expression, sticking to the more obvious or well-known associations and observations. This may reduce the anxiety of the other party—albeit without any guarantee of success, since it is very difficult for the GP to guess precisely what the other can or cannot understand, given that the two parties' brains effectively have a different wiring, as well as a different propagation efficiency. In particular, the GP may simplify more than is necessary, and thus create the unpleasant impression of "lecturing" or "talking down".

This attempt to adapt to the other moreover creates an additional stress on the GP. "Simplifying" a reasoning cannot be done by just reducing the depth of conceptual propagation, since propagation is a spontaneous process that merely flows along the existing paths in the neural network. The GP cannot stop or slow down her reasoning in order to remain in step with the other party. At best, the GP can let the propagation follow its natural course, and then consciously try to wind it back to an earlier, less advanced stage. For example, when discussing the reason for the baby crying, the GP after concluding that eating fish may be a likely cause, may feel obliged first to explain in painstaking detail to the other party that allergy is a kind of disease that may lead babies to feel so bad that they cry. But such controlled propagation requires more effort than merely letting activation run its course, and is more frustrating because the end result does not satisfy the standards of reasoning that the GP normally adheres to.

The resulting cognitive trajectory may be likened to the famous religious procession of Echternach, in which participants take one step backward after every two steps forward, resulting in a movement that is not only much slower, but more tiring,

stressful and frustrating than a normal way of walking. For a somewhat milder metaphor, consider two people, one well trained, the other a couch potato, going out together for a hike in the mountains. The hike will be frustrating for both parties, as the couch potato will need to put in maximum effort just to keep up, while the athlete will have to forcibly slow down from the normal pace in order not to leave the other one behind.

Given the intrinsic frustration to which these kinds of interactions lead, it is normal that both parties will try to avoid them. This is not a particular problem for the non-GP, who can find plenty of other non-GPs to converse with (and perhaps complain about the GP's obscurity, haughtiness or lecturing). Moreover, if the interaction cannot be avoided, it is anyway the GP who will have to accommodate to the cognitive pace of the non-GP, since the other way around is simply impossible. For the GP, on the other hand, avoiding interactions with non-GPs means avoiding interactions with almost everyone, since GPs by definition are a very small subset of the population. This explains why GPs generally feel alienated and isolated, but still won't do much effort to seek company. Their preference for solitude follows both from the fact that social interaction is intrinsically frustrating to them, and from the fact that they have a low need for stimulation and feedback from others to tackle the problems they have set for themselves. Together with their intrinsic sensitivity to stimuli, this explains why they are typically seen as introverts.

Yet, this does not mean that they lack the normal social instincts, such as gregariousness, compassion or fairness, or the desires for love, friendship and recognition. On the contrary, as we argued in the case of emotions, these social needs and feelings are likely to be more intense and more developed in GPs, supported as they are by a more efficient neural infrastructure. For instance, *empathy*—the ability to imagine yourself in someone else's situation—is perhaps the most crucial requirement for effective social interaction, but also one of the most difficult to develop cognitively. But this is typically a domain in which a GP will excel, being able to look at a problem from many different angles simultaneously, feeling sufficiently self-confident about one's own attitude to consider it also from someone else's point of view, being sensitive to small details or hints in the other person's behavior, and having sufficient imagination to create a complex internal picture of how that person may reason or feel. This means that GPs will easily feel compassion for others, as they can vividly imagine their suffering.

Also the idea of justice or *fairness*, even though it may be rooted in a basic instinct for reciprocity, requires advanced cognitive processing for its elaboration. Most people will have little difficulty judging whether a situation is fair or unfair if it concerns themselves or their peers. But if fairness is extended to increasingly remote others, such as in the relations between the Western world and the developing nations, the concept becomes ever more abstract and complex, so that the connection with the underlying emotion is likely to be lost. Because of their higher propagation depth, GPs will be able to sustain this connection between instinctive feeling and cognitive inference for much longer, thus being honestly outraged at social injustices or high level corruptions that others may hardly be concerned about.

Obstacles to the deployment of giftedness

We started this paper by noting that giftedness is a very valuable resource that we should try to optimally exploit. One strategy is to increase the overall level of giftedness in the population. Given the strong biological component of giftedness this may seem unrealistic in the present state of science. Yet, the Flynn effect is the well-confirmed observation that average IQs, and in particular the g-components of IQ, have been steadily increasing over the past century, with some 3 points per decade [Flynn, 1987; Neisser, 1998; Jensen, 1998]. While there is as yet no generally accepted explanation for this phenomenon, plausible causes are on-going advances in general health, nutrition, education, and cognitive stimulation by an increasingly complex environment [Neisser, 1998]. Further research into the physiological bases of what we have called neural propagation efficiency—e.g. examining the roles of essential fatty acids in myelination, of antioxidants in improving cerebral blood circulation, or of cognitive stimulation in creating "synaptic shortcuts"—may help us to understand the most effective ways to further increase the general level of intelligence.

But increasing average IQ is not sufficient to create true genius. Flynn [1987] himself expressed strong doubts about the significance of the effect named after him, noting that if higher IQ scores really implied higher intelligence, then we should see an explosion of creativity and genius over the most recent decades, a conclusion that seemed very implausible to him. A possible explanation for this apparent inconsistency is the observation we made earlier: it is often only possible to recognize true creativity or genius well after the facts. Perhaps it will take us several more decades to acknowledge the true feats of creativity that have been made in our age. Another explanation is suggested by Flynn [1987], when he notes that the IQ increase is most pronounced for the lowest ranges of the scale, and least for the highest ranges, implying that while the average went up, the standard deviation went down. Perhaps the Flynn effect is merely a catching up of the lower classes, whose poverty, poor health and limited education held back their chances to develop their intellect up to what we would now call "normal" levels, but which in earlier periods were only within reach of the highest classes. If that is the case, the number of exceptionally gifted would only increase a little, and the maximum intelligence level may actually remain constant.

Recognizing giftedness

Interesting as these speculations are, the focus of this paper has been on the personality characteristics and concomitant social relations of the gifted. It is here that the biggest obstacles to the full deployment of people's intellectual potentials seem to lie. Probably the biggest problem of all is for an individual's giftedness to be recognized, both by others and by the individual. Our analysis of the multiple aspects of propagation depth has shown how wide-ranging, difficult to categorize and sometimes counter-intuitive its effects are. Typical expectations about very high cognitive abilities focus on exceptional talents in traditionally "intellectual" domains, such as mathematics, IQ tests, or high-level chess, which cover only a fraction of the domains over which

giftedness extends. If the GP happens never to have had the opportunity to explore these domains, or not to take any particular interest in them, the GP's exceptional abilities may never be recognized.

Although at first sight paradoxical, a lack of interest in formal, intellectual domains can be explained by our flow motivation model. Since disciplines such as science and mathematics are difficult for most people, they tend to be taught in schools in a slow, repetitive way, emphasizing rigid rules, by teachers who are not very confident about their own understanding of the domain. For GPs skilled at quickly assimilating and exploring complex concepts this constitutes far too little of a challenge, thus leading them straight into the "boredom zone". Attempts to increase the challenge level by asking difficult questions, are likely to be met by answers that are at best unsatisfactory, at worst intended to discourage any further questioning. Moreover, since the GPs will normally be able to pass tests and examinations about such subjects with hardly any preparation, they will also not be stimulated to study such domains on their own, ending up with a level of formal knowledge that is hardly more advanced than that of their more motivated and hard-working, but less intelligent, peers. As a result, GP test scores may be pretty unremarkable. A case in point is Einstein, who apparently started out as a rather mediocre student, and only began to show his exceptional intelligence when his studies reached the difficulty level of leading-edge science.

Instead, GPs are likely to invest their prodigious intellectual energy in various extracurricular activities, hobbies and avocations, which may include art, computer programming, acting, social activism, nature observation, practical psychology, and philosophical speculation. They may thus build up an extensive "portfolio" of ideas, notes, essays, drawings, compositions, literary experiments, and social activities they organized. Remarkable as this outburst of creativity is, it is unlikely to get them the recognition they deserve, as it typically takes place in a "dilettante" manner, outside the formal channels, and with little sustained focus or long-term planning.

The most likely way for GPs to be quickly recognized is to have a parent or teacher who is sensitive to their unusual talent and who takes special interest in developing it. However, this runs the risk of turning the GP into a child prodigy, intensively trained from an early age in developing an advanced specialization, such as chess, music or maths. While this may satisfy the teacher's ambitions, it is unlikely to lead to a balanced overall development. The risk is high that it makes the GP stand out as some kind of a freak, admired by many for an extraordinary talent, but who remains socially and emotionally ill at ease. Mozart, who at the age of five was paraded around the European courts by his father, to show off his musical prowess, is a well-known case in point. The great mathematician and cyberneticist Norbert Wiener seems to be another example of the child prodigy syndrome. These individuals still ended up well, in the sense that their genius made lasting contributions to our culture. But unfortunately most child prodigies seem to sink into oblivion as they grow adult, perhaps because they have lost the motivation to continue on their artificially imposed course.

The more common situation is that GPs need to find out on their own how to optimally develop their talents. At best, they will be guided by enlightened parents and teachers who try to foster their intelligence, but without imposing their own idea of which career track to follow. At worst, they will live in an environment that is not only

indifferent, but hostile towards any form of intellectual development or non-conformist thinking. In either case, finding the most productive way to channel their talents will be their biggest problem.

Finding the right challenges

We started by assuming that all individuals are intrinsically motivated to achieve flow, by balancing skills and challenges. However, this implies finding the right kind of challenge for your level of skill. This is much more difficult for GPs than for others: given their exceptional skills, they require exceptional challenges to actualize their potential.

Such challenges, first, will be difficult to find in a society that is geared towards people of a more average level of intelligence and creativity: most educational and professional opportunities do not promote or even allow the kind of innovative and integrative thinking at which GPs excel. Second, even where such opportunities exist, as in advanced research degrees or experimental art programs, GPs may well be discouraged by their non-GP milieu to even consider entering such non-practical and elitist career opportunities. This is particularly a problem for women, who do not fit the stereotype that society has of creative genius, such as the ivory tower scientist or the neurotic artist. Instead, women will be directed towards more traditional roles out of the limelight, such as teaching or taking care of their family. Third, because of these social expectations and simple lack of experience, the GPs themselves are unlikely to recognize the true extent of their talents, and for that reason may ignore opportunities that would fit them well. Again, this applies particularly strongly to gifted women, who, lacking good role models, tend to find it more difficult to believe that they are actually much smarter than the people around them. For example, Clark [2006] relates an anecdote of a highly gifted girl who thought she was more stupid than the others in her class because she always had so many questions to ask.

The female handicap in being recognized as gifted may be deeper than mere cultural prejudice, though. Research about cognition and brain organization has shown that there are basic biological differences between the mental abilities of men and women [Halpern, 2000]. For example, men tend to be better at spatial tasks, such as mental rotation, while women excel in tasks that demand verbal fluency. IQ tests normally are balanced to take these differences in account, and do not show any differences in overall ability or g-factor scores between men and women. However, there may still be an asymmetry in the structure of their motivation. From an evolutionary point of view, men's brains have been shaped by their role of hunting, which demands strong concentration or focus on a far-away target, the prey, to the exclusion of other stimuli. Women's role in primitive societies was primarily gathering while keeping an eye on the children. This requires a broad field of attention, and sensitivity to a variety of minor stimuli or distractors (promising locations of fruit or tubers, emotional expressions and movements of children, possible signs of danger...) experienced in parallel. This difference in the breadth of focus is reflected in the visual field: women can generally see things across a much wider angle than men, but discriminate the details of a particular object less well.

From this observation it is a small step to assume that the same difference in width of focus occurs in the more general domain of motivation: men seem more likely to choose well-defined, if far-away, goals to strive for, while women seem likely to have a broader, more holistic, domain of interest that is more sensitive to the immediate context. This implies that the general problem of finding a concrete, publicly recognizable focus or target for a GP's ambitions would be more pronounced in women. In my own (limited) experience with graduate students, when the topic of a PhD thesis is not imposed by the thesis advisor, gifted women tend to be more uncertain and to take more time delimiting their research subject than equally intelligent men (although they also tend to be more conscientious and open to ideas from other domains). In a competitive, result-oriented, academic environment this constitutes a real handicap in getting due recognition for one's capabilities.

Even when GPs are sufficiently ambitious, focused, and confident in their intellectual skills, they may choose challenges that are simply unrealistic so that they fail and eventually lose their motivation. This too is intrinsically difficult to avoid: exceptional challenges by definition have not been explored before, and therefore there is little ground to estimate in how far they can be tackled with a given level of resources. For example, when Einstein initially set out to resolve the paradoxes posed by the observed constancy of the velocity of light, he succeeded beyond all expectations by formulating first the special and then the general theory of relativity, which together revolutionized the whole scientific world view. However, when he then decided to focus on building a unified field theory, a challenge which given his previous record and the then state of knowledge seemed much more realistic, he failed miserably, in spite of decades of diligent work. This failure was not due a lack of talent or effort, but simply to the unforeseen complexity of the problem, as evidenced by the fact that half a century after Einstein's death the solution remains as elusive as ever. Imagine that Einstein would first have focused on unifying gravitational and electromagnetic forces, before developing his theory of relativity. In that case, he might have plodded on for decades without noticeable success, perhaps even gotten demotivated up to the point of giving up his research career, and never achieved a status of scientific genius.

This example probably sketches a too pessimistic picture of exceptional achievement as merely a question of luck, i.e. the coincidental encounter of a GP with the right kind of problem: too tough for ordinary mortals, but just within reach of the GP's formidable intellectual powers. The GPs' constant exploration of novel domains, zooming in on those where the challenges seem to best match their skills, makes it likely that they will sooner or later find a domain where they can make a real difference. Case studies of historical genius, such as a detailed analysis of the notebooks that Darwin kept while developing his theories, indicate that GPs tend to work on several projects in parallel [Gruber & Wallace, 1998], regularly changing their focus to whichever project seems to promise the quickest advance at the moment in order to come back to the others later, with a fresh mind and novel insights. This makes it likely that at any moment they will have available some challenges that provide sufficient flow to keep them motivated and productive.

The difficulty may be less in finding flow-producing challenges, but in finding challenges whose ultimate value to society is at a par with the GP's exceptional talents.

Given our previous observations about the general difficulty society (including GPs themselves) has with acknowledging outstanding intelligence and creativity, many if not most GPs are likely to end up in situations where their talents are severely underutilized. The typical examples are women, who especially in earlier periods were expected to limit their aspirations to being a good homemaker. While a highly gifted woman might be able to find flow in trying to be the perfect mother, wife, cook, party host, house decorator, etc., thus making the joy of her family, the fruits of her talent could potentially have lifted the lives of many more people, if only she had invested her prodigious intellectual energy in more ambitious domains, such as medicine, literature or science. This does not only apply to women, but to male GPs from a non-intellectual background, who might try to find flow in becoming the best plumber or programmer in the state, while moreover engaging in demanding hobbies such as breeding rare tropical fish, or compiling a detailed history of diesel engines—not being aware that with a good university education they could have become leading scientists. In spite of their apparent adjustment, such people are likely to carry a vague feeling of unease or frustration, not knowing precisely what it is they are lacking, just being aware that they are somehow different from the people around them. As such, they could profit from the recognition that they truly are gifted and capable of much more than they have been doing until now [Jacobsen, 2000].

Such problems of lack of recognition are not limited to non-intellectual milieus. Even among scientists or artists, where high intelligence or creativity is the norm, there can still be huge differences in level between merely gifted and exceptionally gifted individuals. Given the competitive atmosphere typical of such milieus, few will be willing to admit that a colleague is actually more talented than they are. If they suspect, consciously or subconsciously, that that may be the case, they are more likely to hinder than to help that colleague getting due recognition, since this would merely highlight their relative incompetence, and siphon off attention and resources that they would have liked to obtain. If the difference in giftedness is large enough, they may not even suspect that the other is more intelligent, dismissing the GP's revolutionary ideas, which to them do not make much sense, as coming from a crackpot or scatterbrain. As a result, GPs may start to self-doubt, especially if their ambitious enterprises have not as yet produced results that are up to their own, perfectionistic standards. In the worst case, such an atmosphere of suspicion may produce on-going hostility, demotivation, and the GP giving up on what would otherwise have been a very promising career.

Conclusion and recommendations

In conclusion, the obstacles that hinder GPs in realizing their potential appear mostly social and motivational. Their relations with others are intrinsically tenuous, characterized by misunderstanding, criticism, and tension, up to the outright fear and hostility that is elicited by a rival that is not only smarter than you, but whose behavior appears intrinsically unpredictable and difficult to comprehend. Society rarely offers them appropriate role models or career choices. Lacking a realistic model of giftedness and constantly receiving the message that they are not as smart as they may think, they themselves are unlikely to understand the true nature of their talent. Their tendency to

explore many different domains simultaneously will initially only contribute to their confusion and lack of clear aims. When they deviate too far from the well-worn paths, they may end up in the wilderness, desperately searching for targets that are effectively out of reach. Their hang towards perfectionism is likely to lead to further frustrations. As a result, they may lose (or never develop) the motivation to achieve the truly outstanding results they are capable of, either settling in a conventional life-style with a few minor eccentricities, or developing some form of neurosis, such as depression.

The simplest way to remedy those problems may be to help GPs develop a more realistic self-concept and corresponding ambitions. This could be achieved by better testing for giftedness (not just IQ, but personality traits, creativity, and perhaps even reaction times or other neurophysiological measures), better theories of what giftedness really is (as this paper has tried to propose), adapted counseling [e.g. Silverman, 1993] and easily available books with psychological advice for the gifted [e.g. Jacobsen, 2000] or with biographies of successful GPs that could function as role models.

The more difficult challenge will be to change the attitude of society, and especially of peers, who feel naturally threatened by a competitor more intelligent than they are. GPs often try to avoid this problem by letting themselves appear less intelligent than they really are, until the moment they have reached a level of eminence high enough so that they can safely claim the intellectual authority they deserve. This is probably the most realistic course of action, if we want to avoid the dangers of envy and elitism associated with a special treatment reserved for GPs. Rather than offering the GPs specific programs or benefits, it may be better to simply make the educational and career system more flexible and merit-based, so that a GP gets more options for self-development, and can move up (or sideways) through the ranks more quickly. In that way, nobody needs to feel disadvantaged, while the GPs can move at their own, typically much faster pace, exploring whatever domain seems interesting, without feeling pressured to achieve any preordained goal.

Discussion

The study of giftedness and its different aspects such as intelligence, creativity and genius is an old and venerable topic within psychology. However, different aspects have typically been studied from within very different approaches: intelligence mostly within the psychometric tradition [e.g. Jensen, 1998] which emphasizes cognitive and neurophysiological measurements; genius through case studies of historical figures [e.g. Simonton, 2001]; creativity by an amalgam of experiments and observations of people performing different tasks in different settings [e.g. Sternberg, 1998]; and giftedness mostly within an educational context of identifying and supporting talented children [e.g. Clark, 2006]. Whereas these different approaches all refer back to the psychological tradition started by pioneers such as Galton, Spearman and Terman, they have diverged strongly in their methodologies, outlooks, and applications. This is most clear in the contrast between the "hard" psychometric approaches trying to capture the abstract g-factor via complex statistical methods and neurophysiological measurements,

and the "soft" historical and educational approaches that are based mostly on qualitative observations and case studies of social, motivational and emotional aspects. Yet, insofar that they cover the same phenomena, there appears to be a remarkable agreement between the different approaches about what I have summarized as the "giftedness Gestalt": the complex of cognitive, emotional, motivational and social traits that typifies a GP.

What is lacking is a unified theoretical framework to explain these observed traits. That is precisely what I have proposed by introducing the concept of neural propagation depth. I have shown how the assumption that GPs have a high propagation depth can directly explain the different cognitive, perceptual and affective traits that are associated with the g-factor. I then introduced the concept of flow motivation to also explain the social and motivational traits. However, it is here that the divergence between the approaches is most pronounced. Researchers in the IQ-measurement tradition tend to ignore the latter traits. Those who study creativity and genius, on the other hand, tend to emphasize how these traits make the difference between very intelligent, but otherwise dull and conventional, individuals, and the true creators, who produce novel contributions of lasting value. The core of the issue seems to be the relationship between intelligence and creativity. Different theorists have formulated different positions on this relationship [Sternberg, 1998], varying from identity (intelligence equals creativity) via subsumption (intelligence is part of creativity, or vice-versa) and overlap, to complete independence.

The present model implicitly assumes identity or at least substantial overlap: intelligence and creativity are merely different aspects of the same underlying property of propagation depth. In this perspective, intelligence as traditionally measured via IQ or scholastic achievement tests represents the "convergent thinking" aspect, where propagating activation zooms in on the one correct solution, and creativity the "divergent thinking" aspect, where activation propagates far and wide with little restriction. Both processes are to the same degree facilitated by high propagation depth, although there may be independent neural factors that facilitate the one and suppress the other. For example, [Eysenck, 1995] has posited that the lack of neural inhibition that characterizes psychosis may also be a prime stimulant of creativity. Such independent factors may explain to some degree why some GPs excell more in coming up with "crazy" ideas and others more in conventional reasoning.

Differences in motivation

Most creativity researchers [e.g. Winner, 2000], however, focus on the factor of motivation or drive to distinguish truly creative individuals from merely intelligent ones. The main idea is that advanced contributions to any one domain require at least a decade of training to develop expertise in the domain, a lot of trial and error exploring different avenues, and plenty of hard work developing the initial ideas into a finished product, such as theory, book, or composition. Without strong and persistent motivation to achieve such a goal, even the most talented individuals will fail to reach it. In the present model, such motivation is implicit in the assumption that everybody is equally

motivated to find flow, but that GPs will find it only in the most difficult challenges. However, as we noted in the section on obstacles to gifted development this does not imply that they will succeed in discovering the right type of challenge, i.e. one that is not only difficult, but realizable given their level of skill.

Moreover, essential parts of Csikszentmihalyi's [1990] concept of "flow" are the experiences of *control* (the individual should feel capable to reach the goal) and of *feedback* (the individual's moves should elicit clear and frequent reactions indicating in how far these moves contribute to achieving the goal). Without these signals, flow will not be achieved, even when the skills are in principle sufficient to meet the challenges. Feedback will depend mostly on the type of situation, being intrinsically high in an activity such as painting, where every brushstroke signals a move towards (or sometimes away from) the goal, while being low in an activity such as theoretical science or philosophy, where hundreds of different avenues may be explored without providing any concrete sense that the solution is coming nearer. As we noted earlier, feedback, while remaining indispensable in the long term, is less important for GPs in the shorter term, as their highly efficient thinking processes can advance and remain focused even with little or no external feedback.

Control is a more tricky matter, though. Intrinsically, GPs have a much higher capability to cope with complex situations, but of course that does not mean that they can tackle any problem they are confronted with. This applies in particular to problems they encounter in childhood, when they are still completely dependent on their family. If the family does not provide the necessary material and emotional support, the child may grow up with a generalized expectation of being unable to tackle fundamental problems—what I have called "perceived incompetence to satisfy basic needs" in an earlier article [Heylighen, 1992]. A primary cause is what Bowlby [1988] has described as "insecure attachment": parents who do not reliably provide the love, understanding and protection that a small, vulnerable child needs. Individuals who grow up in such circumstances typically develop various forms of neuroses, pathologies (such as addictive, self-mutilating, or violent behavior) and anxieties that have at their core a fundamental lack of self-confidence or self-esteem. As a result, such individuals are likely to shy away from situations that appear risky or difficult to control. Even when they are intelligent enough to tackle complex challenges, their emotional insecurity may keep them from approaching the problem, or make them self-doubt and give up at the slightest sign of adversity.

Such people may exhibit most of the traits characterizing giftedness, but fail on the factor of drive or motivation. While they are motivated to look for flow just like everyone, they may not find it because they intrinsically do not feel that they are in control, and therefore avoid challenges even if they would fit their level of skill. As a result, they fail to experience the persistent drive and focus that characterizes a flow-producing activity and that is necessary for true creativity. Seen from this perspective, giftedness or creativity requires more than neural propagation efficiency: it also requires a minimum level of physical and emotional security or the first stages of what Maslow [1970] calls "self-actualization".

In conclusion, while being a good candidate for the most basic factor determining giftedness, propagation depth is not the only factor worth considering when

distinguishing exceptionally creative people. The socio-cultural environment in which an individuals grows up and later builds a career is an essential determinant of whether the cognitive potential offered by that individual's neural functioning will be realized in the form of exceptional achievement. On-going research in the domain of creativity and education will help us to better understand the different obstacles and facilators of gifted development.

The need to test the model

In the meantime, the concept of propagation depth will need to be further developed and tested to ascertain its value as an explanatory model for the brain mechanisms underlying intelligence and creativity. Empirical tests of the model are not obvious, given that our methods of observing brain processes are still not sufficiently refined to follow individual thoughts as they propagate between neuronal assemblies. It may be possible to design more indirect tests by extending traditional methods such as measurement of divergent thinking skills, free association, or priming. For example, a testable prediction deriving from the model would be that more intelligent people, having higher propagation depths, can be primed more easily via indirect associations, like in the example where the word "lion" via its association to "tiger" primes the mind to more quickly recognize the word "striped".

Such tests would provide additional evidence for the hypothesis, but would provide relatively little clarification about the mechanisms of intelligence. An accepted method to investigate these mechanisms is computer simulation of thought processes. Yet, here the risk is great that simulation and brain, while performing apparently similar tasks, do this is in completely different ways. A better approach is to closely integrate simulation and empirical observation, so that we can try to find more fine-grained correlations between the behavior of the simulation model and the one of real individuals [e.g. Van Overwalle & Heylighen, 2006]. One way to apply this method to test the propagation depth model will be elaborated in the appendix.

Appendix: Testing the model with an associative network simulation

The present section proposes a method to test the core hypothesis that intelligence covaries with propagation depth in an associative network. It describes a simple computer simulation that I designed and which was programmed and developed by my PhD student Marko Rodriguez. The intention was to simulate the performance of the brain on simple but general problems, such as those found in common verbal IQ tests, starting from the propagation depth paradigm. This simulation is not intended to propose a full model of intelligent reasoning but merely to illustrate how basic problems can be solved via spreading activation through an associative network. The problems that the network tackles are multiple-choice questions. They are formulated as an initial state consisting of a short list of "input" concepts, represented by common words (e.g. dog, cat, bird, fish), followed by a list of "output" concepts that designate potential solutions (e.g. bush, pig, house, car). The problems can be formulated by sentences such as "Which word of the second list fits best in the first list?" (see table 2 for more examples).

Which word of the second list best fits in the first list?
dog, cat, bird, fish : bush, pig*, house, car
bear, cow, dog, tiger : turtle, carp, parrot, lion*

Which word of the second list is most like the first word?
alligator : crocodile*, cat, snake, lizard
bucket : river, cup*, soap, road

Which word in the second list best represents the combined meaning of the words in the first list? (e.g. combination of big, striped, cat is best represented by : tiger)
king, animal, cat : tiger, snake, elephant, lion*
work, room, paper : building, office*, computer, person

Which word of the following is least like the others in the list?
cow, car*, bird, fish
bear, snake*, dog, tiger

Table 2: *a few examples of questions from our "verbal IQ test" used in the simulation of problem-solving by spreading activation. The asterisk (*) denotes the correct answer.*

The general idea behind such questions is that the test-taker should explore the different associations between the different items so as to determine which one of the output list fits best in with the item(s) of the input list.

If the association were direct, the problem would be easy. Suppose that the question was "Which word is most related to 'baby': cradle, fish, road, corporation?" Given that there is a direct association from "baby" to "cradle", but none to any of the other words, the amount of cognitive processing is minimal, and anybody with a general culture should be able to answer the question correctly. The speed of the response may still give us an indication of the efficiency of processing, but since these kinds of tests are typically not precisely timed, this is of little help in discriminating levels of intelligence.

The problem becomes non-trivial when several indirect associations are involved. For example, take the question "Which word in the second list best represents the combined meaning of the words in the first list? communication, voice, distance : newspaper, telephone, sound, view". "telephone" is (weakly) associated with "communication", but so is "newspaper". "telephone" is (weakly) associated with "voice", but so is "sound". It is only by spreading activation from all three input terms that we find that they all have indirect associations to "telephone", while only part of them have associations with the other concepts. This requires a complex parallel process in which all of the listed concepts, and some intermediate concepts (e.g. "communication" and "voice" together may activate "speaking", which is not in the list, which in turn may activate "sound" and "telephone", which are) must be activated so as to determine a preferred path from the initial concepts to the solution.

Implementation

We simulated such processes in the following way. To start with, we needed to provide our network with common-sense knowledge of associations between words. For this, we used the database of word association norms developed at the University of South Florida [Nelson, McEvoy & Schreiber, 1998]. We implemented this database as a connectionist network, where every unit A represents a word, every link A -> B represents the presence of an association between A and B in the database, and the weight of the link represents the proportion of people who answered B when stimulated with the word A.

We then applied a discrete, stochastic version of spreading activation, called "particle flow" [Rodriguez, 2004], where every activated unit receives a number of "energy particles" proportional to its degree of activation. At each time step, each particle randomly chooses one of the outgoing links, with a probability proportional to the link weight. This means that if A is initially "loaded" with 100 particles, and the link A -> B has weight 0.2 (assuming that weights are normalized so that the total outgoing weight is always 1), then B will receive 20 particles on average from A in the next time step. This probabilistic approach to us seems to capture well the intrinsically error-prone nature of spreading activation in the brain, where activation may or may not cross a synaptic threshold depending on a variety of factors, some of which are the result of random noise. Moreover, the (discrete) number of particles may correspond to the (discrete) number of neurons in the typical "assembly" that represents a concept.

The energy level of the particles decays with each step. If the energy level falls below a threshold, the particle stops propagating.

Units representing potential solutions act as "sinks": particles can enter them, but cannot leave. The solution that is chosen is the one that has gathered *most* particles at the end of the process. The one exception is the type of question where you are required to find the "odd one out", i.e. the word that least fits in with the initial list. In that case, all units receive the same amount of particles and start propagating them until they reach one of the other units where they are retained. The unit that thus gathered *least* particles from other units at the end of the process is considered the odd one out.

This is a very simple, and probably too simple, model of how activation spreads between associated concepts so as to select the best solution. Yet, after some fine-tuning of parameters (e.g. number of particles, strength of decay, ...), we managed to get a network that produced the correct solution in about 75% of the cases. Given that each question had 4 possible answers, this is much better than chance.

It is true that the questions we used are rather easy, and that an educated adult should answer practically all of them correctly. In that sense, the simulation still scores well below average IQ, though its score may be comparable with the one of a 12-year old. This is in part due to the fact that we used a very basic, commonsense knowledge base, which is totally unstructured apart from salient associations between words. Moreover it lacks most abstract or technical concepts such as "mammal" or "cold-blooded" that most people would use to categorize more concrete concepts such as "cat", "pig" and "snake". Adding an extensive, semantically organized word database, such as WordNet [Miller et al., 1990], may remedy that problem. Another shortcoming is that the present program only allows the spreading of *positive* activation: it is not possible to inhibit the activation of certain concepts as being a priori inconsistent with the constraints defining the problem. This also means that the program does not have the higher level control that is needed to make Boolean combinations of concepts—such as finding a concept that is a bird but that *cannot* fly.

Variations in test performance

Even with this limited model as it stands, it is possible to simulate variation in IQ in the sense of differential performance on the "test" consisting of some 100 questions that we compiled.

One obvious variation to explore are changes in the initial amount of activation, i.e. the number of particles initially given to the input concepts. At first sight, this is unlikely to provide a realistic measure of neural differences between gifted and non-gifted individuals. Indeed, fMRI brain scans show that more intelligent individuals require less energy than others to perform a given task [Haier, 1993]. This makes sense if intelligence results from higher propagation efficiency: if less activation is lost during processing, then the same task can be performed with a lower energy input. But neural activation may not be proportional to energy consumption: it is possible that in less intelligent brains, the surplus energy is already dissipated before it is turned into action potentials, and therefore gifted individuals may start out with more neurons being active

even when their overall energy use is lower. Therefore, it is worth exploring the effect of different numbers of particles.

Another obvious parameter to vary is the energy decay factor, which determines how far a particle will travel on average. Here we must note that there seems to be an optimal level, in the sense that if there is not enough decay, particles may continue circulating indefinitely through the network before ending up in one of the potential solutions, thus losing any relation with the initially activated concepts. Since in the simulation we did not take into account the sequence of intermediate nodes, this means that particles may end up in potential solution nodes via circuitous routes that have little to do with the problem statement, thus perturbing the results of more straightforward "inference" sequences. This is particularly a difficulty for questions where the path from problem statement to solution is not very clear. But if we increase decay above the optimal level, problem-solving efficiency decreases even more clearly, as there are simply not enough particles left after a few associative steps to meaningfully activate one of the solution nodes.

A further parameter worth exploring is the amount of noise. This could be simulated by removing or adding part (e.g. 5%) of the particles each time they cross a connection. The percentage might follow a normal distribution, with a standard deviation representing the strength of the corresponding noise. Higher amounts of noise are likely to lead to worse performance.

A less obvious variation may simulate the contribution of neural plasticity [Garlick, 2002] or even crystallized intelligence [Cattell, 1987]. The idea is to minimize decay and diffusion of particles across intervening links by creating shortcuts between nodes that are otherwise several links removed from each other. Normally, shortcuts are learned from experience, which in the present set-up is difficult to implement as the network can hardly be expected to undergo real-world experience. But we can represent some aspect of the process by what may be called "condensation" or "consolidation" of the associative network. Mathematically, a (one-way) "distance" can be defined from node A to B in a network, which is proportional to the average time that a random walker (or a "particle" in our model) starting in A needs to reach B, while wandering through the network and choosing any of the available links with a probability proportional to its weight [Yen et al., 2005]. This distance measure decreases with the number of paths leading from A to B and with the weight of their links, while increasing with the number of their intermediate steps. To build a condensed network, we compute the distances between all nodes, and create new links between all nodes whose distance is smaller than a given threshold, giving them a weight inversely proportional to the distance. Such new links represent shortcuts, since they connect nodes that initially may have been connected only indirectly, with a weight proportional to the summed importance of all direct and indirect connections. We may assume that, using such shortcuts, particles will reach their targets with less intervening steps along which they can lose activation or be perturbed by noise, thus maintaining a higher overall activation.

Comparing simulation and observation

Given these paradigms to simulate possible mechanisms that underlie differences in propagation depth, we could now design an experiment with real people to test the hypotheses. First, we create the equivalent of a realistic IQ test by gathering enough questions of a type (like those in Table 2) that the simulation can tackle. If this test turns out to be too easy for typical adult subjects, we can either submit it to a group of children, or make it more difficult by requiring subjects to respond within a short enough time interval (e.g. 10 seconds). We let the subjects take this test together with a standard, highly g-loaded IQ test (e.g. Ravens Progressive Matrices). We then determine the correlation between the standardized IQ test and the different items of the new test, eliminating those items with poor correlation. Assuming that the remaining test items correlate well, we have now designed an IQ test that accurately measures the performance of both human subjects and simulation program. We can then examine the similarities and differences between the simulated and the human IQ results.

The neural propagation hypothesis underlying our model would be supported if the two answer profiles have a strong and significant correlation, i.e. if the items on which the simulation fails also tend to be the items on which most subjects make mistakes, and vice-versa. To determine an accurate correlation, it is better to have a more fine-grained performance measure than the number of correct answers. Since the simulation chooses the solution on the basis of the amount of accumulated activation, we could design a measure that takes into account the difference in activation between the different options. E.g., a correct choice that has gathered only 1% more activation than the second most activated (incorrect) choice would get a lower score than a correct choice that has double the activation of all other choices combined. Vice versa, an incorrect choice that only has 1% more activation than the correct one would still score some points as being "almost correct". According to this paradigm, "difficult" questions are those where the difference in activation between the highest scoring options is small (implying that a little bit of noise can lead to a wrong answer). If our model is correct, these should also be the questions with the largest percentage of wrong answers from the test-takers.

To design a more precise test of the giftedness model we can then divide the human subjects into different classes (e.g. gifted vs. non-gifted) depending on their overall score. By varying the parameters of the simulation (e.g. the decay rate or the noise level), we should be able to create two versions, one whose results correlates best with those of the gifted group, one whose results resemble best those of the non-gifted group. This would allow us to determine the parameters that best distinguish between gifted and non-gifted reasoning ability in this simple word association paradigm. This may allow us to discriminate between the detailed mechanisms underlying differential propagation efficiency, such as neural plasticity, initial activation, decay, or noise level, and find support for one hypothesis rather than another.

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