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Understanding greater male variability in general intelligence:

The role of hemispheric independence and lateralization

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Abstract

Deary et al. (2003) present data, further analysed by Johnson et al. (2008), showing a sex difference in general intelligence across a whole population: males were more variable than females and were over-represented at the lower *and* upper ends of the distribution. We propose a single-factor explanation based on hemisphericity, the degree of hemispheric independence and lateralization of function. We demonstrate this argument with a conceptual analysis and with neural network simulations of hemispheric interaction. We discuss the nature of abstraction in computational cognitive modelling. Greater male variance in general intelligence can be at least partially understood as emerging from increased hemisphericity, underlining the latter's critical role in the evolution, development and functioning of human cognition.

Keywords: IQ; sex differences; hemisphericity; lateralization; cognitive modelling.

Understanding greater male variability in general intelligence:

The role of hemispheric independence and lateralization

Johnson, Carothers and Deary (2008) present “a new look at an old question”—is general intelligence more biologically variable in males than females? That is, are there more males at the high *and* low ends of the range. They review the history of this ‘variability hypothesis’ and the attendant problems of interpretation—technical, statistical and sociological—before reanalysing data that are unique in their population representativeness; these data belong to the Scottish Mental Surveys (SMS) of 1932 (Scottish Council for Research in Education, 1933) and 1946 (Scottish Council for Research in Education, 1949). Critically, the data approximate the whole Scottish population at ages 11–12 years. The male data are more variable, with more males towards both ends of the range of general intelligence (for which IQ is a proxy), with a negligible difference in the means (Deary, Thorpe, Wilson, Starr, & Whalley, 2003).

This variability effect is also reported elsewhere (Cleary, 1992; Cole, 1997; Deary, Irwing, Der, & Bates, 2007; Dykiert, Gale, & Deary, 2009; Feingold, 1992; Fraiser, 1919; Hedges & Nowel, 1995; Jensen, 1973; Lohman & Lakin, 2009; Maccoby & Jacklin, 1974; McNemar, & Term-an, 1936; Strand, Deary, & Smith, 2006). Only Iliescu, Ilie, Ispas, Dobrean and Clinciu (2016) fail to find such a sex difference.

Johnson et al. also report significantly greater variability in the lower half of the distribution, the left ‘shoulder’ being broader than the right. They suggest the entire distribution is a composite of two normal distributions, “one reflecting normal variation in general intelligence and one reflecting normal variation in effects of genetic and environmental conditions involving mental retardation” (p. 518)¹. They calculate the latter distribution involves almost 20% of the population; because its mean is almost 80, most of the individuals implicated would not be classed as severely mentally retarded and institutionalized². This second, putative distribution contains more males.

Below, we explain the greater male variability in terms of a single factor predicting more high- and low-scoring males than females, with approximately equal means.

We claim a critical role for *hemisphericity*: the relative independence of the left and right hemispheres, their differential parameterization and the lateralization of function to one or other hemisphere. Three arguments suggest that hemisphericity is crucial in the phylogenetic, ontogenetic and cultural development of human cognition.

First, *hemispheric independence*. Hemispheric independence increased during mammalian evolution (Aboitiz & Montiel, 2003; Hopkins & Rilling, 2000; Ringo, Doty, Demeter, & Simard, 1994; Rilling & Insel, 1999), defined by the relative sizes of the corpus callosum and the neocortex. Larger brains do not have proportionately more callosal connections. Larger transfer distances militate in favour of modularity, the most effective version being hemisphericity.

Second, *asymmetry*. A vertical axis of symmetry is evolutionarily ancient. Asymmetry of structure and/or function about the vertical midline is widespread (e.g. Denenberg, 1981; MacNeilage, Rogers, & Vallortigara, 2009), from bees (Letzkus, Ribi, Wood, Zhu, Zhang, & Srinivasan, 2006) to great apes (Quaresmini, Forrester, Spiezio, & Vallortigara, 2014). This asymmetry is greatest in humans (Gazzaniga, 2000, p. 1294).

Third, *the very plastic interdependence of the two hemispheres*. Callosal agenesis (underdevelopment of the corpus callosum) and related disorders have highly variable effects on cognition, sometimes having no apparent effects on IQ and in other cases profoundly impairing it (Chiarello, 1980; Sauerwein, Nolin, & Lassonde, 1994). Hemispherectomy itself may sometimes have less drastic consequences than might be imagined (e.g. Pulsifer, Brandt, Salorio, Vining, Carson, & Freeman, 2004). Adult callosotomy produces the well-known disconnection syndrome, in which the individual appears paradoxically intact, requiring ingenious experiments to reveal the cognitive implications of severing the corpus callosum (e.g., Gazzaniga, 2005; Gazzaniga, Bogen,

& Sperry, 1962; Gazzaniga, Bogen, & Sperry, 1963; Gazzaniga, Bogen, & Sperry, 1965; Gazzaniga & Sperry, 1967; Sperry, 1964). Even here, though, there is individual variation in its effects on, for example, resting state activity (see Johnston et al, 2008; Uddin et al., 2008). This very variation in the role of hemispheric interaction alerts us to its potential.

A complementary argument is that greater hemisphericity has long been associated with the male brain and with less extensive inter-hemispheric transfer. For instance, DeLacoste-Utamsing and Holloway (1982) report a larger female splenium in the corpus callosum, facilitating peristriate, parietal, and superior temporal interaction. However, this issue has remained controversial (e.g. Bishop & Wahlsten, 1997) due to factors such as small sample sizes, individual differences, variation in measurement technique and a failure to control for age-related changes (Allen, Richey, Chai & Gorski, 1991). The picture is also complicated by handedness (Denenberg, Kertesz, & Cowell, 1991) and perhaps above all by brain size (Jäncke, Mérillat, Liem and Hänggi, 2015). Beyond these methodological issues, there is the fact that the gross physical morphology and the functioning of the corpus callosum are mediated by many factors.

Developments in diffusion tensor imaging technology (Basser, Mattiello & Lebihan, 1994) have clarified the issue of hemisphericity. It has provided a detailed picture of connectivity across the whole brain (neologized as the ‘structural connectome’) and has allowed more representative numbers of brains to be studied. This research is still unfolding but the convergent conclusion is as stated by Ingalhalikar et al. (2014, p. 823): “male brains are optimized for intrahemispheric and female brains for interhemispheric communication”. Although that particular high-profile study has attracted controversy, other researchers have drawn similar conclusions (e.g. Jahanshad et al., 2011; Tunç et al., 2016; Tyan, Liao, Shen, Lin & Weng, 2017). Ritchie et al. (2017) report stronger functional connectivity for males in unimodal sensorimotor cortices, and stronger connectivity for females in the default mode network. They also report pervasive size differences, with the

component structures of male brains tending to be larger than the female counterparts; this size difference speaks to the issue of emergent hemisphericity discussed by Ringo et al. (1994). Ritchie et al. also report generally greater male variance in structural measures, a point to which we return below.

Finally, powerful evidence for the role of hemisphericity comes from cases of left hemispherectomy due to Rasmussen's syndrome (Boatman et al., 1999). The right hemisphere is substantially able to take over the additional responsibilities of the left hemisphere.

To conclude, male and female brains both contain inter- and intra-hemispheric connectivity. What is claimed is not a categorical, dichotomous sexual dimorphism but two populations that largely overlap in most respects, but in which it is still possible to distinguish male from female brains on the basis of the mosaic of structural data (Chekroud, Ward, Rosenberg & Holmes, 2016), principal among them being modularity at the level of the hemispheres. Below, we will characterize male and female brains as respectively tending towards *intra*hemispheric connectivity and *inter*hemispheric connectivity, with advantages and disadvantages for both these processing styles.

We tested the hypothesis that greater male hemisphericity produces more variance in the distribution of general intelligence at both high and low ends of the scale. We adopt two perspectives: first, an ordinary-language conceptual analysis, and second, neural network modelling.

An ordinary-language conceptual analysis

Hemispheric division represents the largest grain of *parallelism*, a strategy seen even at the outermost contact with the world, on a much smaller scale (cf. Wässle's, 2004, discussion of the retina). Parallelism confers speed advantages, but it also has implications for the development of 'tools for cognition', which we here define as ranging from high-level domains such as phonological or spatial processing through to small, low-level, distributed, less easily characterized

components of cognitive processing. Cognitive tools may co-operate intrahemispherically and/or they may interact interhemispherically in the rest of the body, in behaviour, in the world outside the body.

There have been longstanding claims regarding broad-brush hemispheric specialisms, such as phonology in the left hemisphere (LH) (e.g. Geschwind, 1970) *versus* spatial processing in the right hemisphere (RH) (e.g. Witelson, 1976). Later claims have concerned differential parameterization of the two hemispheres: for instance, fine-coding in the LH and coarse-coding in the RH (e.g. Beeman, Friedman, Grafman, & Perez, 1994), or a temporal version of the fine/coarse distinction (e.g. Poeppel, 2003). Such a hemispheric division of labour may emerge over the lifespan (e.g. Behrmann & Plaut, 2015).

On the one hand, there is no lack of recognition—from philosophical to theoretical physics approaches—of the complexity of the interactions necessary for unified, conscious behaviour and cognition in individual and in dyadic processing, from Vygotsky's (1934/86) *interfunctional relations*, to Eliasmith's 2008, p. 150) *bandwidth*, to Abney, Paxton, Dale and Kello's *complexity matching*, to Clark's (2009) *Escher spaghetti*.

On the other hand, anatomically-based theories/models of hemispheric interaction are still relatively simplistic, based on data such as the speed of interhemispheric transfer (e.g. Cherbuin & Brinkman, 2006), the inhibitory or excitatory nature of callosal connections (e.g. Bloom & Hynd, 2005), degenerative and developmentally atypical patterns of callosal connectivity (e.g. Barnett, Corballis, & Kirk, 2005; Paul, Brown, Adolphs, Tyszka, Richards, Mukherjee, & Sherr, 2007), the influential 'split-brain' studies (e.g. Sperry, Gazzaniga, & Bogen, 1969), and imaging patterns of behaviour-related activity (e.g. Doron & Gazzaniga, 2008).

Nevertheless, psychologists have delineated some of the conditions under which, for instance, parallel processing with *identical* goals in the two hemispheres may be advantageous rather than

simply redundant. Elementary visual stimuli can be better processed when presented simultaneously to both hemispheres, in a ‘bilateral redundancy paradigm’ (Beaumont & Dimond, 1973; Miller, 1982). Mohr, Endrass, Hauk and Pulvermüller (2007) review ‘superadditive’ processing involving checkerboard patterns (Miniussi, Girelli, & Marzi, 1998), colours (Roser & Corballis, 2003), cvc syllables (Hellige, Taylor, & Eng, 1989; Marks & Hellige, 1999, 2003), words (Hasbrooke & Chiarello, 1998; Mohr, Pulvermüller, & Zaidel, 1994; Mohr, Pulvermüller, Mittelstädt, & Rayman, 1996; Mohr, Landgrebe, & Schweinberger, 2002), and familiar faces (Mohr et al., 2002; Schweinberger, Landgrebe, Mohr, & Kaufmann, 2003). The mechanism underlying superadditivity is not taken to be a simple ‘race’ model, in which separate processes compete to produce the output first (cf. Miller, 1982). Rather, it may involve timing precision (Mohr & Pulvermüller, 2002), stimulus familiarity (Mohr, Pulvermüller, & Zaidel, 1994, 1996; Mohr et al., 2002), stimulus complexity (Banich & Karol, 1992; Hellige et al., 1989) and neurotypicality (Beaumont & Dimond, 1973; Endrass, Mohr, & Rockstroh, 2002; Mohr et al., 2000), among other factors. Differential parameterization in the two hemispheres (e.g. fine and coarse coding) means that there can be an adaptive divergence of ‘identical’ processing with the same goals (i.e. identical cognitive tools) in the two hemispheres, such that they produce overlapping ranges of solutions to the same problem, for instance. Overall, then, there are tractable behavioural aspects of hemispheric interaction, even in the absence of a determinate theory.

There can also be *complementary/collaborating* goals and cognitive tools operating across the two hemispheres. Bimanual manipulation is a clear example. At the other extreme of a range of collaboration, the hemispheric split can accommodate independently useful but mutually incompatible tools, such as avoidance (RH) and approach (LH) behaviours (cf. Rutherford & Lindell, 2011); hemisphericity effectively insulates the two behaviours from each other, preventing them from interfering with each other.

Hemispheric division can be adaptive. Processes may have more scope for variation if they originate in only one or other hemisphere and such variation may result in fortuitously adaptive collaboration between the hemispheres. This possibility corresponds to the high-scoring idealized ‘male’ brain: greater hemisphericity, more varied cognitive tools, successful interhemispheric collaboration, enhanced general intelligence.

However, greater hemisphericity is *risky*. First, differential parameterization may be insufficient to make the hemispheres importantly different, resulting in two small versions of what could be one large, more powerful processor.

Second, hemisphere-specific tools may not collaborate adaptively; instead, they may step on each other’s toes. This possibility corresponds to the low-scoring idealized male brain: greater hemisphericity, varied but incommensurate cognitive tools, unsuccessful interhemispheric collaboration, impaired general intelligence.

The resulting male distribution of general intelligence is not necessarily symmetrical; the human male data have a broader left shoulder. There may be more ways for parallel processing to mismatch maladaptively than to fortuitously combine adaptively. However, the goal here is not curve-fitting to the human data, but an understanding of the material essence of the processing.

In summary, the greater hemisphericity of the male brain means its hemispheres interact adaptively *or* maladaptively, providing a *single* explanation for the human data. Reduced female hemisphericity, tending in the limit to ‘one large brain’, guarantees more compatible, but potentially less radical, component processing and less chance of a fortuitous radical collaboration—a ‘safer’ option. This sex difference has no implications for the two population means, which can be identical.

A Neural Network Model

We modelled success in a task of ‘general intelligence’ as the learning of an identity mapping by a 3-layer neural network: input vector X is identical to output vector Y . Such a network represents one individual. Randomizing initial connection weights ensures that a population of such networks achieves a range of results after a specified training regime. The distribution of mean error across this population is analogous to the human data. Qualitative similarity between the two distributions is an existence proof of the conceptual analysis, above.

The models we trained were ‘hemispherically divided’ (cf. Anninos & Cook, 1988; Monaghan, Shillcock, & McDonald, 2004; Reggia, Goodall, Shkuro, & Glezer, 2013; Shillcock & Monaghan, 2001a,b; Monaghan & Pollmann, 2003; Shkuro, Glezer, & Reggia, 2000) (See Fig. 1). We divided the hidden layer and manipulated intra- and inter-hemispheric communication to be in inverse proportions by using recurrent connections inside or between the hemispheres, respectively. Recurrent connections allow activation to pass between the relevant nodes over a series of timesteps. A ‘male’ model contained more intrahemispheric connections and fewer interhemispheric connections than a ‘female’ model. We kept the resources of the networks (the total number of connections) constant but manipulated the degree of ‘hemisphericity’.

We tested the hypothesis that the ‘male’ networks would be more represented at both ends of the distribution of success in learning the identity mapping.

Network Architecture

The data comprised 100 training vectors and 100 validation vectors in $\{0, 1\}^{20}$. In each vector the elements were independently and identically distributed. The input layer of the network consisted of 20 units, each representing a vector element from the data. The hidden layer was composed of 16 units, enforcing data compression. For a given input vector, the activation a of each hidden unit i at time step t was defined as:

$$a_i(t) = \sigma\left(\sum_{s=1}^S w_{si}^{(I-H)} + \sum_{r=1}^R w_{ri}^{(H-H)} a_r(t-1) + b_i^{(H)}\right)$$

where $w_{si}^{(I-H)}$ is the weight from the s -th input unit to the i -th hidden unit, $a_r(t-1)$ is the activation of the r -th hidden unit at the previous time step, $w_{ri}^{(H-H)}$ is the weight from the r -th hidden unit to the i -th hidden unit within the recurrent layer, $b_i^{(H)}$ is a bias term for the i -th hidden unit and σ is a rectifying activation function with $\sigma(x) = \max(0, x)$. The recurrent structure of the hidden inputs enabled the exploitation of sequential information: the activation of each hidden node at a given time step is the rectified and linearly weighted sum of the input units, the activation of all hidden units at the previous time step, and a bias unit. Formally, the output o of each unit i in the output layer is defined as:

$$o_i = \sigma\left(\sum_{r=1}^R w_{ri}^{(H-O)} a_r(T) + b_i^{(O)}\right)$$

where $w_{ri}^{(H-O)}$ is the weight from the r -th hidden unit of the recurrent layer to the i -th output unit and $b_i^{(O)}$ is a bias for the i -th output unit. That is, the activation of each output unit was the rectified and weighted sum of the final activation of all recurrent hidden units and a bias.

Network weights were randomly assigned from a uniform distribution with a random number generator seed S for a fully deterministic process. All inter- and intra-layer weights were sampled from the range $[-0.005, 0.005]$. Bias weights were initialized with constant weight 0. In order to impose a hemispheric structure on the network, some weights were initialized to 0 (see below). Each model was then trained for 1000 epochs, where each epoch involved the entire training set. After each epoch, the network's output was evaluated by means of a mean squared error (MSE) objective function:

$$MSE = \frac{1}{N_{train}} \frac{1}{S} \sum_{i=1}^{N_{train}} \sum_{s=1}^S (o_{is} - x_{is})^2$$

where o_{is} is the network's output for the i -th instance at the s -th output units, and x_{is} is the respective network input and thereby target output.

The Backpropagation Through Time algorithm was then applied to the network error, and weights were updated by the Adagrad algorithm (Duchi, Hazan, & Singer, 2011). This adaptation of the more standard stochastic gradient descent algorithm decreased the learning rate monotonically across epochs depending on the gradients of previous epochs. The learning rate was initialized at $\mu = 0.05$.

Imposing a hemispheric structure

To impose a hemispheric structure, certain weights between the layers were systematically fixed to zero, nullifying the connection. The 'male' model was 7:1: each hidden unit was connected to 7 units in its own hemisphere and 1 unit in the opposite hemisphere. The 'female' model was 5:3.

Input and output vectors were split in two. Each half of the input vector was projected to the ipsilateral hidden units. Contralateral connections (e.g. left half of the input vector to right hidden units) were fixed at zero. After activity had circulated in the hidden units, information was contralaterally projected to the output layer, thus enforcing hemispheric interaction (see Fig. 1).

Without this pattern of connectivity, the two hemispheres could in principle work independently.

Experimental procedure

To compare male and female models, 200 networks of each type were trained, differing only in the random initialization of weights. Mean, variance, and standard deviation of mean squared error terms (MSE) were computed at each epoch. Differences in MSE between the two sets at a given epoch were described using Cohen's d for pooled variances.

To test for differences in mean model performance on a population level, we use a two-sided Mann-Whitney U test for each epoch. To reduce the incidence of false-negative results, a significance level of $\alpha = 0.1$ was used. To test for difference in variance of network performance on a population level, a Levene's test based on the sample medians for each epoch was used, with a significance level of $\alpha = 0.05$. Since the comparison of models was conducted across epochs, p-values were corrected by means of the Benjamini-Hochberg procedure to control for the effects of positive correlation. We considered an epoch as exhibiting a *greater variability pattern* if, with respect to MSE, the two models differed significantly in variance but not in mean.

Results

After 200 training epochs, the two models exhibited no significance difference in mean performance on the validation data ($d \approx 0$), although this result may be partly attributable to the correction for positive correlation. With uncorrected p-values, the mean difference reached (marginal) significance in several epochs from epoch 694 onwards. In both cases, however, the majority of epochs exhibited no significant difference in mean performance.

In both models, the error terms at a given epoch followed a unimodal distribution (Fig. 2. Note that high 'cognitive ability' is represented by a low MSE). Using a Shapiro-Wilk test, the distribution of MSE terms in 7:1/'male' networks did not deviate from a Gaussian distribution ($p = 0.66$). For the 5:3/'female' networks, however, the distribution was not Gaussian ($p = 0.04$) but rather skewed to the right ($\gamma_1 = 0.43$) and exhibited excess kurtosis ($k = 0.26$).

Figure 3 shows that 'female' networks performed with smaller variance whereas 'male' networks were over-represented at the extremes of the distribution. Crucially, the over-representation of the 7:1/'male' networks was an emergent property of the models' hemispheric structure.

Discussion and Conclusion

How can we understand the reported sex difference in the distribution of measured IQ? We adopted two different Cognitive Science perspectives: a conceptual explanation involving ‘cognitive tools’ and a neural-network existence proof. Both approaches abstract from the complexity of the active brain to consider the material hemisphericity that we suggest is essential to the emergence of cognition and that we claim underlies greater male IQ variance.

This explanation is not necessarily exclusive. Many factors, including sociocultural ones, potentially contribute to one or other end of the distribution. However, our explanation is parsimonious—it involves a single mechanism—and is successfully modelled.

There are two other potential explanations. The first is specifically genetic. Female development depends on two *X* chromosomes, male development on a single *X* chromosome. As Johnson et al. (2009, p. 599) observe, this situation necessarily reduces female variability; a deleterious mutation on one *X* chromosome may be offset by the non-mutated other *X* chromosome. However, they argue that this sex difference does not wholly explain the IQ data: “This evidence ... is limited to the involvement of the *X* chromosome in *disrupting* general intelligence.” (p. 602, our italics). “It is much more difficult to imagine how one particular protein could similarly enhance the overall function of these complexes” (p. 601).

The second, potential explanation rests on general structural differences between male and female brains: the anatomical components of male brains tend to be larger and to vary more in size (e.g. Ritchie et al., 2017). Brain structure mediates cognition, so we may expect greater variance in IQ. This explanation, like our hemisphericity explanation, addresses both ends of the distribution.

However, correlations between sex and size of brain structure do not constitute a productive explanation. First, there is no agreed mechanism for why ‘more brain means more cognition’, within the normal range (see, e.g., Foster et al., 1999; Pietschnig, Penke, Wicherts, Zeiler, &

Voracek, 2015). The same holds phylogenetically (see, e.g., Aboitiz, 1996; Henneberg, 1998).

Modularity and connectivity may mediate simple quantity (cf. Ringo et al., 1994). Our claim here is that hemisphericity is the prime consideration. ‘Greater male variance’ is sufficiently general to subsume our hemisphericity explanation, when applied to the size of the corpus callosum and other commissures. However, there are important philosophical distinctions.

Cognitive scientists conventionally specify qualitatively different mechanisms, functions, conceptual vocabularies at different ‘levels of processing’ (cf. Marr & Poggio, 1976). In a related characterization, Coltheart and Jackson (1998) distinguish ‘proximal’ from ‘distal’ causes in cognitive impairments. A distal cause might be a genetic atypicality. A proximal cause might be atypical orthographic or phonological processing (in dyslexia)—structured activity ‘closer’ to the behavioural data.

Neither of these conventional characterizations of interaction within complex systems is adequate; they both underspecify the relations within the totality of cognitive processing, genes, behaviour, neurophysiology, brain anatomy, social interaction, and so on, in the lives of real individuals. In place of fuller explanations, these approaches result in cognitive models composed exclusively of generalized abstractions (abstractions that are ‘universals’ in that they identify something similar across a number of different entities). We typically see such abstractions as the labels in box-and-arrow diagrams. The conventional way of filling in the interactions in the rest of the totality is paraphrased by Ritchie (2015, Chapter 4), in the context of behavioural genetics, as “a set of studies finding a daisy chain of results: specific genes leading to specific brain differences, which themselves lead to differences in intelligence.” This philosophically *positivist* theory of explanation is characterized by claiming that there is a firm, known ‘atomic’ foundation (genetic material) for the domain under study (intelligence), such that scientists can build up step by step,

verifying every move, until the ‘highest’ phenomena (intelligence differences) in the domain have been fully reproduced.

We will not visit the checkered history of positivism here. Rather, we will provide a materialist theory of explanation. It appears as Vygotsky’s (1934/86) ‘unit of analysis’ (cf. the history of the ‘concrete universal’, Shillcock, 2014). As an example, Vygotsky considers how to understand the fluid, fire-extinguishing properties of water. The relevant level of explanation, or unit of analysis, is the molecule. Below that are the atoms of hydrogen and oxygen. More generally, we require the simplest material entity that both exhibits and explains the ‘logic’ of the domain (i.e. how the domain works, not an attempted reduction to formal logic). For cognition, an attractive candidate for that entity is the hemisphere. We have seen, in Rasmussen’s syndrome, the RH can substantially take over the role of the whole brain. We never see the two frontal cortices, or the cerebellum, or any other subset of brain components smaller than a single hemisphere, doing the same. In this sense, the hemisphere is the unit of analysis for higher cognition, the material essence of the domain. Hemisphericity, the material division of the brain, pervades the domain and speaks to everything else in cognition—every aspect of cognition has a hemispheric dimension, in that it is affected by lateralization. We can therefore characterize hemisphericity as a ‘universal’.

A conventional objection is ‘a hemisphere is half of the whole brain—where is the *detail* in this claimed explanation?’ The analysis in which hemisphericity is the essence of cognition in no way excludes the exploration of detailed intra-hemispheric mechanisms. It *does* exclude a gene-centred view of higher cognition that *reduces* the latter to the former. The goal is not to reduce the domain to supposed atomic entities or to descriptive laws, but to understand how the full complexity of higher cognition can be ‘rebuilt’ from the farthest abstraction that we can make. This farthest abstraction may not seem very far—only down to half of the whole brain, not down to some ‘elemental’ neural circuit—but it allows us to talk about the whole of higher cognition, a domain

pervaded by ‘hemispheric effects’. This abstraction is the materialist alternative to the conventional positivist abstraction found in the cognitive sciences. In taking the ‘return journey’ for this type of abstraction, from the hemispheres to the whole brain, we are led to understand the exigences of hemisphericity, the unique situation of two mutually-predicting ‘brains’ side-by-side in the same context.

In conclusion, a philosophically grounded approach to modelling cognition points us to an understanding of the reported sex difference in the distribution of IQ across a population. It orients us towards a productive research program in which the goal is to understand the processing implications of hemisphericity, an architectural principle that is at the very centre of the phylogenetic and developmental emergence of higher cognition.

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Figure 1. General network architecture, showing 'male' 7:1 connectivity. There is complete connectivity between the two input vectors and their respective sets of hidden units, and between the two sets of hidden units and their respective output vectors. See text for details of the connectivity between the two sets of hidden units.

Figure 2. Distribution of mean squared error for the ‘female’ 5:3 and ‘male’ 7:1 networks for the validation test-set after 1000 epochs of training. Bin-size was determined with the Freedman-Diaconis rule (Freedman & Diaconis, 1981). (The zero scores at the second bin from the left represent noise in the modelling, at the given granularity.)

Figure 3. Complementary distributions of the proportions of 'female' 5:3 and 'male' 7:1 networks for different levels of mean squared error. At each level the two types of network sum to 1. N.B.

Low MSE corresponds to high scores on tests of general intelligence.

Footnote

¹ The test in fact seems to generate a slightly negatively skewed distribution of scores, probably for psychometric reasons; confounding of psychometric precision and sampling selectivity is endemic to testing (Johnson, *pers. comm.*)

² N.B. The second distribution is generated by mutation and environmental noise affecting 20% of the population represented in the basic, ‘underlying’ symmetrical distribution. This second distribution is thus also symmetrical, and is overlaid on the first.