

Heritability lost; intelligence found

Intelligence is integral to the adaptation and survival of all organisms faced with changing environments

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Probably nothing makes human beings more different from other species—and from one another—than their intelligence. The subject is of profound general interest—what the brain is for and how it works, the distinctiveness of the human mind, what makes us individual and human—yet delivers so little. Human intelligence remains poorly defined and characterized, even among those who most study it. Rather, it is described through metaphors such as processing strength, capacity or power—referred to as ‘*g*’—or intuitively meaningful attributes such as “‘catching on’, ‘making sense’ of things, or ‘figuring out’ what to do” [1]. James Flynn, Emeritus Professor in the Department of Politics at the University of Otago, New Zealand, has noted how attempts to define ‘general intelligence’ or *g* have lacked precision and have attracted little scientific consensus [2]. According to Ian Deary, Professor of Differential Psychology at the University of Edinburgh, UK, “There is no such thing as a theory of human intelligence differences—not in the way that grown-up sciences like physics or chemistry have theories” [3].

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Much of the research into intelligence over the past century has sought enlightenment in biology. It has been dominated by heritability estimates of variation in IQ test scores by using twin studies, which have given widely accepted estimates of between 0.5 and 0.8. Yet, partitioning

variance neither identifies specific genes nor describes pathways that lead to trait variation. Over the past two decades, remarkable advances in molecular biology have promised methods for leaping ‘beyond heritability’ to the identification of specific genes involved in IQ variation, but the results have been disappointing and associations have been few, of small effect and are often not replicable.

The question has arisen, therefore, about what has happened to the ‘missing heritability’ and what this means for intelligence. One popular explanation is that there are simply too many genes—perhaps hundreds or thousands—each making only a small contribution to variation. If true, huge sample sizes and new statistical techniques would be needed to see these tiny contributions. Another possibility is that heritability estimates are illusory. There are serious misgivings about the assumptions of the twin method on which most estimates, and genome-wide association studies, are predicated. In fact, individual differences usually attributed to genetic variation might actually be due to intense genetic interactions, creating ‘phantom’ heritabilities [4].

Here I am interested in what else molecular biology has suggested: the reasons why heritability is missing could actually form the basis of a new understanding of the true nature of intelligence as a natural phenomenon. Whilst psychologists attribute function and variation to ‘dumb’ independent genes, molecular biologists are increasingly telling us about ‘prokaryotic intelligence’, cells with ‘cognitive resources’, ‘bioinformation intelligence’, ‘cell intelligence’, ‘cell knowledge’ and so on [5,6]. Others have suggested that research indicates “a level

of memory and information processing that has not been normally associated with single cells, suggesting that such organisms do in fact have the capacity to ‘think’ [7].

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Where could such powers of intelligence in primitive organisms have come from? And what implications do they have for more evolved species? One line of argument is that, in a constantly changing world, organisms must be able to predict future states. The traditional darwinian view is that such predictability arises from random variation of genes and natural selection. Selected genes are then, in a sense, predicting that the environments of progeny will be similar in crucial ways to the environments of parents. But, as Darwin himself pointed out, this form of intelligence is only good enough in circumstances of slow, intergenerational change. As these ‘simpler ways of life’, as Darwin put it, became overcrowded, so species were forced into more complex environments in which conditions change more rapidly, often by the activities of organisms themselves; so different intelligent systems had to evolve.

If the response of an organism to an environmental change is to be better than random, that response must involve the gathering and analysis of information of some sort. The simplest source of information for prediction is temporal association, in which a change in one variable is reliably correlated with change in another at some future time. Indeed, although the

assimilation of such correlations in brains has long been the subject of human learning, some excitement has been created by its apparent existence in single cells. Researchers at Princeton University, USA, for example, have demonstrated how the bacterium *Escherichia coli* can use an initial temperature increase, such as when it enters your mouth, as a signal for the impending drop in oxygen levels, when it inevitably arrives in your stomach [8]. The speed at which the bug can switch to anaerobic metabolism, even when oxygen levels are still high—a superficially maladaptive response—suggests that it can somehow assimilate the external correlation structure of those events and can predict one from the other. Similar responses have been demonstrated with amoebic slime moulds [9].

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The availability of such simple, predictable associations is probably limited. Even so, as we have looked more closely at the nature of complex environments, other sources of predictability have since come to light. Although we have tended to idealize environments as arrays of independent factors, we know there is much more structure-for-predictability in complex, changing environments. For example, pairwise associations can be further associated with, and conditioned by, a third variable—and so on to higher dimensions—that is, two-way, three-way and higher interactions. When the dimensions are changing in time and space and are nonlinear, information of great depth and predictability is possible. “Behind the veil of apparent randomness, many processes are highly ordered, following simple rules” [10].

This deeper correlation structure within natural environmental change presents a definition of complex information. It is measurable in terms of ‘mutual information’ derived from Shannon entropy, which generalizes naturally to higher order dependencies among variables. Such information theoretic measures correspond with intuitive ideas of underlying structure in

systems. Increasingly, wherever we have looked, we have found deeper, dynamic structure in environments, which can render complex environments predictable. As such, the most interesting aspects of animal evolution have been the increasingly complex intelligent systems, able to abstract such dynamic structures to render changeable environments more predictable.

It is certainly possible that adaptable interactive structures—a kind of ‘compositional’ intelligence—might have been present in early molecular ensembles before genes had even evolved, but recent discoveries of a staggering array of variation-producing processes in cells suggest much more than autistic genes acting alone. The addition of regulatory regions on genes, transcription factors, activators, repressors, enhancers and other factors, operating in different combinations, have vastly expanded the ‘transcriptome’—or ways of varying gene expression. A proliferation of signalling proteins, with increased numbers of interaction domains that can be recombined in various ways, has helped to create more variable networks of signalling pathways. The hierarchical organization of these as sub-networks, or modules, have allowed emergent properties such as integrations of signals across space and time, new feedback loops, and new developmental and metabolic pathways. The phenomenon of exon shuffling—the dicing and splicing of immediate gene products—allows a greater variety of proteins to be produced from the same gene, with potentially widely different functions. The highly fluid, dynamic process that winds and unwinds the protein packaging (histones) around DNA, allows more variable access to genes. Newly discovered forms of RNA perform additional variegating functions, such as the modulation of promoters, gene silencing and as co-activators of transcription. All of these processes have become more important in more complex organisms in more changeable environments.

More to the point is how this exuberant variation production is far from ‘blind’. Investigators have noted how these processes are self-organized, spatio-temporally coordinated, structurally integrated, full of cross-talk, are combinatorially regulated and so on. Transcriptional regulatory and signalling networks seem to operate with a higher ‘logic’, sensitive to changes in the external and internal contexts. In contrast to the old

picture of autocratic gene-centred command systems, investigators see how genes are used cooperatively or ‘democratically’ in co-expression patterns [1]. Such apparent harmony has also invited musical metaphors including the “signalling ballet” [12], “the symphony of transcription” [13], an orchestra without a conductor [14], or “orchestrating the orchestrators” [15].

...the nature of [...] intelligence is changed from a simple linear deterministic mode to a nonlinear dynamic one

There are strong indications that the molecular tune is being called by the deeper correlation structures in changing environments. A team of researchers from the UK, the Netherlands and Germany has demonstrated the associative learning—assimilating pairwise correlations—mentioned above, within the molecular circuits of *E. coli* [16]. There is evidence for the tuning of networks to the deeper correlations experienced in more complex environments, at least at the level of three-component systems [5]. In orienting its chemotactic movements towards nutrient gradients, *E. coli* must assimilate, in its signalling and transcription networks, the spatio-temporal statistical structure of signals arriving at surface receptors. Further evidence comes from cells and organisms that rapidly entrain to seasonally changing circadian rhythms; migrating and differentiating cells in developing embryos that assimilate the spatio-temporal structure of guidance signals; or the correlated activity of transcription factors, which is conditioned by other levels in the regulatory hierarchy, according to experienced contexts. Signalling networks are similarly periodically reconfigured to “form the basis for cellular ‘memory modules’” [17], whilst the emergence of network properties “depends strongly on cell history” [18].

With a massively increasing number of variables, however, it is important to appreciate how the nature of this intelligence is changed from a simple linear deterministic mode to a nonlinear dynamic one. Changing environments in the open system of cells keeps them in ‘far from equilibrium’ states in which nonlinear dynamics create ‘criticality’ in molecular networks. This is a state of maximum



information in which the greatest expression of variation can be searched and balanced against optimization of order [19,20]. Computations ensue according to principles of least energy, depending on input and high-order correlations—the ‘basins of attraction’—in the networks induced from previous experience [21].

So we get extraordinary robustness against perturbations and enormous adaptability in response to new external changes, both short- and long-term. In this way, ostensibly the same signal on a cell—such as the reception of an epidermal growth factor molecule—can initiate a variety of responses such as growth, cell division, differentiation, migration and so on, depending on the physiological context. Similarly, new ways can be found around previous developmental constraints, opening up new gene expressions and new adaptabilities that can alter evolutionary trajectories. Different alleles and varying environments can make a difference

in the development of a trait. But, in the labyrinth of pathways of dynamic processes, genotype–phenotype correlations tend to be highly labile. So the same phenotype can be obtained from a variety of genotypes, and a population of individuals with identical genes developing in identical or closely similar environments can show a normal range of behavioural phenotypes. The processes in which heritability becomes lost, then, seem to be the ones that provide the roots of living intelligence.

This emerging perspective places intelligence as a theoretical construct, at the centre of evolutionarily important systems, and not merely as the enigmatic *g* associated with the IQ test. IQ heritability studies try to describe variation in human intelligence as the sums of dumb, independent factors, which might explain the absence of ‘grown-up’ theory in that area. By contrast, the lively intelligence and logic of nonlinear dynamics among molecular systems allows

us to discern a continuous evolutionary trail to those more complex forms.

Intelligent sensitivity to intercellular activities supported the emergence of multicellular organisms. In these, self-organizing physiological systems coordinate cellular interactions with each other and with environmental changes. Many recent studies have shown how the traditional ‘homeostatic’ model of physiological systems is too narrow. Rather they often show nonlinear dynamics, so that, today, physiological intelligence is described as homeodynamic rather than homeostatic. Increasingly, physiologists have begun to see chaotic—or close to criticality—states as healthy, allowing organisms to respond to circumstances that vary rapidly and unpredictably, again balancing variation and optimization of order with impressive harmony. For example, normal stress responses are described as “an orchestrated ‘symphony’ that enables fine-tuned responses to diverse challenges” [22].

Physiological systems soon became embedded within evolving nervous systems sensitive to increasingly changeable environments. Through rich beds of chemoreceptors, even in primitive brains, physiology interfaces with signals from all sensory systems: vision, hearing, smell and so on. However, these would only seem to present what William James once famously described as a “blooming, buzzing confusion”, or what was more recently described as “an onslaught of spatio-temporal change” [23], without further intelligent action. Oddly, although nervous systems and brains are seen as special seats of intelligence, investigators complain about “the absence of a consistent central theory in the neurosciences” [6], whilst others, reflecting on the mountains of particular findings, suggest that “relatively little progress has been made to integrate the results of this work into a global synthetic view of how the brain works” [24].

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Yet, the same logic of structure abstraction and dynamic processing that has evolved in epigenetic intelligence seems to apply here, too, except that the structures that nervous systems evolved to deal with lie deeper and can themselves change more rapidly. As in physiological intelligence, nervous systems use the emergent structure of activity of the whole network to modulate the activity of specific cells. But the intelligence is vastly scaled-up through the sheer number of cells and their interconnections. Individual neurons have modest computational powers, but networks of neurons can collectively perform complex operations—often, if not usually, from fleeting or fragmentary sensory data. Moreover, the plasticity of connections allows a more or less constant tracking of changes of environmental structure. Even the connections among the million neurons of a honeybee allow impressive inferential abilities. Whether in honeybees or in more complex brains the objective seems to lie in the distillation within nerve networks of the deep correlation parameters of environmental change. These developing basins of attraction allow the nonlinear dynamical processing among them that can be so creative (see [25] for review).

These dynamics are most evident in the cognitive systems emergent from, but superordinate to, their nervous systems. They form a whole new universe of abstractions and predictabilities. Neural actions in the eye, for example, deal only with two-dimensional patterns of light falling on the retinal surface. Perception and cognition, on the other hand, induce the four-dimensional spatial and temporal structures lying deeper within them. These include compound features, whole object images, abstract classes or concepts, and the vast range of predictabilities that give them meaning. As Walter Freeman, head of the Laboratory for Nonlinear Neurodynamics at the University of California at Berkeley, USA, has observed in work on the olfactory bulb of mice, it is not external smells *per se* that animals respond to, at least directly [26]. Rather, they respond to derivative activity patterns created by the nonlinear dynamics within the olfactory bulb. Such constructions are cognitive agents, emergent from the neural ones, but entering into new levels of activity with other such agents. Although emergent from them, this is a far more adaptable and intelligent system than even the epigenetic and developmental systems already mentioned.

It is important to stress how the specific function of cognitive intelligence is to generate much more complex intelligence from its own activity. Jean Piaget—the Swiss developmental psychologist and philosopher—called this property ‘reflective abstraction’, and it was, of course, well demonstrated in his own research. But it has also been demonstrated with artificial neural networks on computers. Ensembles of separately trained networks then yoked and activated together show important emergent properties, such as clustered and hierarchically organized activities evolving over time [27]. This self-organizing ability of cognitive systems, yielding knowledge about the world deeper than that in immediate experience, allowed organisms to predict, anticipate and ‘make’ the future with ever increasing depth of cognition and action.

This was not the end of the evolution of intelligent systems however. Similarly to pulling out another section of a telescope, a further and more complex level of intelligent systems emerged when our ancestors started to cooperate in their perceptions and actions two or three million years ago. As happened between single cells billions of years

previously, cooperation between individuals was itself an adaptation to more changeable environments. Humans constitute the first genuinely cooperative species among advanced animals; however, that has created uniquely complex cognitive challenges. Two individuals cooperating just to lift a rock, need ‘metaperception’—perception of others’ perceptions; metacognition—cognitions about others’ cognitions; and meta-action—action with others’ actions.

Consider helping someone move a wardrobe downstairs—an activity mundane to us, but impossible in any other species. In the joint attentions and actions, pains and exclamations, a whole new interactive world is created. The dynamic structure of ordinary experience becomes embedded in the ‘inter-object’ structures created by and with other people. We needed bigger brains—three times bigger than our nearest animal relatives—for handling this new mass of rapidly changing data. But we also needed a new, emergent level of intelligence. Just as the activities of individual neurons have to be coordinated by the patterns emerging between them, so coordinating individual attentions and actions needed new epicognitive regulations between individuals.

Individual neurons have modest computational powers, but networks of neurons can collectively perform complex operations

Such epicognitive regulations have been well-studied within a dynamic systems perspective. They include shared concepts of the world; the myriad rules and procedures through which we organize our joint activities; the knowledge structures arising through them; the language through which they are mediated; the hardware tools, technologies and skills through which they are implemented and so on. This is what we mean by human culture, and it is these cultural tools and devices that make human cognitions so distinctive. As neural connections become shaped by the patterns of activity between them, so patterns of cognition become shaped by the dominant structure of activities in cultures and subcultures.

As the Soviet psychologist Lev Vygotsky insisted, this form of intelligence vastly extends and amplifies the cognitive abilities

and adaptable variation of primate intelligence. The dynamics between brains interact with those within brains—just as the dynamics of physiology interact with those of epigenetics—emerging as hierarchies of nested attractors showing reflective abstraction. The cultural tool we call science is one of the best examples: a theory is a collective model emergent from the dialectics of scientific method, taking us beyond specific empirical experience. It is such ‘socio-psychonomics’ that have driven human history across millennia.

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Variation, as well as typical function, of intelligence at all levels should probably be viewed in such a dynamic context. At all levels intelligent performance is a resolution of nonlinear dynamical processes involving interactions among myriad variables at several levels. Experience with specific cultural tools or procedures, for example, results in changes in brain networks [28], which will alter epigenetics, transcription regulation and so on. As performance and ‘outputs’ are so diverse, by evolutionary design, it seems perverse to attempt to reduce them to the expression of a single ‘strength’ variable as IQ tests pretend to do. The human socio-cognitive intelligence system evolved to deal with unprecedented environmental change. Its implementation is invariably through cultural tools—language forms, reasoning patterns and so on—which vary with social background. Even so-called ‘culture-free’ intelligence tests are embedded in such patterns—for example, items on the Raven’s matrices tests follow the top-left to bottom-right layout of text in dominant western culture. IQ scores might be more an index of individuals’ distance from the cultural tools making up the test than performance on a singular strength variable.

Heritability studies and genome-wide association studies search for direct genotype phenotype correlations in populations

as the causes of variation. They thus aim to untangle the complex interplay between genes and environments. But that completely misses the point: it is the nature of the tangle, not the untangled, that offers understanding about the system and its variation. It is precisely in such tangles that heritabilities go missing and intelligent life is born—and a ‘grown-up’ science might become possible.

CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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