Contents

List of Illustrations ix
Preface xii
Notes on Contributors xiv

Part I  Complexity and the Animal Mind

Introduction 3
Maggie McGonigle-Chalmers

1  Relational and Absolute Discrimination Learning by Squirrel Monkeys: Establishing a Common Ground with Human Cognition 12
Barry T. Jones

2  Serial List Retention by Non-Human Primates: Complexity and Cognitive Continuity 25
F. Robert Treichler

3  The Use of Spatial Structure in Working Memory: A Comparative Standpoint 38
Carlo De Lillo

4  The Emergence of Linear Sequencing in Children: A Continuity Account and a Formal Model 55
Maggie McGonigle and Iain Kusel

5  Sensitivity to Quantity: What Counts across Species? 80
Sarah T. Boysen and Anna M. Yocom

Part II  Complexity in Robots

Introduction 99
David McFarland

6  Towards Cognitive Robotics: Robotics, Biology and Developmental Psychology 103
Mark Lee, Ulrich Nehmzow and Marcos Rodriguez
### Contents

7 Structuring Intelligence: The Role of Hierarchy, Modularity and Learning in Generating Intelligent Behaviour  
*Joanna J. Bryson*  
126

8 Epistemology, Access and Computational Models  
*George Luger*  
144

9 Reasoning about Representations in Autonomous Systems: What Pólya and Lakatos Have to Say  
*Alan Bundy*  
167

#### Part III Language, Evolution and the Complex Mind

Introduction  
*Keith Stenning*  
187

10 How to Qualify for a Cognitive Upgrade: Executive Control, Glass Ceilings and the Limits of Simian Success  
*Andy Clark*  
197

11 Private Codes and Public Structures  
*Colin Allen*  
223

12 The Emergence of Complex Language  
*Wolfram Hinzen*  
243

13 Language Evolution: Enlarging the Picture  
*Keith Stenning and Michael van Lambalgen*  
264

Epilogue: Brendan McGonigle  
283

Index  
289
Part I
Complexity and the Animal Mind
Introduction

Maggie McGonigle-Chalmers

‘Contemporary study of the animal mind is perhaps the most powerful integrative movement in biological science since Darwin.’

– Hendry (2008)

Humans are well practiced at lauding their achievements. A recent example from Penn, Holyoak and Povinelli (2008) notes, for example, that human animals ‘build fires and wheels, diagnose each other’s illnesses, communicate using symbols, navigate with maps, risk their lives for ideals, collaborate with each other, explain the world in terms of hypothetical causes, punish strangers for breaking rules, imagine possible scenarios and teach each other how to do all of the above’ (Penn, Holyoak and Povinelli, 2008), a list which they proceed to augment in particular and considered detail with respect to analogical reasoning, rule-based learning, reasoning about spatial relations, transitive inference, hierarchical reasoning, causal reasoning and theory of mind. All of these achievements deserve the epithet ‘complex’, insofar as this refers to emergent higher-order properties of the biological system. Whether this is represented conceptually via the interacting elements of mental representations, or more literally via the large pathways connecting sensory, motor, memorial and planning areas of the brain, it is not difficult to argue the case for the complexity of the human mind.

It is ironic that such a capability, which has used its powers to penetrate the mysteries of the physical universe for several millennia, has so very belatedly come to look at how it itself may have emerged from a cognitive substrate that we share with other species. It is nothing short of astonishing that, having pronounced so shrilly on our ‘unique’ linguistic capabilities down the centuries, we have so very recently only started to actually ‘listen’ for differentiation of meaning and communicative intentionality in other species (Cheney and Seyfarth, 2005; Deecke, Ford and Slater, 2005; Hollen and Manser, 2005; Marler and Evans, 1997). But perhaps the greatest misfortune that befell comparative psychology in its inception was the force of
Morgan’s canon when he presaged decades of the tyranny of behaviourism with the edict that:

In no case may we interpret an action as the outcome of the exercise of a higher psychical faculty, if it can be interpreted as the outcome of one which stands lower on the psychological scale. (Morgan, 1894)

The problem was that in the reductionism that followed (albeit arguably based on a misinterpretation of Morgan; see Thomas, 1998), the tools of measurement were perhaps paradoxically drawn from our own invented culture of science and engineering. As Jones describes in Chapter 1, the criteria by which animal intelligence was judged were based on dependable indices such as energetic values measured in actual size, brightness or pitch. And although the (much later) birth of a new comparative approach in the form of animal ‘cognition’ eschewed much of the old reductionism, it introduced criteria that drew substantially on abilities that appear relatively late within human development, with little regard for the extent to which they owed their emergence to enculturation and formal schooling. From this tradition there have been some ‘no-win’ debates about whether animals make transitive ‘inferences’ using criteria based on deductive mechanisms that are not particularly in evidence even in late childhood (Clark, 1969; Hunter, 1957) or show a readiness to adopt counting mechanisms that in human development are patently not only the product of formal tuition but actually work ‘against the grain’ of the human tendency to quantify by more primitive means (Fuson, 1988; Nunes and Bryant, 1996).

It is therefore only relatively recently that animal cognition has started to embrace the study of core cognitive skills that are not end-state defined, but instead are highly plausible candidates for how ‘higher-level’ abilities get off the ground. In doing so they have had to re-establish what that ground actually consists of. One place to start in every sense is with the basic connectives in the visual world without which complex behaviours and the internal representations that guide them would have no roots or primitives from which to grow. These connectives are argued by Fodor and Pylyshyn (1988) to provide the core indivisible semantics for human cognition and include causal, temporal and spatial relations and relations of equality, similarity and difference.

One of the first triumphs of research in animal cognition, therefore, was to start reclaiming this ‘relational’ ground from the grip of behaviourist accounts that had attempted to replace the concept of relational perception through reduction. Denying animals the ability to ‘comprehend’ a relation between one object and another, theories were built instead around the energetic properties of individual stimuli, rendering ‘relational learning’ in animals as a mere mechanical outcome of stimulus/response strengths. In Chapter 1 of this volume, Jones details a probing archival study that was
one of the first to challenge the veracity of this claim. In the spirit of simply ‘opening the horse’s mouth’, the ease and stability of size-relational learning in monkeys was compared explicitly with the proposed alternative of absolute stimulus learning, concluding not only that the former is a perceptual primitive in non-human primates, but that the absolute response is also fundamentally relational. Drawing, as they appear to, on ad hoc relationships within the stimulus environment, such absolute codes are shown to be highly unstable when that environment changes. These conclusions are virtually identical in every respect to those drawn by the developmental psychologist, Peter Bryant, during his pioneering studies of size-relational learning in young children (Lawrenson and Bryant, 1972).

With a common ground based on fundamental relational connectives firmly reinstated by such research, we might ask, ‘Where next?’ One route is to see how far relational comprehension can extend beyond the binary case, encompassing relations between relations such as ‘middle-sized’ and ‘second smallest’ (see McGonigle and Chalmers, 2002). The monkeys were successful in all of this and patterns of acquisition and relative difficulty were almost astonishingly similar to those obtained with preschool children. While gratifying to obtain yet another analogue with human performance, was this capability as evinced within the lab really informing us as to how ‘complex’ knowledge grows from simple primitives in evolution and development? Certainly it had been demonstrated that by making the multiple response requirements explicit, we could indeed sharpen the fine-tuning of the relational learning (and also of transitivity of choice; see McGonigle and Chalmers, 1992), but by what means, and with what exact implications for natural knowledge growth? Is it plausible that the heavily supervised designs of single-choice discrimination tasks are remotely analogous to the environmental conditions that have provoked complex decision-making in nature? The real world of dominance hierarchies, foraging and mating may be one within which binary choice may still effectively prevail (‘this one or that one’, ‘fight or flee’, ‘aggressor or appeaser’, etc.), but those decision-making capabilities appear to emerge in the form of a ranking process that can unite piecemeal input and thereby govern rational choice. In our search for cognitive continuities across species, is it not this ability to create overall order from partial sampling of the data that holds a clue to what may lie at the roots of higher-order logico-mathematical abilities in humans? Discrimination learning was not the tool for exploring this possibility. It was time to look at ranking behaviours more explicitly. And it was time to do so in the laboratory.

The second chapter of this volume reviews one of the most fundamental of all ranking mechanisms; the order of events in time. Despite Lashley’s injunction to reject simple associative chaining accounts in a seminal paper on the problem of serial order and to view it as ‘the most complex type of behaviour’, that is, ‘the logical arrangement of thought and action’ (Lashley,
seriality has become synonymous with a low-level ‘explanation’ of a solution to a cognitive task. Within the long tradition of assessing cognition in animals through training and test, the issue of whether the animal has simply conserved the order of events during training rather than their ‘deeper’ structure has plagued areas such as transitivity research. Here evidence is sought that binary relations of, for example, size (red is bigger than green; green bigger than blue) can be integrated into a linear structure affording ‘deductions’ based on combining these relations into a connected order (red>green>blue). To assess this, the original pairings have to be trained. In young children, responses to novel test pairings do seem to be initially dependent on a substructure formed by the temporal ordering of the relations in a monotonic linear sequence, AB, BC, CD and so on, and any training that violates this temporal sequencing is likely to result in failure (Kallio, 1982). Despite the fact that this might afford a clue as to how children subsequently become aware of transitive relations based on object properties alone, there has been nothing short of an obsession with eliminating temporal chaining when studying transitive choice mechanisms in animals. Without the end-state evidence (as with children) that at some point a higher-level solution will emerge based on the relational connectives alone (Halford, 1984), this is perhaps not too surprising. More surprising is how long it has taken to see that temporal relations can themselves be integrated into linear structures in precisely the same way as object relations. If A comes before B and before C, can the relationship between A and C be resolved by some mechanism of integration and ranking? And, if so, what are the properties of the resulting representations; what long-term dependencies can be supported by learning several adjacent relations? How precise and fine-tuned are the resulting linear orders? Given how fundamental temporality is to all organised behaviour, these were questions that were long overdue for investigation in the lab.

In Chapter 2, Robert Treichler reviews the two main types of experimental paradigm designed to assess temporal-ordering mechanisms. The first, the ‘concurrent conditional’ method, is largely inherited from binary discrimination techniques: the transitivity training paradigm (after Bryant and Trabasso, 1971) that involves presenting a set of linked comparisons in which reward contingencies are switched (A>B; B>C; C>D; D>E) such that novel comparisons can only be resolved if the pairs are united into an overall structure (A>B>C>D>E) (Bryant and Trabasso, 1971). With numerous theories as to how associative mechanisms could explain the patterns of transitive choices on novel pairs (such as B>D) in monkeys without implying overall ranking or serial integration, some disambiguation came in the form of the simultaneous chaining method pioneered at Columbia University by Herb Terrace and his group based on the method of rewarding serial choices such as select A then B, B then C and so forth. The switch to looking directly at ordering operations rather than inferring them from single choices has
led to a wealth of new and impressive evidence on ranking capabilities in monkeys that Treichler reviews. He also provides a persuasive argument that these sorts of serial behaviours offer a platform for converging neuro-imaging evidence on brain organisation across human and non-human primates, bringing with it a new objectivity into the continuity/discontinuity debate. Finally, Treichler returns to the current conditional paradigm exemplified by some of his own research, but adding a new twist to the story of serial-order memory in monkeys. Here we learn how macaques could combine two separate serial ‘lists’ such as A<B<C<D<E and F<G<H<I<J simply by dint of subsequently learning one connecting pair (E<F). Latency measures and tests for ordinal position all combine to present a convincing case that serial memory is both highly organised and independent of test procedure in at least some non-human primate species.

If temporal order is a fundamental, then surely spatial order is too? Also once considered to be an ‘artefact’ getting in the way of the measurement of transitive reasoning abilities in children and monkeys (McGonigle and Chalmers, 2001), the inescapable fact (and the very reason for this concern) is that humans use spatial location as an aid to memory and spatial vectors as an aid to thinking about relations (Huttenlocher, 1968; Trabasso, 1977). But viewed as an important cognitive device, rather than an uninteresting basis for solving a problem, the deployment of spatial location in the control behaviour is now receiving the attention it deserves as a fundamental property of the complex mind. Clearly what is at issue here is not so much the spatial coding of the environment that permits instinctive foraging, homing and migrational behaviour, but rather the active and flexible use of spatial information to manage novel environments in a way that is maximally adaptive. In Chapter 3, Carlo De Lillo addresses the important issue of how the spatial properties of an environment may be used to reduce Working Memory (WM) demands. A first important strand in the evidence he reviews was the move towards allowing space to operate in an ecologically valid way in experiments on animals’ memory for food locations. Thus instead of artificially engineering a spatially neutral environment (like the radial maze), De Lillo and others have now manipulated natural spatial properties (such as clustering) and measured the extent to which different species can exploit spatial structure to remember food locations and to avoid revisiting locations that have already been searched. De Lillo reports clear and interesting evidence of large differences across taxa in terms of this index of WM, from mice, tree shrews, capuchin monkeys and human children. An obvious question is whether this is a cognitive achievement of the individual or whether it is an adaptation engineered by evolution over which the monkey (say) has no control. For example, when foraging efficiency improves in monkeys when clusters rather than random layouts are provided, is this simply because the clusters, like fruit distributions on trees, represent their natural ‘patchy’ foraging niche? De Lillo argues that
this not the case, as primates also seem able to benefit from circular and linear layouts. Crucially, however, his research has also shown that monkeys actively learn how to exploit spatial layout in novel environments. Spatial clusters when exhaustively searched can be represented hierarchically, each as a region that can be abandoned before moving on, thus reducing the need to remember every single location within it. Monkeys did not start with exhaustive searches within clusters but gradually acquired expertise in doing so. De Lillo then raises an important observation regarding the emergence of such efficient searches. Not only do they reduce the cognitive (and motoric) costs of inefficient search, they also produce trajectories that we would describe as ‘simple’ (i.e. linear, circular etc.). He describes intriguing results based on adults’ Likert scale ratings of the simulated travel paths of rats, monkeys and children as well as actual verbal descriptions in support of this view. Towards the end of his chapter, De Lillo reports on his recent and novel variant of the Corsi tapping task in which he confirms the hypothesis that memory for serial spatial information is enabled by hierarchical and other types of spatial organisation, suggesting the representation of space and time in a coherent and memory-sparing manner. Although some of the studies reviewed in this chapter were carried out with human adults, the substance of the research reviewed by De Lillo strongly suggests that what emerges in human evolution is the cognitive cost-reducing aspects of principled spatial search, precursors of which are likely to be found in non-human primates.

Emergence of efficient search is also the theme of Chapter 4 by McGonigle-Chalmers and Kusel, but now in the context of the perhaps more contentious territory of how one moves from trial-and-error search to logico-mathematical understanding. A long-standing index of this in human development is size seriation (Kingma, 1984; Piaget and Szeminska, 1941). Analogous to the linear spatial searches documented by De Lillo, rods or blocks of different sizes must be placed in a linear arrangement from biggest to smallest or vice versa, true ‘success’ being the ability to do so using an errorless strategy of selection and ‘end-to-end’ placement. That this is a skill that is not ‘readily available’ (to borrow a phrase from De Lillo) until well into the school years is beyond dispute. But how and why it becomes available in the form of spontaneous, non-trained behaviour of older children and adults has never been satisfactorily explained. One good reason is that the experiences provoking such change almost certainly occur beyond the capture of laboratory situations. However, the seeds of these changes are likely to be found in the early trial-and-error routes to success. If this is true, is it possible to characterise the mechanisms of change in such a way that they could characterise in principle the nature of the learning in human and animal that might lead to such a powerful device? The objective that lies at the heart of this chapter is to capture how simple binary relational rules (as described in Chapter 1 with regard to squirrel monkeys’ ‘natural’ mode of computing
size differences) can generate, by means of self-regulated learning, the fine-tuned ‘ranking’ that seriation requires. This is tackled by an attempt to computationally model the acquisition of five-item seriation using minimalist assumptions, while incorporating known psychological constraints on how size relations are apprehended by young children. The rationale for the latter is that it is these constraints that provide a non-arbitrary rule for searching and selecting items and in that respect make size seriation very different from association learning based on arbitrary list learning. The simulation successfully models the obtained learning data and does indeed map onto the very specific profile obtained in size seriation as compared with an arbitrary sequence learning task (a colour string). The changes that occur to allow spontaneous seriation are not captured (as yet) by the model, and it is acknowledged that we may have to look to the role of a symbol system (or other cultural devices) in supporting this change (see Clark, Chapter 11). However, the force of this chapter is in showing how the effort to control potentially explosive amounts of information can be supported by a cycle of exchange between simple binary perceptual judgements and their actionable consequences. With sufficient experience, principled ranking and its associated characteristics of self-regulated learning and apparent ‘simplicity’ of a linear monotonic solution (as also seen in the spatial searches of De Lillo’s primate subjects) is what emerges, and is surely where to look for the origins of logico-mathematical structure.

In Chapter 5, Boysen and Yocom take us still further into the underpinnings of logico-mathematical structure: the apprehension of numerosities. Reminding us at the start that discrimination of different numerosities has now been studied (and found) across vertebrate classes including fish, birds and mammals, they focus in particular on what can be learned from relative difficulty with different number judgements made and its implications for how numerosity is represented by different animals. We first learn of accumulating evidence across all species that smaller numerosities are easier to discriminate than larger ones, leading to a proposal that the fundamental (and perhaps universal) representation of number is logarithmic and that numerosity comparisons are ratiomorphic, a proposal that leads in turn to the speculation that species taxonomically closer to humans can discriminate amounts at smaller ratios. In the child, number judgements become inextricably entangled with the count alphabet and formal tuition in how to enumerate (Fuson, 1988). A truly fascinating insight into how support through the symbol system can indeed radically alter the level at which number judgements are made forms the core of this chapter. For in Boysen’s research with chimpanzees (Sarah, famous for being one of the pioneer language-trained chimps of David Premack, and Sheba), a plan to study social deception was gradually hijacked by an even more compelling issue: why could the chimps obey a reverse contingency training regime (RCT) and select a smaller amount of food (rewarded by giving them the
larger amount) when the amount was signalled by the Arabic numerals (on which both chimps had been trained) but not by the food itself? Boysen and colleagues went on to show that this was not a function of competition with another chimp, nor even of some overriding compulsion from the appetitive system, as it also occurred when the amounts to be compared were represented by inedible items. They review subsequent studies with monkeys and other species of apes (in which the ‘symbolic’ cue was the colour of the food container), all of which found the same basic effect. Boysen and Yocom conclude their chapter by drawing a compelling analogy between the ‘biological imperative’ operating with apes in the presence of a real food reward and a similar effect found with three-year-children and children with autism in deception tasks. This leads them to the plausible speculation that the representational symbols that allow apes to overcome this imperative alter their level of functioning in ways that are directly comparable to the maturational changes that take place in children between the ages of three and four.

In this last chapter, therefore, we cross a threshold from natural adaptive skills of perception and judgement to the deployment of symbols that have been explicitly taught and can be used to control behaviour in new ways. It is worth noting that this final theme of Section 1 is taken up by Andy Clark in Chapter 11 of this book, where he comments on how the symbol system might operate to overcome the intrinsic ‘limits’ of simian success, a thesis which he himself notes was partly prompted by Boysen’s discoveries with Sarah and Sheba; in other words, with a species that is denied access to the infinite store of symbols provided by speech, but, as this section attests, perhaps less so to the coherent structuring of thought and action on which the symbol system is predicated.

References


Index

absolute discrimination learning, 12–24
absolute hypothesis, 13–16
absolute stimulus learning, 5, 17–18, 23
absolute stimulus value, 17–18, 23
abstract relationships, 147
accommodation, 148, 159, 163
action-based learning, 76
adaptationist hypothesis of language, 248–9, 251
adaptive behaviour, 134–8
agent/world interactions, 144–5, 149–64
agnosticism, 146–7
alternative idealisations, 176–7
altruism, 137
analogy, 170–2
animal cognition, 224
assessment of, 6
criteria for judging, 4
vs. human cognition, 187–96, 225,
233–4
research on, 3–5, 12–16, 227–8, 230–5
animal communication, 229–30
animal robotics, 99
animals
see also primates
number sense of, 80–93
serial memory in, 26–35
anthropomorphism, 191, 196
a priori equilibrium, 163–4
arbitrary sequence learning, 63, 64
Aristotle, 147
articulatory loop, 189
artificial intelligence
behaviour-based, 99
empiricism and, 147–8
New AI, 101, 103–4
assimilation, 148, 152, 159, 163, 235–8
associationism, 13, 190–1, 224, 227
associative learning, 9, 26, 27, 190–1,
235–8
associative mechanisms, 6, 224, 235–6
attention, selective, 203
attractor networks, 162
augmented reality, 198–201
autonomous agents, 167
autonomous reasoning, 167–81
autonomous systems, 104–8, 116
Bayesian-based models, 144, 150–4
Bayesian belief net, 156–7
Bayesian inference, 69–72
behaviour
adaptive, 134–8
culture as source of, 137–8
hierarchical structure and, 126–38,
266, 269
learned, 135–7
modification, 45
modular structure and, 126–38
robotic, 100
behavioural sequences, 117
behaviour-based robotics, 103–4,
107–15
behaviourism, 4, 128, 224–5, 236
binary choice, 5
binary codification, 62–3
binary relations, 6, 8–9, 61, 68
biological innovations, 274–9
biolinguistics, 246–51
brain, enlargement in human evolution,
274, see also encephalisation
brightness discrimination, 23
bright-noisy-tasty water experiment, 15
Cauchy’s proof, 173–5
causality, 146, 147, 210, 223–5, 236
children
emergence of linear sequencing in,
55–78
emergence of new life stages in
evolution, 266, 274, 278
imitation by, 192–3, 228–9, 233
language learning in, 188–9
search organisation and performance
in, 41–2, 47, 49–50
seriation by, 206–7
understanding of strategic deception
in, 91–2
Chomsky, Noam, 191, 234, 249, 250, 261
chunking, 50
classical conditioning, 13, 235
clustering, 41–2, 49–50
cognition, 100
  see also animal cognition; human cognition
animal vs. human, 187–96, 225, 233–4
cultural practices and, 210–13, 216–17
dynamic theory of, 129–30
embodied, 99, 103–4, 117, 122–3, 209–10, 226
externalisation of, 223
language and, 187–9, 192, 193, 196–205, 215–16, 265, 276
models of, 148
search organisation and, 39–40
simian, 206–15
species-level differences in, 135–8
trade-offs, 137–8
cognitive continuity, 26–35, 196
cognitive development, 224, 225, 232–3, 279
cognitive economy, 45–9
cognitive ethology, 100, 225
cognitive growth, 116–17
cognitive robotics, 103–23
cognitive scaffolding, 197–205, 215–17, 223–4, 238
cognitive science, 234–5
cognitive skills
  advanced, 38
core, 4
cognitivism, 235–8
communication
  see also language
animal, 229–30
code model of, 266–8
discourse model of, 266–8
phatic, 275
symbolic, 229–30
systems, 194, 248–9
comparative development, 230–4
comparative psychology, 3–4, 13–15, 225–38
comparative study, of working memory, 38–51
complexity, 25, 35, 56
complex behaviours, 4, 25, 55
complex decision-making, 5
  in language, 243–62
  in robots, 99–101
comprehension, 4
  relational, 5
computer science, 126–7
concurrent conditional method, 6, 27–8, 31–3
connectionism, 236
constraints, 118–19, 123, 249–50
constructivist computational model, 150–4
constructive omega rule, 175
constructivism, 145, 148–50
continuity/discontinuity debate, 7, 29–31, 77–8, 191
culture, 137–8, 190
cybernetics, 103
Darwin, Charles, 25
decision-making, complex, 5
declarative representation, 100, 194–5, 273
deixis, 193, 244, 256–61, 273
Descartes, Rene, 146
development
  cognitive, 224, 225, 232–3
  in cognitive robots, 116–23
  in evolution, see evo-devo
  comparative, 230–5
developmental psychology, 116–17, 234–5, 238
developmental robotics, 117–22, 123
diagnostic reasoning, 153, 163–4
discontinuities, 191, 192
discourse, 193–6, 256, 265–80
discrimination learning, 5, 12–24
size discrimination, 16–24
dorsolateral prefrontal cortex (DLPFC), 50
dualism, 146, 271
dynamic intelligence, 128–30
ecological validity, 225
efficient search, 8–9, 41, 43–5
embodiment, 104–6
emergence, 129–30
empiricism, 145–50
encephalisation, 274–6
energetic costs, 48–9
environment
agent/world interactions, 144–5, 149–64, 190
robot-environment interaction, 110–15
spatial properties of, 7–8
epistemological access, 149–50
epistemology, 144–64
equilibration, 148, 149
equipotentiality premise, 14–15
equivalence of associability, 14–15
ethological theory, 128
ethology, 225, 234
Euler’s theorem, 173–80
evolution, 188, 193
cognitive, 77–8, 188, 194, 197–219, 243–62
of language, 243–62, 264–81
evolutionary continuity, 77, 191–2, see also saltatory evolution
evolutionary developmental theoretical biology (evo-devo), 101, 195–6, 264
evolutionary discontinuity thesis, 13
executive control, 56
executive functions, 189, 206, 208, see also planning
face detection, 120–2
fatigue, 48–9
foraging, 7, 43, 48
functional reference, 229

Gaussian variables, 69
genes, 190, 264

genetic epistemology, 149
geometric knowledge, 119–22
Gestalt psychology, 13
glass ceiling problem, 192, 213
grammar, 193–5, 248–61
Universal Grammar (UG), 243–4, 251–6
greatest likelihood calculation, 153–64
Great Leap Forward, 243, 244–6
Hebbs’ reinforcement rule, 163
hierarchical organisation and structure, 50, 51, 126–38, 266, 269–72, see also recursion
homing behaviour, 99
hominids, 244–6
How to solve it (Pólya), 168–72
human cognition, 4
vs. animal cognition, 187–96, 225, 233–4
continuity/discontinuity debate, 29–31, 77–8, 191
cultural practices, 210–13, 216–17
language and, 187–9, 192, 193, 267
models of, 148
uniqueness of, 35
human infants, 196, 201–2, 264, 272–3
human mind, complexity of, 3
human planning, 195, 266, 268–75, see also primate planning; thought
Hume, David, 146, 150, 236
imitation, 192–3, 228–9, 233
inductive bias, 148, 224
infants, 196, 201–2, 264, 272–3
information
processing, 100
self-generated, 192, 214–15
inhibition, 61
instrumental conditioning, 13
intelligence
see also artificial intelligence
dynamic theory of, 128, 129–30
embodied, 99, 103–4, 117, 122–3, 209–10, 226
human, 226
structuring, 126–38
International Society for Adaptive Behaviour, 99
intrinsic motivation, 123
Kant, Immanuel, 148
knowledge
diagnostic, 153, 163–4
geometric, 119–22
laboratory experimentation, 229
labelling, 188–9, 199–200
Lakatos, Imre, 167, 173–80
language, 187–9, 192
language and non-linguistic context, 268
see also communication
as anchoring thought, 203–5
biological basis of, 246–51
cognition and, 193, 196–205, 215–16
discourse, 193–6, 256, 265–80
emergence of complex, 243–62
evolution, 194–5, 264–81
grammar, 193–5, 248–61
learning, 235–6
recursive sentence structure, 256–60, 265–6, 269–70
semantics, 193, 267
thought and, 195, 247
learning
absolute discrimination, 12–24
action-based, 76
arbitrary sequence, 63, 64
associative, 9, 26, 27, 190–1, 235–8
behaviour, 135–7
culture and, 190
discrimination, 5, 12–24
as evolution, 135–6
language, 235–6
machine, 129
relational, 4–5, 12–24, 189–90, 224
as remembering, 147
speed of, 135
stimulus, 5, 17–18, 23
lemma incorporation, 178
lesion studies, 204
lexical content, 193, 194, 257–8
Lift-Constraint, Act, Saturate (LCAS) approach, 118–19
linear relationships, 6
linear search, 44–5
linear sequencing, in children, 55–78
linguistic evolution, 194
linguistic rehearsal, 201
linguistics, 191, 193–5, 234, 246–51
list linking, 31–5
list memory, 25–35
logic, 191, 193, 256, 269
logico-mathematical structure, 8–10
long-term memory, 192
loopy belief propagation, 164
machine learning, 129
Markov models, 129, 159
mark test, 228, 231
material symbols, 198–9
mathematical methodology, 167, 173–80
mathematical thought, 203–5
mathematics, 146
memory
long-term, 192
serial, 25–35, 50–1
short-term, 26
spatial, 40–5, 48–50
working, 38–51, 191, 192
memory demand, 40, 48
mental capacity, 38
mental state attribution, 228
metabolic efficiency, 126
method of proofs and refutations, 179
mind/body dualism, 146
mirror self-recognition task, 192, 228, 231–2
mobile robots, 106–13
model induction, 154
model-refinement process, 150–64
models
Bayesian-based, 144, 150–4
connectionist model of seriation, 191, 236
discourse models, 267
of human cognition, 148
Markov, 129, 159
Narmax, 116
of robot-environment interaction, 113–15
of seriation, 60–1
modularity, 101, 126–38
monkeys
number sense of, 80–1
relational and absolute discrimination learning in, 12–24
relational learning in, 189–90
search organisation and performance in, 40–5, 47, 49–50
serial memory in, 25–35
seriation by, 56–7, 206–8, 226
monotonicity, 59
monotonic seriation, 63–8, 73, 76
motor action, 268–9

naive Bayes, 153
Narmax models, 116
narratives, 271–2
nativism, 234
Neanderthals, 244–6
neutral innovations, 197, 213–16, 217
neuro-imaging, 7
New AI, 101, 103–4
number judgments, 9
numerosities, 9–10
numerosity, 80–93

Occam’s razor, 12, 14
ontologies, 167
ontology evolution, 167
OpenCV Intel libraries, 120
ordered-list memory, 25–35
ordering of events, 5–6
ordering operations, 6–7

parsimony, 126
path dependency, 126
pattern discrimination, 23
pattern recognition, 45–8, 121
perception, in mobile robots, 106–8
perceptual bias, 62
persistent agents, 167
philosophy, 145–50
phylogenetic scale, 15
phylogenetic tree, 15
Physical Symbol System Hypothesis, 103
Piaget, Jean, 55, 57, 148, 149, 152, 159,
163, 164, 234
pigeons, serial memory in, 26, 29
planning, 193, 266, 268–75, see also
communication; human planning;
primate planning; thought
plasticity, 134, 137
Plato, 146, 147
pointer, 61
Pólya, George, 167–72, 173
polyhedra, 173–80
Popper, Karl, 173
precondition analysis, 178
prefrontal function, 50–1
primates
cognitive evolution, 50–1
communication systems, 194, 264–6,
270–4
imitation by, 228–9, 233
limits on, 206–15
number sense of, 80–93
planning, 194, 196, 270–1, see also
human planning; thought
search organisation and performance
in, 40–5
serial memory in, 25–35
seriation by, 56–7, 206–8, 226
private codes, 226, 235–8
probabilities, 150–61
problem solving, 101, 167–81
counter-examples, 175–80
mathematical methodology,
173–80
Pólya’s method for, 168–72
Production Systems model, 60
proof plan, 170–2
proofs, 173–80
Proofs and Refutations (Lakatos), 173–80
psychology, 193
comparative, 3–4, 13–15, 225–38
developmental, 116–17, 234–5, 238
Gestalt, 13
quantity judgments, 83–93
radial maze studies, 39–40
ranking behaviours, 5–6, 62–3
rationalism, 145–50
rats, search organisation and
performance in, 41–2
reasoning
autonomous, 167–81
prognostic, 150–61
recapitulationism, 195
recursion, 256–60, 265–6, 269–70
reductionism, 4
reference to absent objects, 272
reincarnation, 146
relational hypothesis, 13–16
relational learning, 4–5, 12–24, 189–90,
224
relational perception, 4
representations, 101, 167–81, 228, 247
reverse contingency task (RCT), 9–10,
84–93
robot-environment interaction, 110–15
robots/robotics, 147–8
autonomy and embodiment, 104–8, 116
behaviour-based, 103–4, 107–15
behaviour of, 100
cognitive, 103–23
complexity in, 99–101
control and perception in, 106–8, 115–16
developmental, 117–22, 123
epistemological sophistication in, 101
mobile, 106–13
recognition tasks, 119–22
research, 103–4
scientific method in, 110–13
rostrolateral prefrontal cortex (RLPFC), 192, 214–15
saltatory evolution 194–5
schemata, 148, 149
search, 55
efficient, 8–9, 41–5
linear, 44–5
organisation, 39–45, 49–50
patterns, 45–8
performance, 49–50
serial, 59
simplicity in, 45–8
spatial, 8
strategies, 39–40
trial-and-error, 8
selective attention, 203
self-awareness, 192, 228, 231–2
self-generated information, 192, 214–15
self-regulated learning, 9
self-structuring, 210
semantics, 257–8, 273
Sense-Think-Act cycle, 103
sensory-motor development, 117, 118–19
serial list retention, 25–35
serial memory, 7, 25–35
effect of serial position contrasts, 33–4
neuronal correlates of, 29–31
organisation of, 50–1
structure and, 48–9
serial order, 5–7, 56, 206–7
serial search, 59
serial spatial recall, 48–50
seriation, 8–9, 56–78, 206–8
monotonic, 63–8, 73, 76
size, 8, 9, 55, 57–78, 206–8, 226
simian thought, 206–15, 248
simple explanations, 12
simplicity, 45–8
simultaneous chaining method, 6–7, 27–9
size discrimination, 15–24
size-relational learning, 5
size seriation, 8, 9, 55, 57–78, 206–8, 226
snapshot theory, 99
[social group size, 275]
sorting, 55
spatial location, 7–8
spatial memory, 40–5, 48–50
spatial structure, in working memory, 38–51
stimulus, evaluation of, 19–22
strategic deception, 91–2
structured control, 127–38
structured intelligence, 126–38
subsumption, 101
successive chaining technique, 33–4
symbolic communication, 229–30
symbolic distances, 31–2, 189
symbolic representation, 247
symbol systems, 9–10
syntactic theory, 191
syntax, 265
temporal-ordering mechanisms, 6–7
temporal sequencing, 6
theorem generalisation, 179–80
time, order of events in, 5–6
theor of mind, 91, 228–30, 232, 271, 273
thought, 203–5
language and, 194–5, 203–5, 247
mathematical, 203–5
simian, 206–15, 248
3D reconstruction, 120–2
three-stimulus discrimination learning, 18–19
toolmaking, 229, 276–9
touch screens, 225–6
transitivity, 26–7, 29, 224
transitivity training paradigm, 6
transposition, 12–13, 16
Index 295

trial-and-error search, 8
2D tracking, 120–2
two-stimulus discrimination learning, 12–16, 18–19

Universal Grammar (UG), 243–4, 251–6
urgency variables, 66–7, 69–72, 74–75

value transfer theory, 28
visual cortex, 127

working memory (WM), 7–8, 191, 192
comparative study of, 38–51
search organisation and, 39–40