First author's note: This article was originally conceived written in 1990 and accepted as a chapter in a multivolume *Handbook of Semiotics*. In 1999 the authors decided to update the chapter. Subsequently, however, there was a further delay of four years until the actual date of publication in 2003. At that time we still subscribed to the lines of argument in the text, but it should be clear that we were not ignorant of the fact that psychology and, more generally, the cognitive sciences now provide more recent and often more convincing support for our arguments. Eventually the article did appear as chapter 141 in R. Posner, K. Robering, & T. A. Sebeok (Eds.). (2003). *Handbuch der Semiotik/Handbook of semiotics* (Vol. 3, pp. 2722-2758). Berlin: W. de Gruyter. It is made available here in memory of Janet L. Jackson who, sadly, died early in 2005.

Psychosemiotics:

Semiotic aspects of psychology

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1. INTRODUCTION

1.1 Symbol systems

The aim of this chapter is to review contemporary scientific psychology in the light of its semiotic structure and content. What do we mean by this? Semiotics deals with types of signs, for example signals, indexes and symbols, with sign systems and with sign generation, sign interpretation and sign understanding, also known as semiosis. This is less remote from the concerns of psychology than it may seem at first blush; signals, signs and symbols are also of central concern to psychology (Daddesio, 1995; Bouissac, 1998; Dölling, 1998). We have come to conceive of the object of scientific psychology—the integrated, active individual person—as a physical symbol system (Newell & Simon, 1972). This important concept was described by Pylyshyn (1989) in the following way:

> "Knowledge is encoded by a system of symbolic codes, which themselves are physically realized; it is the physical properties of the codes that cause the behaviors in question. (o.c. p. 61) [...] Cognition is literally a species of computation, carried out in a particular type of biological mechanism (o.c. p. 52)."

In other words, structure and function of the human cognitive system are expressed in terms of sign, signal and symbol processes, under the constraint that this system is embodied in a material object. This psychological view has a semiotic counterpart. The semiotician Morris summarized the latter view as follows:

> "Something is a sign of something only because it is interpreted as a sign of something by some interpreter. Semiotics, then, is not concerned with the study of a particular kind of object but with ordinary objects insofar (and only insofar) as they participate in semiosis" (Morris, 1938, p. 20).

Semiotics, and more in particular semiosis or sign interpretation, is a process causing X to be Y for Z, a *cognitive* process, in other words. A semiotic approach to psychology hinges on the question what sort of sign or symbol systems qualify as a medium for describing the human qua cognitive system. If, as Bouissac (1998) says, semiotics and psychology have converging parallels, the perspective taken here is to illustrate the semiotic aspect of psychological phenomena, rather than to prove that semiotics or semiosis is a psychological topic. What is added to the semiotic perspective is, in the case of psychology, the aspect of embodiment: how are symbol systems constrained by the physical and biological properties of the human organism. And, acknowledging the inherent social nature of humankind, another aspect to be considered is communication, the exchange of information between components within the individual, as well as between the individual and its environment (Barwise & Etchemendy, 1989, p. 207; Jorna, 1990, p. 7).

Only during the last five years have the issues raised here become of central concern to scholars from both sides of the fence (Bouissac, 1998; Daddesio, 1995; Dölling, 1993, 1998). In December 1998 a special issue of the journal *Theory and Psychology* was devoted to this problem. In it several of its contributors observe that not only have psychologists and semioticians repeatedly re-invented each others' wheels, but also there have been active attempts at neglecting each other's achievements. As Bouissac points out:

> "It is [...] symptomatic of this state of affairs that in his influential *A Theory of Semiotics* Eco ignores psychology and psychologists, with the exception of a very few passing remarks on J. J. Gibson and Jean Piaget. This is all the more striking as 'communication', 'empathy',

> ‘inference’, ‘judgment’, ‘perception’, ‘representation’, ‘visual communication’' and many other psychological concepts form recurring topics of discussion in this book. Such a blatant elimination of psychology amounts to an attempted displacement of psychology to the margins, and footnotes, of semiotics.” (o.c., p. 736).

The explanation given by Daddesio (1995) for this state of affairs is twofold. On the one hand semioticians, such as Peirce, Morris and Eco advocated a pure semiotics without taking refuge to non-semiotic terms. Semiotics is about signs and not about cognition or the external world. On the other hand many semioticians were influenced by the behaviourist rejection of introspection as a method and mental processes as legitimate research topic and did not want to return to the Cartesian approach that was so vehemently rejected by Peirce, the father of semiotics. As a consequence semioticians have missed many of the debates about cognition, information processing and artificial and natural intelligence that took place over the past 40 years.

1.2 Development of cognitive psychology

The tremendous progress of psychology during the second half of the 20th century derives to a large extent from the successful adoption of the cognitive, or information processing point of view. Cognitive psychology has brought the processing of signals, signs, and symbols to a prominent place in psychological theory and experiment. It has greatly facilitated a conceptualization of psychological matters in terms of formal representational (generative) systems. The formalization of cognition and behaviour in terms of computation and computational complexity has indeed proved to be scientifically very productive.

Cognitive psychology is rooted in almost simultaneous breakthroughs in linguistics, computer science, control theory, artificial intelligence and general psychology which occurred around 1956 (Gardner, 1985). Breaking a half century spell cast by Behaviourism, it was readily accepted by the psychological community in the United States as the principal inroad to the study of mind and behaviour. In Europe, that never quite embraced the behaviouristic doctrine, the cognitive approach was adopted as a matter of fact. In the first place it did smoothly fit a long and essentially uninterrupted mentalist tradition, which included Selz, Bartlett, Piaget and many others. In addition it appeared to be capable of satisfying a long and sorely felt need for theoretical rigor and quantification: many young experimental psychologists, especially in Great Britain, The Netherlands, and Sweden were quick to adopt the cognitive, or human information processing perspective, other countries soon following suit. Since then cognitive psychology has become the major approach to scientific psychology, a position that is likely to persist for reasons that will become clear later in this chapter. Not only has the cognitive approach created a strong internal coherence in psychological theory, it has also made it possible to connect psychology in a natural way to other disciplines dealing with cognition, including linguistics, AI, neurosciences, epistemology, and logic.

Recently these connections have culminated in the foundation of a new discipline, *cognitive science* (e.g., Hunt, 1989; Posner, 1989). On the negative side it has to be acknowledged that as a consequence of the interactions between researchers with quite different scientific backgrounds, cognitive science has, thus far at least, not been progressing as a disciplinary unity. Besides divisions on the basis of traditional discussions about what is and belongs to learning, perception and action at an adequate level of description, cognitive science presently entertains three major orientations: the ‘symbol processing’ approach (mainly attracting psychologists and computer scientists), the ‘connectionist’ approach (mainly neuropsychologists and many computer scientists) and the ‘situated action’ approach (mainly psychologists and philosophers) (Dölling, 1998). Recently a fourth orientation has been gaining prominence, however, as a result of the development of highly sophisticated brain-imaging techniques that allow a fine-grained study of the central nervous system (Gazzaniga, 1995). This has led to an wave of interest in neurocognition that, as many cognitive scientists of different disciplinary background believe, may provide the necessary common ground. Time will learn.

In retrospect a possible role for semiotics in theoretical psychology would have been quite feasible. Much as was the case with cognition in the functional sense, there was considerable psychological interest in signs and symbols at the more abstract level that is characteristic for semiotics (Arnheim, 1969; Kolers & Smythe, 1979; Rasmussen, 1986). Karl Bühler, for instance, stands out in this respect, travelling a long way towards concepts that we would now recognize as modularity of mind, conceptual prototypes, and language of thought (Innis, 1992). Like the ideas that would eventually support cognitive psychology proper, however, relevant semiotic issues were suppressed by the 'Zeitgeist.' Only now cross-fertilization appears to be taking place (see the relevant chapters in this handbook; see also Fetzer (1990) for a related trend in artificial intelligence).

1.3 The scope of psychology

Many textbooks describe psychology as the scientific (empirical and theoretical) study of man's behaviour and thinking. Although this is generally accepted, it does not give a clue about the basic quantities and concepts—the entities—in behaviour and cognition. What is the 'real' subject of psychology? A number of 'entities' have been around since the last century. Between the 1930s and the 1950s there were stimuli and responses, between the 1960s and the 1990s we had symbols and representations, and presently we also have neurons, neural nets and synapses on the one hand and actions and action patterns on the other. All these entities appear to be dealt with at the same time, although they frequently also seem to mutually exclude one another. To make things even more complicated it has also been argued that the basic concepts in psychology are 'character' and 'personality'. All these concepts cannot be equally useful, but the problem is that the demarcation criteria are not undisputed. Psychologists have lived with this disparate state of affairs for more than a century, thus far failing to come up with a strategy to settle these controversies.

The perspective on psychology we will adopt here is that the study of cognition and its connected behaviour constitutes the core of the discipline. Although many psychologists still strive towards one all-embracing theory, the state of affairs at the moment is that psychologists work with local theories. This is illustrated in the various domains within psychology that we will discuss in later sections of this chapter. And even though areas such as social psychology, developmental psychology and abnormal or clinical psychology may share scientific methods and procedures, psychologists may strongly disagree about the conceptual implications of their (mini)-theories even within a single domain. This makes it is impossible to cover the whole field in a balanced way. In the remainder we concentrate on cognition and its behavioural expressions. However, before delving into with what we consider the core of the discipline, we wish to show a glimpse of the context within which this core appears. Psychology as a domain of scientific activity can suitably be partitioned into six, more or less independent, fields of activity. These fields are readily recognizable in text books of psychology (e.g., Atkinson, Atkinson, Smith, & Hilgard, 1990).

1.3.1 Functions (general psychology)

Information processing by the human organism can be considered at the physiological level (physiological psychology, psychophysiology, neuropsychology) or from the functional (behavioural and cognitive) point of view. Perception, cognition, action, learning and motivation are the major groups of functions that are studied in this context (for a recent overview of the entire domain of experimental psychology see, e.g., Atkinson, Herrnstein, & Lindzey, 1988a, 1988b). One interesting way of partitioning the domain of general psychology has been proposed by Newell in his monograph *Unified Theories of Cognition* (Newell, 1990). It is based on the idea that the transfer of symbols between the components of a symbol system during information processing is subject to spatio-temporal constraints which increase stepwise roughly by orders of magnitude, for systems of increasing adaptive capability. More and more complex symbols needed for the communication between components require increasingly larger computational units and lead to longer processing times. At the bottom of the scale we appear to be dealing with the functions studied by neuropsychology (10 milliseconds), whereas higher levels can be characterized as elementary automatic skills (100 milliseconds), deliberate action (1 second), and rational behaviour (10 seconds and upward).

1.3.2 Personality (differential psychology)

The study of personality involves the definition of traits, in terms of weighted combinations of typical patterns of behaviour. Some such combinations are stable and permanent or semi-permanent over a considerable period of time, and these we call person or self. Whilst the classification of personality traits has itself not been tremendously successful, the heuristic value of research on personality has been great. In recent years personality theory is becoming more and more entwined with social psychology and clinical psychology. At the same time attempts are increasingly being made to describe ‘individual differences’ in terms of cognitive processes and mechanisms (Hall & Lindzey, 1970; Pervin, 1984; Ewen, 1994).

1.3.3 Development and learning

Functions and mechanisms, but also personality traits change over time. This is partly the result of biological processes such as maturation, but is also partly derived from individual experience or learning. In terms of human information processing this means that the processes involved may themselves change over time, but also that the information being processed is subject to change as a result of the processing as such. For example, memory contents are not passive, invariant symbols, but they may change as a result of being manipulated (Sternberg, 1984; Siegler, 1989). A renewed interest in learning has emerged over the last ten years, especially integrating results and theoretical perspectives taken from cognitive science and computer science. An example of the former is the work on creativity and learning (Boden, 1994), and an example of the latter is the work on machine learning (Laird, 1996).

1.3.4 Social psychology

All human activity takes place in a social context (even if in some cases this exists only in the mind of the actor; see Schneider, Hastorf, & Elsworth, 1979). This context includes external constraints such as aggressive behaviour of others, and internalized constraints such as norms or conscience. Locus of control, that is, the feeling of being or not being in command of the situation, social dilemma, etc. are examples of social mechanisms that determine the behaviour of the individual (Fiske & Taylor, 1984). Taking an information processing point of view, the social context is necessary in order to extend the processing resources of the system beyond the limited capacity of the individual human brain. This extension requires pre-attunement plus the attribution of personhood to other individuals: such understanding rests on the assumption of common symbol structures (Dennett, 1978, p. 267). Cognitive psychologists themselves have stepped into this debate by introducing the term ‘social cognition’ or, more generally, ‘situated action’ (Vera & Simon, 1993). In the debate on ‘situated action’ the issue is how and to what extent the internal symbolic domain is connected to the external environment. External may also include ‘meaningful other individuals’ thereby emphasizing the social character of humans. As the name indicates ‘situated action’ takes as its starting point actions rather than symbols.

1.3.5 Abnormal psychology

The human information processor may perform inadequately as a result of misapprehension (lack of knowledge), errors of reasoning or judgment (rule-based errors), or architecture-based malfunctioning (organic lesions, disease, etc.). In each case the resulting activity of the human information processing will be maladaptive. The causes and remedies are studied in a normative context of what constitutes appropriate error free behaviour at each of these three levels (Davison & Neale, 1984).

1.3.6 Areas of application

Psychology finds applications in numerous professional domains. These include school, work, health and therapy, religion, and others. The degree to which these fields may be considered as rooted in psychological theory, however, is very different. Some approaches to psychotherapy, for instance, such as psychodrama or sensitivity training, have hardly any scientific underpinning, whilst others, such as behaviour therapy and cognitive therapy are consistent with major mainstream psychological theories. In other domains, including work and training, psychology has come to play an important role, frequently filling the gap between the policy maker/administrator and the engineering profession (Michon, 1992).

1.4 Beyond the limits of scientific psychology

Besides the active research fields mentioned above, psychology has a great many dead branches. These were abandoned, at one time or another, because they proved untenable in the light of theoretical analysis or empirical fact, but they stayed around and somehow retain some of their popularity. Likewise, psychology is surrounded by a great many pseudo-scientific movements, for the simple reason that the phenomena studied by psychology are central to the curiosity of human beings about themselves.

There are essentially two ways of dealing with these pseudo-psychological movements. One is trying to understand the underlying religious, or emotional motives for postulating elaborate analogies between human behaviour and celestial events, configurations of sticks or cards, bumps on the skull, lines in the palm of the hand, or what not. The second way is to consider a pseudo-psychology as simply maintaining a symbol structure, and to establish which behavioural or cognitive facts are claimed to be mapped onto this structure. On this view, pseudo-psychology seriously tries to attain symbolic explanations of human behaviour, intelligence, and consciousness, just like psychology, only less successfully so and without the commonly accepted scientific rigor in method and testing.

The question how one should distinguish between pseudo-psychology and ‘genuine’ psychological knowledge has been a tricky one. There is admittedly a narrow dividing line: psychologists are, for instance, deeply divided over the question of the scientific meaning of Freud's psychoanalysis (Erdelyi, 1985; Grünbaum, 1984). Unlike scientific psychology, however, pseudo-psychology is generally based on an arbitrary syntactics and an equally arbitrary semantics. We may judge claims in the light of Goodman's adagium “People make versions and true versions make worlds” (Goodman, 1984, p. 34), and it would seem that the computational approach allows a fair judgment to be passed on each claim. A concomitant problem is, however, that the narrative appeal of pseudo-psychologies offering celestine promises or eternal health, is frequently so powerful as to override the force of empirical falsification.

1.5 The scope of this chapter

Whilst the territory covered by psychological research has expanded quite considerably during the past half century, it is not entirely clear to everyone where the main stream of the discipline really is leading us. This was pointed out, for instance, by Staats (1983):

> “Psychologists in general cannot see where the science is headed, or that it is progressing on the path. The typical psychologist cannot even get a feel for what his science is about, because the materials in it are so diverse and disorganized” (o.c, p. 12).

We are of a quite different opinion. In this chapter psychology will be treated strictly from the cognitive point of view. We claim that psychology in all its scientific dressings is indeed essentially concerned with the representations of reality and with actions performed on the basis of these representations. Others are of a similar opinion. Simon (1990), for instance, points out that

> “it is still incorrectly thought by some that contemporary information processing psychology leaves unexplained such ‘holistic’ phenomena—treasured by humanistic, existentialist, Marxist, and Gestalt psychologists—as intuition, insight, understanding, and creativity” (o.c., p. 4).

The computational approach adopted by cognitive psychology implies that we should try to find symbol systems on which the internal representations and processes can be mapped. The computational approach may not be the only road to formalization in psychology, but it is the only one we know so far. Even though many of its theorems may eventually have to be replaced, it appears to give us psychological knowledge that is essentially cumulative (Newell, 1990).

Adopting the cognitive point of view it may seem as if we are abandoning approximately one quarter of scientific psychology as well as most professional psychology, but this is not really the case. As suggested above the cognitive approach is, in fact, fundamental to psychology as a whole. Cognitive theories and models, although dealing with general aspects of human and animal behaviour, can explain and predict individual behaviour as special cases which depend on the parameters of the situation, the task at hand, and the cognitive make up of the individual under concern (Mayer, 1981; Sternberg, 1982, 1985). Cognitive theory should, in other words, be taken as applying to the entire range of psychological concerns, including personality, social psychology, developmental psychology, as well as the special professional domains, such as occupational, forensic, and cultural psychology. Indeed, in recognition of this fact, a good many of the publications in these fields nowadays carry the term ‘cognitive’ in their titles (e.g., Dryden & Trower, 1988; Stahl, Iversen, & Goodman, 1987).

The body of this chapter is structured as follows. In Section 2 we will deal with a number of fundamental issues that are relevant to a general psychology which, in a broad sense, understands the human being as a physical symbol system. Subsequently, in Section 3, we will present an overview of the major, active research topics in scientific psychology: perception and attention, memory, language, thinking (conceptualizing, reasoning, and problem solving), and action. Finally, in Section 4 we will draw some conclusions and consider a few more or less speculative points about a semiotic framework for psychology. At the end of several sub-sections, especially in section 2, we will anchor the topics to a semiotic framework and to semiotic terminology.

2. THEORETICAL UNDERPINNINGS

2.1 The computational approach

2.1.1 Functionalism

Psychology must ultimately be able to give an account of intentionality, that is, it must explain mental phenomena such as consciousness, intelligence, action, and the pursuit of complex goals. Rather than aiming for the unique experiences of the individual, however, scientific psychology seeks to investigate the conditions that will generate these unique experiences. It is concerned with the processes and the functional architecture which underlie intelligent behaviour.

The approach adopted most frequently by cognitive psychologists is functionalistic (Bechtel, 1988; Block, 1980; Dennett, 1978). The cognitive system is described in terms of interactions between the functional components of the system. These interactions are neutral with respect to the physical embodiment of the system. This implies that intelligence may be, in principle, be displayed by all kinds of systems, Martians, angels, and even computers, as long as they instantiate the right kind of functional architecture. Although the functionalistic view is widespread and has a very long history (Smith, 1990), in its strict form it is not without its problems and is therefore rejected by some (e.g., Searle, 1980; Churchland, 1986).

2.1.2 Explanatory metaphors

In the course of time the explanatory power of psychology has been derived to a large extent from a series of metaphors, including the mechanical clock, the steam engine, and the telephone switchboard (Vroon & Draaisma, 1985). We must realize that the use of such metaphors is almost a necessary characteristic of functionalistic theories. They attempt to describe and explain what the mind does in order to achieve its goals, irrespective of the physical architecture in which this mind is implemented. Lacking the right kind of formal language, theorists in the past had no other option than to choose as their conceptual framework an existing analogue, a physical architecture which seemed to be capable of generating the kinds of behaviour they wished to explain. Such an analogue carried at least part of the weight of the functionalistic description. Thus, ‘time discounting’, the “drop in subjective value of events as a function of the delay expected until their occurrence” (Kacelnik, 1998), p. 55), is a straightforward derivative of taking the adagium *Time is money* seriously (Michon, 1998). This almost automatically implies that theorists explaining complex mental processes in functional terms, were likely to choose the most intricate information processing structure known to them (Michon, 1988, p. 174).

2.1.3 Computer metaphor versus computational theory

At the present time the (programmable) computer would seem to qualify as the basic metaphor. Psychology has indeed been quick to adopt the computer as such. In this particular case, however, the situation has turned out to be much more principled than previously. Rather than being just a suitable metaphor for dressing up our ideas about the mind and its workings, the computer is now recognized as being a close relative: humans, animals, and computers are species in the class of cognitive systems, capable of behaving intelligently, or rationally, under a variety of circumstances and also capable of learning from their experiences (Boden, 1989). This perspective has led to the computational view which may be characterized in the following way.

(a) All cognitive systems, including humans, are physical symbol systems (Newell, 1980). Physical symbol systems are characterized by the following three properties:
    - they represent external and internal conditions, objects, and events in symbol structures;
    - their activity consists of formal manipulations, or operations, on these symbol structures, either by means of computational rules (symbolic manipulation) or by spreading activation across a network (parallel processing);
    - their physical embodiment imposes certain constraints (speed, reliability) on their performance.

(b) It is possible to provide a formal description, a computational theory, of these representations and rules. A computational theory about a cognitive system must explicate the overall goals of the ensemble of mechanisms and processes which constitute this system. It must also formulate the internal and external (environmental) constraints under which the system operates.

The importance of computational theories in psychology was particularly emphasized by Marr (1982). Before one may fruitfully study a psychological function such as, for instance, form perception or stereopsis, one must first formulate a computational theory for that function. Such a theory must formally describe the conditions that are to be met if the function is be realized (computed) at all. In other words, a computational theory is required to impose constraints on the set of possible mechanisms that can realize the function or functions under study. And accordingly, psychology is about finding constraints that enable a symbol system to behave as a cognitive system. The term computational is used throughout this chapter in the sense of formal, implementation-independent description, that is, in the sense used by Marr. It should be emphasized, however, that the term ‘computational’ is not entirely fortunate, since it raises unintended associations with algorithmic computation. More recently the term ‘rational’ has been used in order to circumvent such unwanted associations (Anderson, 1990; Oaksford & Chater, 1998).

From the semiotic perspective three remarks are in place. First, the term ‘symbol’ is meant to be equal to ‘sign’. Within cognitive psychology ‘symbol’ is an unproblematic term not sharing any connotations with the Peircean notion of symbol, that is, a conventional or cultural relation between sign and object. The preference for symbol over sign is that implicitly symbols have syntactic and semantic characteristics. Second, although symbols are supposed to be static, that is, to have a form, there is no well-defined core description of this form. Icons, characters and images also have forms. Goodman’s (1968) convention is followed as he says:

> “‘Symbol’ is used [...] as a very general and colourless term. It covers letters, words, texts, pictures, diagrams, maps, models, and more, but carries no implication of the oblique or the occult. The most literal portrait and the most prosaic passage are as much symbols, and as ‘highly symbolic’, as the most fanciful and figurative.” (o.c., p. xi).

Third, for some semioticians a close relationship may seem to exist between computation or manipulation and semiosis (Dölling, 1998). The big difference, however, is that cognitive scientists usually take the functional existence of symbols for granted, whereas semioticians (Van Heusden, 1994) are directly concerned with the process of symbol generation. For them semiosis is the process of the initialization or generation (genesis) of symbols: symbols are the product of semiosis. Irrespective of these differences of perspective the question that, at the end of the day, has to be answered empirically is whether a particular model describing these mechanisms is powerful enough to realize the computational theory under concern. This would be the case if and only if that model would generate all correct behaviours upon a given input, as predicted by the computational theory, without generating at the same time any incorrect behaviour.

2.2 Symbolic and parallel distributed processing

2.2.1 The two views of 'computation'

A computational theory is an abstract, formal representation. In order to become a theory about a cognitive system, natural or artificial, a functional architecture is required, a material system and a program that can effectively and efficiently instantiate the computational theory. Presently there are two successful architectures that are able to accommodate the computational theories developed by cognitive psychology. The first approach, which was in fact the only canonized model in cognitive psychology between 1955 and 1985, treats computations in terms of operations on symbolic structures. It is now already known as the classical approach. In the second approach computations appear as dynamic patterns of activation over networks of interconnected nodes that, unlike symbols, do not directly represent objects or events, but instead partake in a distributed representation of these entities. This 'connectionist' approach has made a considerable impact on cognitive psychology during the 1980s, after having made a false start already in the fifties (Minsky & Papert, 1969; Rumelhart & Zipser, 1986). Recently a third view has been gaining prominence. neurocognition takes its point of departure in the neurosciences. The advent of highly sophisticated non-invasive techniques for studying brain activity in the normal, intact organism has led to high hopes that the study of mental activity and consciousness will finally merge with that of brain structure and function.

2.2.2 The Von Neumann architecture

The symbol-processing tradition is based on the Von Neumann architecture. So is the standard view of human information processing. This is, in fact, not surprising, because Von Neumann's aim was indeed to build a machine that could duplicate his own thinking as a human, if mathematically trained, person. The canonical human information processor consists of a number of input channels in which incoming information is selected and encoded into internal symbols. Depending on their momentary significance for the activity of the organism these symbols are subsequently stored in an inactive long term memory for later use, or kept in an active, short term memory where they may be transformed, matched and integrated with other active symbols and symbol structures. Information may be retrieved from, or transferred to long term memory, or it may be used to activate output devices which will act upon the environment. Whilst internal capacity restrictions on the input and output devices and on long term memory are fairly arbitrary, a severe constraint that is inherent in the Von Neumann architecture lies in the limited capacity of its working memory: it forces the architecture to process its information serially. This, however, has proved untenable in the case of the human information processing system. Therefore psychological information processing models that originated in the past 30 years, although essentially based on this architecture, circumvent this unrealistic constraint in various ways. Currently these detours are frequently stated in terms of so-called ‘energetic’ resources (arousal, activation, effort) that can be allocated to various processing mechanisms. This allows, among other things, for certain forms of parallel processing (Hockey, Gaillard, & Coles, 1986; Sanders, 1983, 1998).

2.2.3 Symbolic or mental representation

An important question is how we should describe the information that is being processed in models of this kind. In other words, what are the properties of the mind's symbol structures? Here again there used to be considerable consensus up to the middle of the 1980s. Most models for the structure of human knowledge can be qualified as propositional or semantic networks (for a summary of various approaches, see the various foundational chapters in Posner, 1989, or Daddesio, 1995). Semantic networks have made it possible to represent the subjective organization of, say, a text or a complex visual shape, as well as the search for information in such a network. In the first place is it possible to represent concepts (nodes), and relations (links) between concepts. In the second place a network can embody the rules according to which activation will spread through the network if certain initial conditions are met. All the same, there are good reasons to assume the existence of a second, spatio-visual or quasi-spatial, medium for the representation of knowledge (Kosslyn, 1983; Paivio, 1971). Shepard, for instance, in an extensive research program (e.g., Shepard & Cooper, 1982; Shepard, 1984), has shown that the time to mentally rotate two- and three-dimensional objects is proportional to the spatial angle through which the object must be rotated. Larkin and Simon (1987) argue that the spatio-visual mode has the particular advantage that topographical relations such as left-of, under, and behind, are intrinsically encoded and retrieved and, consequently, do not require information processing resources. The spatio-visual mode is not universally accepted, however. Some authors claim that all encoding is ultimately in propositional form (Pylyshyn, 1973), a point of view vehemently rejected by others, including Kosslyn (1983). In addition there are those who argue that the debate is undecidable and therefore meaningless (Anderson, 1978). In our opinion there is at least one extra reason, rarely considered, to be critical about much of the imagery debate. It seems plausible that, if there is indeed a non-propositional representational medium, it should incorporate various aspects of the physical world, rather than the visible ones alone. Recent studies on ‘qualitative physics’ appear to provide a strong case for such a generalized imagery mode (Bobrow, 1985; DiSessa, 1983; Hobbs & Moore, 1985) as do studies on the role of imagery in scientific thought (Langley, Simon, Bradshaw, & Zytkow, 1987; Miller, 1986), dynamic affordances (Freyd, 1987; Jones & Boltz, 1989), or natural computation (Richards, 1988).

2.2.4 Connectionism

Since 1985 the connectionist approach to the structure of representations has come to play an important role. In this case networks consist of large ensembles of functionally identical nodes that are richly and arbitrarily connected to each other. These nodes do not individually relate to concepts. Representations of objects or events are in fact distributed, that is, they form an activation pattern throughout the entire network. For this reason connectionist networks are frequently considered as addressing information processing at a sub-symbolic level. The interaction between nodes is realized through spread of activation according to functions that are defined over the entire network. If the system enters into a state of disequilibrium, particularly if it is subject to a change in the external situation, then the activation field will change until, after some delay, a new equilibrium is found (Smolensky, 1988; Rumelhart, 1989).

The popularity of connectionist models has been partly due to the fact that it appears to bring psychological research closer to neurophysiology: frequently these models are referred to as ‘neural networks’ or as ‘brain-style computational models’. In our view great care should be taken in adopting this metaphor, for reasons that will be explained below. More importantly, however, the approach offers a number of advantages as a descriptive framework for a number of specific psychological phenomena that are not immediately accessible to the conventional symbol processing model. These phenomena include, for instance, the conjoint weighting of evidence (constraint satisfaction), the formation of prototypical concepts, generalization and, particularly interesting from a clinical point of view, the ‘graceful degradation’ of performance in the face of information overload or damage to the network (Rumelhart, 1989).

2.2.5 Critique of the connectionist ‘revolution’

As is frequently the case with innovations in science, the connectionist approach has been introduced with an amount of rumbling rhetoric that is likely to obscure an equanimous evaluation of the true significance of the approach for some time (Clark, 1989; Bechtel & Abrahamsen, 1991). “It is likely that connectionist models will offer the most significant progress of the past several millennia on the mind/body problem,” writes Smolensky (1988, p.3). But will they? And he adds that it is the “theory from which the multiplicity of conceptual theories can be seen to emerge” (ibid.). But is it really?

From a functionalistic point of view it is hardly the architecture which is important and consequently claims such as these are, in our opinion, hardly to the point. Functionally speaking the architecture of a cognitive system may be more or less efficient in running a particular algorithm, but the Turing universality of computing machines will guarantee that a particular function will eventually be computed. The real issues lie in the computational theories that are to be instantiated on a particular architecture, and it is there where connectionist theories are open to some fundamental criticisms. In this we largely follow Fodor and Pylyshyn (1988) and Levelt (1989), who have pointed out with great force of argument that by throwing out the bath water of symbolic representation connectionists are abandoning a host of babies at the same time (see also Pinker & Mehler, 1988). In the first place, connectionism has not found a way of proving the learnability of a knowledge domain. Any connectionist model can learn some part of a knowledge domain, but this ability is not the same thing as a computational theory of the domain in the sense of Marr (1982). From the performance of the network given a set X of facts (propositions), no prediction can be made with respect to the learnability of a slightly larger set X + DX. In other words, “[a]ll claims that a connectionist model can learn X, where X is a non-regular set, are bally hoo.” (Levelt, 1989, p. 213, *our translation)*.

A second, related, issue is that a connectionist model, even if it does essentially learn set X, will not inform the investigator why it was able to do so. At face value this may seem too harsh a verdict, since models have been made with a particular connectivity (i.e., bottlenecks) which allows us to understand why the model can indeed achieve a particular result. In fact however, the organization of such models has been implemented by the programmer, rather than having emerged from the dynamic properties of the network as such, which defeats the claim of self-organization that is so central to the concept of connectionist modelling.

A third weakness of connectionist models is—still following Levelt's argument—that it is far from clear to what extent these models can be generative, in Chomsky's sense. Connectionist models appear to be finite automata and consequently they should be capable of representing regular sets but not natural languages or predicate logic. A fourth problematic issue is a direct consequence of giving up the powerful, and perhaps essential, ‘stored program’ concept: if a connectionist network learns set Y after it has first mastered set X, it will forget X and especially, when the task is to learn the conjunction of X and Y it will have to relearn all the old information. In contrast, the simple message sent to you by Telecom that the phone numbers in your area will be changed and that you are now required to dial a 5 before the old number, does not require retraining but is stored as a single rule operating on all the relevant entries in your mental telephone directory.

Finally connectionist networks appear to be indifferent for semantic coherence: learning a complex sentence does not imply that the model will be able to make inferences about the constituent clauses of that sentence. This does not exhaust the list of problems, and the discussion thus far does not imply that connectionism will forever be unable to solve or explain such problems. What may be derived from this discussion, however, is the suspicion that those critics who see connectionist modelling simply as a convenient architecture for implementing certain lower level perceptual and cognitive functions may not be forced to revise their opinion for quite some time to come.

Until now the connectionist models, sophisticated as they may have become, have not succeeded in replacing the classical perspective. On counterbalance, however, it should be recognized that the connectionist approach, apart from its main focus, had at least three positive side effects. First, it renewed the interest in issues of learning or the dynamics of cognition that had almost been neglected in mainstream cognitive psychology (Van Gelder, 1998). The symbolic approach was mainly internal and non-learning. This is not to say that learning was absent in the symbolic approach, but it was limited to chunking and the speeding up of processes and had little to do with the dynamics and the generation of symbols. Second, the connectionist approach again drew attention to the relevance of the determination of the levels of description in explaining psychological phenomena. Connectionists, and in their slipstream neurologists and neuropsychologists, have emphasized the physical or physiological level of description, but they forgot to take into account that changing the levels of description requires at least that one provides correspondence rules—explanations to bridge the gap between these levels—barring that one would adhere rigorously to a reductionist position, something that can hardly be expected to provide a satisfactory perspective to the psychologist. Third, the connectionist attack paved the way for other critics of the symbol processing paradigm, such as ‘situated action’ (Dölling, 1998). This attack had nothing to do with the issue of the levels of description, but focused on the problematic relation between internal symbolic structure and external environment (Fodor, 1987; Vera & Simon, 1993).

2.2.6 Recent trends: neurocognition

The most conspicuous development over the last decade is, without doubt, the rapid development of the field of neurocognition. The number of articles in scientific journals dealing with the relation between brain and mind, for instance, tripled between 1984 and 1998. The recent conferences of the *Society for Neuroscience* attract approximately 25000 participants.

The central issue at play in this development can best be characterized as the genuine feeling that—largely as a result of the development of non-evasive methods for recording brain events—it is now possible to study the material basis of cognitive functions. These methods, including PET (positron emission tomography), fMRI (fast or functional magnetic resonance imaging) and MEG (magnetic encephalography), allow a coherent analysis across the range from the single nerve cell to the entire, intact organism. The amazing outcomes of the use of all these techniques may hide the fact that the real issue to be solved for any theory of neurocognition still is to bridge the gap between the physiological and the functional, or in classic terms, between the physical and the mental. Newell in particular has stipulated the importance of understanding the functional constraints that the cognitive domain and the neurological and physiological domain impose on one another, bearing in mind that the lower levels of description always underdetermine the higher levels (Newell, 1990).

From a semiotic point of view there is no big difference between the symbolic and the connectionist or sub-symbolic approach. Both use the term symbol in the same sense that the term sign is used in common discourse. Discussions about the internal structure of symbols, sub-symbols, reference and interpretation in semiotic terms are largely absent in mainstream connectionist work. However, many implicit semiotic assumptions are present in this work as has recently been stipulated by Dölling (1998) and Daddesio (1995). The connectionist approach offers an opportunity to put the notion of semiosis in a more empirical perspective, but because ‘meaning’ and by implication therefore also semiosis are treated as an emerging property proceeding from the activity of the network, the explanatory power of this statement remains as problematic as it is in discussions within the philosophy of science.

2.3 Modularity of the mind

Not only Von Neumann architectures have intrinsic difficulties doing several things at once. Paradoxically, by capitalizing on massive parallel processing connectionist networks are suffering from the same handicap, albeit for the opposite reasons. This brings us to the issue of modularity, another important aspect of cognitive architectures.

2.3.1 Associationism and the homogeneous mind

This question goes a long way back into the history of philosophy of mind. To what extent should we consider the human mind as a homogeneous object, perhaps consisting of a large number of identical units, such as neurons, but in which the function of these units is determined by the conditions rather than by the properties of individual components. The alternative is a mind consisting of specialized units or modules. The concept of a uniform mind derives from the 18th century attempts to mimic Newtonian mechanics, the successful description of the physical world as consisting of elementary point masses in uniform space and time, subject only to a few simple natural laws (Michon & Jorna, 1989).

The dissociation of matter and mind by Descartes initiated a search for a mechanics of the mind. Through the centuries the basis for such a mental mechanics has been sought in the concept of association, the ‘natural tendency’ of perceptions and ideas to form connections. Various associative theories have seen the light of day, those of James Mill and John Stuart Mill in the middle of last century but also much more recent ones, including behaviourism and the theory of human associative memory (Anderson & Bower, 1973). We may add that the computational approach is consistent with the conceptual framework of associationism. Not surprisingly, this framework also fits in with the connectionist approach (Jorna & Haselager, 1993). Perhaps it is the mechanistic origin of associationist theories that has prevented them from adopting the idea that the mind may be composed of functionally distinct modules, each operating on different symbol structures or different processing principles, even though they should in some way or another collaborate in generating what we perceive as integrated, intelligent behaviour. The fact is that both the symbol processing approach and the connectionist approach are largely confined to the idea of a uniform mind.

2.3.2 The modular mind

The alternative also has been around in psychology, albeit for a very long time mostly in individual psychology. The modularity of the mind got some notoriety through the phrenological work of Franz Joseph Gall. Convinced that training specific mental functions, such as mathematical reasoning or charity, would locally increase nervous tissue, Gall looked for the external signs of mental calisthenics, that is for bumps and bulges on the skull (Fodor, 1983).

The concept of modularity was reintroduced in general psychology through Chomsky's work (e.g., Chomsky, 1980). He suggested that apart from anatomically and physiologically well-defined sensory and motor systems ‘mental organs’ may exist, that is, integrated systems of principles and rules that generate representations. Language, and more specifically the ‘universal grammar' that lies at the root of or ability to acquire our mother tongue quickly and effectively, is the prime example of such a mental organ. Like physical organs and limbs such mental organs would be encoded in the human genotype. Chomsky's suggestion was given an important follow-up by Fodor (1983), in an attempt at uniting the concepts of uniform mind and modular mind into one model. For this purpose Fodor distinguished horizontal and vertical mental processes. The horizontal ones are those that we usually label as higher or conscious processes. These are the ones that we should conceive as uniform and homogeneous, since they take inputs from different sensory systems and cognitive domains. Horizontal information processing causes us to forget, say, whether we have initially heard or read a particular fact. The vertical processes are truly modular, in a sense that is open to empirical test. Fodor has formulated a set of criteria, including domain specificity, stimulus driven operation, cognitive impenetrability, speed of operation, and specific localization. Since the publication of Fodor's essay in 1983, many studies have addressed the question of modularity, generally with mixed success (e.g., Garfield, 1987).

Initially the functional domain of modules was supposed to be quite large, so as to require, for instance, a single module for language. Then gradually assumptions about more limited modules began to be introduced into the discussion, viz. Jackendoff's proposal to distinguish separate modules for handling the phonological, lexical, syntactic, and semantic/pragmatic features of language (Jackendoff, 1987). This trend has not stopped, and this may eventually lead to modules that are so limited as to become indistinguishable from the rules of symbol processing that are characteristic of the conceptualizations of the mind as a homogeneous entity (Michon & Jorna, 1989).

2.4 Levels of psychological explanation

2.4.1 Reductionism

From a conventional perspective science usually appears to proceed by reduction, the methodological or formal reformulation of the elements and relations at one descriptive level to a lower, that is, more abstract and simpler level. Reduction specifies the well known ‘pecking order’ between sciences from history and sociology, via psychology, to physiology, chemistry, and physics. In its most radical form we find reductionism in psychology as eliminative materialism. Its adherents believe that each and any scientific explanation can eventually be mapped onto the laws of physics and that, therefore, any higher level explanation must be eliminated. A more widely accepted form of reductionism is instrumentalism which holds that even if reductionism is ultimately possible and even desirable, it is convenient and economical to maintain higher levels of explanation, since it would be very cumbersome to describe, for instance, foreign language acquisition in terms of quantum-mechanical interactions between elementary particles. There is, however, a non-reductionist approach to psychology that recognizes the independence of psychological explanations. The higher levels of explanation contribute essentially new qualities, so-called emergent properties, to a phenomenon. In this perception higher levels of explanation are underdetermined by the lower levels. This implies that there exists between these levels a gap that cannot be bridged. In this view reductionism will never succeed in its aim of giving an exhaustive explanation of reality in terms of physical laws.

2.4.2. Dennett's stances

The idea of levels of explanation has been worked out most elegantly by Dennett (1978, 1987, 1991) who distinguishes three independent levels, the physical stance, the design (or functional) stance, and the intentional stance. Other authors (Newell, 1982, 1990; Pylyshyn, 1984) have given similar accounts in which, however, the number of levels may vary. In the following paragraphs we summarize Dennett's discussion of levels (1987, 1998).

The physical stance explains behaviour in terms of physical properties of the states and the behaviour of the system under concern. For its proper functioning the human organism requires a complex interaction between its parts and with the external world. The central nervous system, and the endocrine system are there to transmit information that reveals the state of one part of the system to other parts. This stance is, as it were, the endpoint of successful ontological reduction.

The second level of explanation takes the point of view of the functional design of a system. The behaviour of a system is conceived as the result of the interaction between a number of functional components or processes. The physical structure (architecture) of the system is not explicitly taken into account, although it may impose constraints on the behaviour of the system. The capacity limitations of human memory will, for instance, impose a boundary on the complexity of decision making.

In the third place Dennett distinguishes the intentional stance. Complex behaviour that is adapted to the prevailing circumstances, according to some criterion of optimality is said to be rational or intelligent. A behaving system to which we can successfully attribute rationality or intelligence qualifies as an intentional system. It is not necessary for a behaving system to ‘really’ possess rationality or intelligence, as long as the assumption allows us to correctly predict the behaviour of the system on the basis of our knowledge of the circumstances in which the system is operating.

One may deal with this three-cornered distinction in two essentially different ways. Dennett (1978) has taken this it in a strictly instrumentalist way, claiming only a pragmatic validity. Summarizing his position twenty years later, he wrote

> “As I have put it, physical stance predictions trump design [or functional] stance predictions which trump intentional stance predictions—but one pays for the power with a loss of portability and a (usually unbearable) computational cost.” (Dennett, 1998, o.c., p. 119).

In contrast authors such as Fodor (1975), Newell (1990), and Pylyshyn (1984) assign an ontological significance to each level. According to these authors the higher levels introduce emergent qualities into human behaviour that make no sense if we maintain an instrumentalist point of view.

From a semiotic point of view the levels of description or explanation can be equated with the types of signs and its processing. Sebeok (1994) distinguishes six kinds of signs:

- *signals* are meant to elicit a reaction in a receiver in a mechanical or conventional way;
- *symptoms* are automatic, compelling, non-arbitrary signs that naturally connect the sign with what it refers to;
- *icons* are signs that indicate a topological similarity between the sign and where it refers to;
- *indexes* are signs that refer by means of physical proximity;
- *symbols* refer by means of conventions;
- *names* are signs with class extensions.

With this classification a distinctions can be made between causal relations (signal and symptom) and semantic relations (index, icon, symbol and name). Furthermore, signals are processed automatically by most information processing systems, whereas names require a high degree of abstraction. Signals and, to a certain extent, symptoms can be located at the physical level, the other kinds of signs at the functional and intentional levels. One could argue that the more interpretation is required—thus, names do require more interpretation than indexes—the more we are shifting from a functional to an intentional level. In other words, going from an intentional to a functional level means that high-level interpretations are decomposed into low-level interpretations. This is in line with Dennett's argument that the explanatory mission of cognitive science is to break down intelligent homunculi into simple, stupid homunculi (Dennett, 1991; see also section 2.6 below).

2.4.3 Computation and the functional stance

Computational theories are in principle confined to the functional level. This implies in the first place that intentional states of mind, propositional attitudes, emotional states, and 'mental images' are as much as possible reduced to the functional level. Although a majority of cognitive psychologists do indeed accept this point of view, acceptance of the functional point of view is not universal. The most focused debate took place on the basis of Searle's Chinese Room metaphor (Searle, 1980). In the second place adopting computationalism and the functional stance implies that a reduction to the physical level is avoided. The actual implementation of a computational system is not relevant, although it is generally recognized that the architecture will, as a rule, impose constraints on the efficiency of the computations being carried out. Limitations of memory and processing speed and structural bottlenecks will affect performance but not the competence of a program. Psychological models at the functional level come in three varieties: stage models, process models and structure models (Mayer, 1981).

(a) *Stage models*. The underlying assumption is that it should be possible to distinguish primitive processing operations that operate on incoming information in a modular way, that is, uninfluenced by other operations. Important stages in perceptual motor skills would be stimulus encoding, response selection, motor preparation, and action control (Sanders, 1998). In language processing the evidence favours a distinction between the phonological, lexical, syntactic, and semantic/pragmatic stage or module (Jackendoff, 1983, 1987). Tasks differ in the extent to which they make use of these stages and errors or malfunctions are attributed to specific shortcomings or the absence of particular stages. Initially stage models used to have a strictly serial control structure on the assumption that the output of one stage must be available before a second stage can accept this output for further processing (Sternberg, 1969; Welford, 1967). Gradually it became clear, however, that many processes can only be understood if this severe constraint is somewhat relaxed by allowing certain overlaps in processing (Card, Moran, & Newell, 1983; Gopher & Donchin, 1986).

(b) *Process models*. They consist of a set of rewriting or production rules, that is, a grammar or production system and a control structure which governs the communication between the various parts of the set. Control structures may differ in two respects: (1) control may be sent from its present locus, or it may be captured by its new locus; (2) control may be directed to a particular locus, or ‘broadcast’ to all potential loci (Pylyshyn,1989).These possibilities admit the ranking of process models on a scale of rigidity, ranging from very strict (algorithmic) procedure models to very flexible strategy models. The latter category relies heavily on heuristic or ‘weak’ methods for assigning control (Mayer, 1981).

(c) *Structure models (networks)*. The best known among these are semantic networks. A semantic network embodies sets of propositions. Each concept is represented by a labelled node, and each relation, depending on the modelling formalism, by a node or a link between nodes (Sowa, 1984). By means of the processes that determine the behaviour of the network information can be encoded into or retrieved from the network and inferences made. The set of relations between a node and its environment constitute the node's meaning (Norman & Rumelhart, 1975). In addition semantic models specify in what ways the nodes and their relations can be activated. The difference between models resides primarily in the assumptions about the activation processes (Rumelhart & Norman, 1988, p. 528).

2.5 Syntactics and semantics

2.5.1 Syntax and intentionality

The functionalistic program of cognitive psychology has not remained without critique. Some fundamental criticisms against the computational approach have been raised by Searle (1980). They attracted much attention at the time and the discussion still rages on (e.g., Penrose, 1989). Searle's argument essentially holds that machines that instantiate programs which behave intelligently (intentionally), so that they will be capable of passing Turing's test, are not really intelligent because machines happen not to have the right kind of (biological) architecture that is required for the ‘production’ of intentionality. The rules according to which such programs operate are purely syntactic: they can operate only on the form of the symbols not on their meanings. It should be borne in mind here that Searle’s notion of intentionality is not the same as Dennett’s intentional stance. Whilst Dennett is essentially referring to rationality, Searle (1983) appears to follow Meinong’s old notion of intentionality as the ‘aboutness’ of mental states.

Many objections have been made against Searle's position, ultimately because it identifies a problem but fails to even suggest a solution. In the words of Simon and Kaplan: “If you reject the idea that machines can think, you must come up with a theory explaining why the appearance of intelligence is not intelligence” (1989, p. 6). This claim still stands and recent developments in cognitive science have not (yet) opened a new perspective on the functional level (Hogan, 1997).

2.5.2 Meaning and sensory inputs

Although we may give any symbol system a semantic interpretation, normally such interpretations are imparted by the observer or the programmer, not by the program, let alone the machine. It seems, however, that much of our *natural* semantics is not imparted on our symbol systems by some external agent, but is instead grounded in these symbol systems themselves. This is what Gibson (1979) has called affordances: the structure of the environment, which he called the ’ambient array,’ affords certain interpretations of reality. Thus, for instance, a chair and a slab of marble may both afford ‘sit-on-ableness’ if—and occasionally only if—the perceiver happens to be tired.

The question is how the meanings of symbols can be grounded within the symbol system itself (Michon, 1984; Newell, 1982). This would seem to be impossible in a pure symbol system. However, for human beings or, for that matter, for any physical symbol system (see section 2.1.3 above) that has been in evolutionary contact with its environment for aeons, this possibility is indeed present (Dupré, 1987; Schull, 1990). Such systems will normally include any number of so-called bottom-up functions, provided by sensors which do extract certain invariant aspects of the environment in ways that we cannot possibly consider as symbolic, although their output is subsequently subject to translation into mental symbols (Pylyshyn, 1984). Whilst these internal symbols may be manipulated in a purely syntactic way to form higher order symbols or symbol structures, their meaning resides in the system's capacity to discriminate, categorize and name certain objects and events. In living organisms the evolutionary process has largely taken care of tuning sensory systems to non- arbitrary objects and events, that is, to situations that have a certain survival value. For artificial systems this will not be different, except for the fact that the sensory surfaces that interface between the system's environment—which itself may be natural or artificial—are brought about by human intervention (Simon, 1969).

Answering the question how the meaning of symbols can come to reside in a symbol system as such, requires an understanding of the evolutionary, developmental, and learning processes that lead to sensory categorization (Cosmides & Tooby, 1987; Schull, 1990).

2.6 Consciousness

Perhaps the most formidable problem confronting psychology is to provide an explanation of consciousness. In the computational context adopted in this chapter this means providing a functionalistic answer to the question “What causes my perception of this book to be my perception of this book?” This question involves two cardinal functions of human consciousness—psychological identity and reference—and it has received innumerable answers in the course of time. It appears to be impossible to explain these two functions independent of the concept of consciousness itself. Solutions have, nevertheless, been attempted along different roads (Churchland, 1984; Jackendoff, 1987; Marcel & Bislach, 1988). The first ‘solution’—a straightforward denial of the direct experience of psychological reality—is one which only the most explicit nihilist may be willing to accept. The solution adopted by classical behaviourism was to equate psychological reality with behaviour (and, for instance, language with verbal behaviour); this too has proved to be a highly implausible alternative.

According to current views, psychological reality is a consequence of the computational operations carried out on the symbolic representations of the mind. These representations have a physical implementation in the brain. Within the confines of this view two main lines of thought can be distinguished, a reductionistic and a homuncular one. As explanations for consciousness both are presenting difficult problems. The first view wishes to reduce mental phenomena to physical, or at least neuro- physiological mechanisms. There is, however, no plausible scheme that would seem to explain what it means, neuro-physiologically speaking, to be aware of something. The second, so-called homuncular view does accept a coherent consciousness, that is, a psychological identity or Self, but in its attempts at explaining this identity it should carefully try not to introduce pernicious homunculi.

A homuncular theory appears to explain a mental phenomenon in terms of the phenomenon itself. If, for instance, a theory of visual perception incorporates a function ‘interpretation of the retinal image’ we have a (pernicious) homunculus because the interpretation of incoming visual information is precisely what the theory is supposed to explain. There is disagreement among philosophers as to whether some or all homunculi are, ultimately, pernicious. Those who adhere to the homuncular view, in the belief that some homunculi are benign, try to explain complex mental phenomena such as consciousness in a series of steps involving simpler and simpler homunculi until they reach a level where the homunculi have become so simple that they can be implemented in a computational routine. It will be clear (see section 2.5.1 above) that there is no general agreement that this can be, in principle, a legitimate, successful strategy.

In recent, psychologically inspired discussions based on some (presumably benign) form of homuncular strategy, three distinct types of models of consciousness have been proposed: the monitor, the emergent property, and the spotlight models (Michon, 1990).

> (a) *Monitor model*. This model assumes the presence of an integrative function which allocates all relevant information entering into the system and which also controls the various processing mechanisms. This function is variously known as monitor, executive, or task schema. What happens inside this monitor is what is consciously experienced. The problem with this model has been known for many centuries: who (or what) is monitoring the monitor? The homunculus of the monitor model is pernicious and will not yield a scientifically acceptable explanation of consciousness (Dennett, 1978, 1991, 1998).
>
> (b) *Emergent property model*. On this view there is no direct mapping of cognitive, or neuro-physiological, processes on conscious experience (or vice versa). The process level will only impose certain constraints, such as speed and capacity restrictions. Conscious experience can therefore not be reduced to the processes underlying it, but if the system is complex enough and if certain boundary conditions have been fulfilled, new properties will emerge that require an explanatory level of their own. The gap between process and emergent domain cannot be bridged (Dennett, 1978; Herrmann, 1982) without introducing pernicious homunculi. Function and conscious experience are separate, incompatible worlds, and cognitive psychology, from its functional point of view can—and should—say nothing intrinsic about consciousness.
>
> (c) *Spotlight model*. At any time parts of the knowledge and skill structures of the organism are activated. Whatever knowledge elements are active are—by definition—part of working memory. Whatever finds itself in the limelight constitutes the content of our consciousness. Most cognitive theories subscribe to this view, in one way or another (Schneider & Shiffrin, 1977). An interesting extension of this point of view was proposed by Jackendoff (1987). He argues that not everything that is activated and therefore accessible to focal cognitive processing is necessarily ‘projected’ into consciousness. There are certain privileged domains and what penetrates into conscious awareness is

> only what is both privileged and activated. Consciousness, according to Jackendoff, is an epiphenomenon: “Consciousness is not good for anything” (o.c. p. 26). An explanation of consciousness on the basis of a functional analysis of behaviour and cognition should therefore be sufficient, and it should be related to the questions of the what and how of the mapping of the privileged domains into consciousness. Jackendoff's position is attractive because it allows us to understand that we have cognitive access to the phonological aspects of speech but not to its syntactic aspects. On the other hand, like the emergent property model, the spotlight model cannot explain why certain aspects of the computational mind do penetrate into the conscious mind and others do not.

This discussion about the theoretical underpinnings shows once again that there are many issues and unanswered questions in cognitive psychology that have a semiotic undertone. They can be categorized into three main groups: the nature of signs and semiosis, the static aspects of signs and the dynamic aspects of signs.

> (a) Concerning the nature of signs and semiosis, the central questions are what the constituent elements of our thinking and reasoning are and what characteristics they have. Firstly, signs must have carriers. They may be physical (e.g., white reflective lines on black boards), chemical (e.g., fluorescent substances), physiological (neuro-transmitters) or electronic (electrons and currents). Because the symbols or signs in our cognitive system have a hypothetical character, the functional properties of signs are only partly dependent upon the material grounding of signs. But what does this exactly mean? Secondly, symbols have references. It is unlikely, however, that internal symbols have only internal references. If that is so, what is the nature and extent of the relations between internal and external reference. Thirdly, if symbols are the constituent elements of mental representations, what operations guide the composition and the interpretation of symbols and representations? And finally, where do (internal) symbols come from and how are these representations realized? That is one interpretation of the much debated term ‘semiosis’.
>
> (b) Concerning the static aspects of signs and symbols, attention is primarily focused on the analysis of properties of signs, such as illustrated by the work of Peirce, Goodman (1968), Rasmussen (1986), and Sebeok (1994), all of whom proposed a categorization of signs. Its importance is to be found in the discussion about presenting, storing, retrieving and processing various kinds of signs. Sign typologies should provide a conceptual framework for the analysis of diagrams, propositions, images, icons, indexes and symbols without immediately taking into account their effect on users.
>
> (c) With respect to the dynamic aspects of signs, one may think of the genesis of signs or the adaptation or conversion of existing (internal) signs. Semiosis may be applicable to both or only to the first. In terms of present cognitive science this implies operations like the generation, the deletion, the mutation and the copying of signs. For some sign types this may be easier than for other types, but in principle it can be applied to all types.

Long before Newell and Simon (1972) provided a conceptual framework in terms of the manipulation of symbols, the ‘behaviourist’ Charles Morris (1925) already considered the static and dynamic aspects of symbols. He suggested that cognition itself refers to the symbolic repertoire of an organism. According to him, sign interpretation can be seen as a five-place relation consisting of a sign (*S*), that is related by signification (*SI*) to an object in a context (*C*) and this sign leads to certain kind of behaviour or disposition (*D*) in an interpreter (*I*). It is interesting to see that in this formulation Morris refers to the external environment (object and context), the internal environment (signification and interpreter) and to behaviour (dispositions). Morris' analysis did show that as soon as referential and representational issues are included within psychological theorizing, the rigorous borderline between cognitive psychology and semiotics becomes vague. There is nothing wrong with this, provided that empirical and experimental testing can be integrated into the discipline. Psychology did succeed in doing this and thus paved the way for a scientifically valid accumulation of relevant facts and insights. In the next section we will consider some details of what this accumulation has led to in the course of the past forty years, during which progress in scientific psychology has accelerated considerably.

3. DOMAINS

In this section we will consider the major active research domains in cognitive psychology, in particular those that have made progress towards a computational account in either the symbolic or connectionist paradigm (or both). Taking the standard information processing model as our lead we will successively deal with perception and the selection of inputs, memory, language (acquisition, comprehension, and production), thinking (conceptualizing, reasoning, and problem solving), emotion, creativity and action. This order of presentation defines a canonical trajectory from input to output. Readers may consult any of recent standard text or handbook of general and experimental psychology for further details (e.g., Atkinson, Herrnstein, Lindzey, & Luce, 1988; Boff, Kaufman, & Thomas, 1986; Eysenck, 1989; Posner, 1989). For each domain we will outline the computational perspective—broadly understood—and indicate how the massive empirical evidence does support the theoretical tenets under concern.

Several important topics will not be touched upon. We have, for instance, left out the important field of motivation, largely because the computational approach has not yet led to substantial bodies of theoretical insights (Simon, 1967; Mandler, 1975; but for various perspectives see, e.g., Atkinson, Herrnstein, Lindzey, & Luce, 1988; Brehm & Self, 1989; Hockey, Gaillard, & Coles, 1986; Izard, 1977).

Although it may seem that learning (Atkinson, Herrnstein, Lindzey, & Luce, 1988; Hilgard & Bower, 1975) is also lacking from our list of topics, this is not really the case. The study of intelligent architectures and the ways they are constrained implies the study of their capacity for learning, that is, of the ways in which such architectures change as a function of experience. Consequently learning is pervasive in the cognitive approach. It has to be acknowledged, however, that because of the emergence of the connectionist approach in the 1980s, learning has recently (re)gained a more prominent place on the research agenda.

3.1 Perception

Extensive covering of all aspects of perception is found the various chapters of Boff, Kaufman, and Thomas (1986) and in a new edition of Stevens' celebrated *Handbook of Experimental Psychology*, edited by Atkinson, Herrnstein, Lindzey, and Luce (1988). Although auditory perception has been studied very extensively (in contrast to tactile, olfactory, and gustatory perception), we will restrict the discussion here almost entirely to the visual system. The computational approach to the other senses has been treated in some detail by Richards (1988) and Ossebaard (1993). For the computational approach to music perception the reader may consult Lerdahl and Jackendoff (1983).

3.1.1 Low level vision: from feature to surface

Research in visual perception considers the problem of constructing a 3-dimensional (3-D) representation of objects on the basis of the heterogeneous inputs to the peripheral receptors of the visual system, the cones and rods of the retinas of both eyes. The early stages of analysis of the sensory signal have been studied extensively by sensory psychologists, physiologists, and biophysicists alike. An attempt at integration into a coherent stage model has been provided by Laming (1986). Since the foundational work of Marr (1982) three levels of computational mechanisms are conventionally distinguished (Hildreth & Ullman, 1989; Horn, 1986). The first level takes the nervous signals from the retina and transforms these into signs for edges, patches, and spatial orientations. These signs, which constitute a primal sketch of the visual environment, are then input to the next computational level at which they are integrated into consolidated information about planes, inclination, curvature, texture, relative distance, stereopsis, and motion.

Much work has been directed at specifying the computational mechanisms that would produce just these low- and intermediate-level outputs (e.g., Hildreth & Ullman, 1989; Marr, 1982; Richards, 1988). Evidence has been gathered for such processes as spectral analysis, smoothing, differentiation, stereo-alignment. Given the structure of the visual system most of these processes will run in parallel. Thus a stimulus may be analyzed simultaneously under several levels of resolution.

3.1.2 High level vision: from shape to object

At this level depth cues are extracted but not yet integrated into solids, a reason to call this level the 2.5-D sketch. Only at the third level, a 3-D image of solids in their relative spatial positions is computed. Only subsequent to this third level of analysis a semantic interpretation is given of these solids.

Much work has been devoted to the specification of computational functions that constrain the features at each level of analysis in such a way that a stable representation of the visual field ensues (Gibson, 1979; Hochberg, 1986, 1988). A simple example is that the spatial arrangement of an ensemble of hexahedrons (blocks) of different shapes can easily be extracted from the 2.5-D sketch since there are essentially only five ways in which the edges of these blocks can meet or overlap each other: as a K, L, Y, T, or ® connection respectively (Winston, 1975). The most elegant description of the computational constraints on complex solids was provided by Biederman (1987). He defined a set of so-called ‘geons’, consisting of 36 elementary convex solids, including sphere, cylinder, cone, and parallelepiped. Any complex object can be parsed into elements from this set. The characteristic feature that constrains the parsing procedure is concavity. Wherever the surface of an object shows a concave edge, two or more geons are touching. In addition the constraints that govern the arrangements of simple blocks mentioned above apply to the arrangement of geons in general.

As an experimental test of this theory Biederman presented subjects with line drawings of complex objects such as a penguin, a torch light, or an airplane. Each drawing was partly blotted out in such a way that the parts which showed the concavities and edge connections were visible or occluded. In the latter case parsing (recognition) of the object became entirely impossible.

Such studies show how computationally simple functions defined over very complex domains like the visual field may nevertheless impose the right kind of constraints. Evidence has been gathered which indicates that other computational processes may be at work in the difficult task of reconstructing the world of objects from the elementary features extracted at the lower levels of analysis. Some of these appear to be highly specific bottom-up and task-independent (primitive) processes. This includes processes for determining topological properties such as whether a stimulus is inside another stimulus, and for the practically automatic recognition of human faces (Richards, 1988). Others are definitely top-down, since what is perceived appears to depend on the knowledge already available to the viewer: what determines the recognition of a bird depends on the image of what constitutes a prototypical bird (Clark & Clark, 1977; Rosch & Lloyd, 1978).

3.1.3 Structural Information Theory

The work outlined above constitutes a major field of interest for cognitive science. However, it is not the only approach. A second, extremely fruitful, approach is known as structural information theory, a line of research greatly stimulated by the work of Garner (1974), Leeuwenberg and Buffart (1978), and Restle (1970). Structural information theory starts from the assumption that the constraints under which perceptual processes operate can be found to a considerable extent in the stimulus pattern itself. The shape of objects, and even their three-dimensionality depends on a limited set of encoding rules specifying the distributive properties, and the translation, repetition, and reflection of primitive elements—line segments and angles in vision, but equally pitch and duration of tones in auditory perception (Chase, 1986; Pomerantz & Kubovy, 1986).

Perceptual processes generate abstract representations of patterned stimuli. If more than one representation is possible all are generated in parallel; subsequently a preference measure determines which percept ensues; conventionally this will select the simplest representation, having the lowest structural information load. Structural information load is defined as the number of parameters required to encode a pattern. The representations in structural information theory being abstract, however, a semantics (rules and operators) must be defined for each class of stimuli. For instance, a pattern such as *axaxax* may be interpreted as 60^{o} angle-line-60^{o} angle-line-60^{o} angle-line if the interpretation is over the class of plain geometric figures. In that case it describes a triangle. The semantics is not normally part of structural information theory.

Recently it has been shown that—as was also the case for the set of possible connections between Biederman geons—there are severe constraints on the possible set of such relations and a procedure has been developed that will automatically generate all possible representations for a given configuration (Van der Helm, 1988). If these representations are stored, together with their generation paths, the result is a network that may be considered as an architecture for the processing of structural information (Van der Vegt, Buffart, & Van Leeuwen, 1989).

3.2 Attention

While the visual system appears to be capable of dealing with a practically unlimited amount of information at any time, the capacity of the human cognitive system seems to be severely limited. An early estimate of the processing capacity of the human information processor is that the input rate of information from the environment may be of the order of 1-10 million bits per second, whereas the central processor can cope only with an information load of the order of 10-100 bits per second, demanding perhaps as much as a million-fold reduction. While most of this reduction will be managed by the processes discussed in the preceding section, there still remain requirements to be met—partly imposed by bottlenecks in the cognitive architecture (automatic processing), partly by the structure of the task to be performed.

Attention, that is, the selection of some parts of a situation over others results from capacity limitations which impose constraints on the amount of information that can be processed in parallel. When these become manifest the organism must process information sequentially, or leave parts of the information out altogether. Initially it was thought that the human cognitive system was essentially a single-channel serial processor (Broadbent, 1958; Welford, 1967).

More recently a much more differentiated picture has emerged. A first constraint that had to be determined was the principal locus of selection. The question to be answered was whether information was selected at the perceptual level, prior to its cognitive processing, or only later after a massive parallel processing of most or all of the incoming information? The issue has not been resolved unambiguously; the task- dependent results generated by the ample research devoted to these issues during the sixties testifies to the partly top-down cognitive control of the selection processes (Duncan, 1980; Posner, 1982).

3.3 Memory

Memory is one of the core concepts in psychology. A severe initial constraint which has dominated memory research is that we appear to know more than we do actively use at any instant. This has caused memory theories to distinguish two kinds of memory, a fairly volatile working memory in which currently relevant processing is taking place, and in addition to this a repository for facts and skills that are not currently required but that may be reactivated for later use (Baddeley, 1990).

Despite its century-long tradition, the experimental study of memory has only recently begun to converge towards the desired computational theory. This is mainly due to influences from the field of artificial intelligence where the need for formal descriptions of memory architecture and computational constraints is paramount.

3.3.1 Short term memory

The 1960s and early 1970s was a fruitful period for cognitive memory research with many reliable experimental techniques being devised and tested in well controlled laboratory experiments. This progress was largely influenced by the analogy of the digital computer which in turn, tended to produce models of memory which were based on the serial processing of symbolic information. This created a plethora of detailed theoretical models; thus, in a book edited by Norman in 1970, there were 13 contributors each of whom presented a different model (Norman, 1970). However, most of the models had a great deal in common, with the central feature being the area of short-term memory. In general, they postulated that information is first processed in parallel by a range of sensory buffer stores which then feed information into a limited capacity short-term buffer or store, which could hold only a small number of items, relied largely on acoustic coding and was subject to very rapid decay unless continuous rehearsal and recycling of information took place. In its turn, the short-term store was able to communicate with a capacity-unlimited long- term store.

While such dichotomous models appeared to be based on a firm foundation of empirical evidence and were indeed very popular for more than a decade, new evidence began to accumulate in the 1970s which raised serious problems for such models and showed them to be grossly over-simplified. For example, neurological data did not fit predictions from the model: these indicated that patients with short- term memory deficits should also have problems in long-term learning—but such deficits did not always appear (Craik & Lockhart, 1972; Crowder, 1976, 1982).

3.3.2 Working memory

One response to such problems was the development of the working memory model proposed by Baddeley and Hitch (1974). The main question posed was functional and related to whether the short-term store acts as a working memory which plays an important role in cognitive activities such as learning, comprehending, and reasoning. Using a concurrent task technique, these authors collected data which challenged the earlier concept of a unitary short-term store and replaced it by a related but more complex concept, that of a multi-component working memory model.

The most important, though the least studied and most vaguely conceptualized component in this theoretical framework, is the modality-free central executive. This is viewed as being a limited- capacity processor and, as was discussed in the previous section, it closely resembles attention and is involved in control and selection functions. Two further subsidiary components, or ‘slave systems’ of the executive have been studied in much more depth. These are: the articulatory loop which is responsible for the temporary storage of speech- based information; and the spatio- visual scratch pad which allows the temporary storage of visual and spatial information. In comparison with the earlier dichotomous models, the working memory system offers a number of obvious advantages. Firstly, it has been shown not only to be concerned with the temporary storage of information, but also with its active processing. This in turn, means that the system is highly relevant for many cognitive tasks such as reading, mental arithmetic, verbal reasoning and comprehension, as well as in more traditional memory tasks. Moreover, converging evidence from developmental studies as well as from cognitive neuropsychology have both strengthened and improved the original model.

Although there are still considerable gaps in the framework, the concept of working memory has made a great impact on cognitive psychology and is widely acknowledged, not only among memory researchers but also among those working in related fields such as visual processing, speech perception and production, attention, and attentional control of action (Baddeley, 1986; Daneman & Carpenter, 1980; Morris, 1984).

3.3.3 Long term memory

With respect to long term memory a major question has been how information gets encoded and stored. Encoding is understood here as transforming and integrating (chunking) incoming information in such a way that it will fit with knowledge structures that are already available. Computationally speaking this process creates an explosive problem. The time required for adding a new fact to a knowledge base increases exponentially with the number of facts already present, at least if inconsistencies (contradictions) are to be weeded out. This is known as the truth maintenance problem, and is essential for an artificial knowledge base to function at all (Pylyshyn, 1987). Human beings are less likely to suffer from this problem; they manage by a variety of mechanisms and processes that greatly reduce the complexity of the truth maintenance task they are facing. These include first of all parallel processing and modularity of input channels (tuning of the latter is in many cases guaranteed by the natural constraints that operate on the environment. Secondly much cognitive activity consists of selecting the right kind of problem representation (problem space) which may further reduce the computational burden on the person. Thirdly, and related to the previous issue, it seems that human beings succeed in getting around with huge inconsistencies in their knowledge bases or belief systems. Apart from processes for partitioning the contents of memory into mutually exclusive parts, processes are available to actively suppress inconsistencies. A well known example is the mechanism to resolve cognitive dissonance—the nagging feeling of regret that may follow the forced choice between two equally attractive alternatives. Cognitive dissonance is suppressed by rejecting all information denigrating the actual choice and actively soliciting information that supports it.

Encoding operations may vary a great deal and several may be operating simultaneously. In speech perception, for instance, information is processed at the phonological, lexical, syntactic, and semantic level. Separate modules may be at work to achieve this without conscious effort. Given this great variety the question is not only which constraints are operative in each case; this is known for at least a number of the encoding processes. The second, equally important question is why a particular constraint will control encoding in one case and not in another. Why does one remember who said something in one case (vocal information), what was said in the other (semantic information), and how it was said (lexical/syntactic information) on a third occasion, frequently at the exclusion of the alternatives? Tulving (1983) and several others have emphasized that the actual encoding constraints are frequently goal-determined, that is by our expectations about the use we will later make of the stored knowledge. If no such goals can be guessed, as in the case of most memory experiments in the psychological laboratory no particular encoding strategy is more likely to be selected than another, and as a result performance may be mediocre. On the other hand, as Chase and Ericsson (1981) have shown, a very strict encoding scheme, geared to a very narrow retrieval task, may lead to an exorbitant retention score. In a particular case their subject succeeded in encoding strings of well over 100 digits in a single presentation.

3.3.4 Schemata and episodes

What would seem to be a very effective strategy along this goal-determined line is to encode information as semantically interpreted schemata which would normally be remembered as episodes in context. The use of schemata for the encoding and retention of memory contents was first suggested by Bartlett (1932). Since then the idea has gained considerable popularity. A schema is a spatio-temporally organized structure which is an abstracted version of an experienced episode. It contains variables which when given a specific value will lead to an instantiation of the schema. Generally speaking this will lead to a highly stable form of storing information into long-term memory. When retrieved the schema can be made to fit the momentary requirements by adjusting the values to be substituted for the variables. This is achieved by ‘tweaking’ the schema, an operation for which we have a series of strategies or meta-processes available (Schank, 1986).

These processes have their counterparts in other cognitive domains as well. An example to be discussed later in this paper is the case-based approach to language comprehension. Case grammars (Fillmore, 1977; Jackendoff, 1983) for instance, treat words as elementary schemata with a number slots attached which must be filled in if the meaning of the word in context is to be understood. Thus understanding the verb ‘put’ in context requires a specification of slots for the agent (subject), the object, the destination of the object, and perhaps also its origin and the modality of the putting.

3.4 Language

Psychologically speaking there are two major problem areas with respect to language: how do people, particularly infants, acquire language and, secondly, how is language used once it has been acquired. We will discuss these two sub-domains within the psychology of language separately.

3.4.1 Language acquisition

From the cognitive point of view the problem of language acquisition is to determine what is required for a human being to acquire a symbol system that can carry the weight of natural language.

In the past, language has simply been equated with cognition, mostly under the influence of philosophical epistemology. This position cannot be maintained, however, in the light of what we have learned about the cognitive abilities of pre-language children, and of deaf and deep aphasic persons. The received view is that language is implemented on top of a generic cognitive system which is at least as rich, syntactically and semantically, as any natural language. Acquisition of a natural language ‘simply’ requires the fine tuning of the parameters of a set of innate functions or modules, including a phonological, a lexical, a syntactic, and a semantic/pragmatic module. These parameters, which are sufficient to determine the grammaticality of later linguistic performance, can apparently be estimated on the basis of a very limited experience. This is proved by the fact that certain errors of speech are never made, even though the speaker may never have been confronted with them.

The question is how the various constraints are implemented, a question which becomes answerable at least in part if it is restated as: How do we map semantics onto a syntactic structure? It has become evident that factors such as, for instance, the communication between infant and mother in a special dialect known as ‘motherese’, are not crucially important. What appears to be crucial, however, is the presence of a sufficiently detailed perceptual context. “The input to language acquisition consists of sounds and situations; the output is formal grammar” (Pinker, 1989, p. 377).

Acquisition of a natural language is dependent on a number of processes, some of which can be described with fair precision. The first is the presence of a sensitive period; a language is best learned during a period roughly extending from the end of the first year to the end of the third year. When this time window is closed, learning becomes slow and effortful, at all levels, even to the extent that command of a language may never become quite perfect afterward. In the second place language acquisition depends on a set of processing abilities, some of which can only be inferred (such as parameter settings for the various modules), while others can be demonstrated experimentally. An example of the latter category is the rule of morphological uniqueness; this ascertains, for instance that once the past tense of the verb *throw* has successfully been marked as *threw*, this will exclude a subsequent adoption of *throwed*. More generally, semantic relations are severely constrained by the limited syntactic relations that are enabled in early speech. Children usually begin with 2-word utterances, which involve only a dozen or so semantic relations. As soon as 3-word utterances occur, the complexity of the child's language will increase explosively. Facilitating processes also operate at other levels, for instance, the acoustic level. Prosody, stress, and word boundary features offer important support to the language learner. Here again a sensitive period may be at work, because at a later age the detection of word boundaries in a foreign language is usually a difficult task.

3.4.2 Discourse comprehension

Once a language has been acquired the idea, of course, is to use it. This brings us to a second topic, language understanding, or discourse comprehension. Discourse involves the production and perception of coherent sets of utterances. What are the computational problems involved?

In discourse comprehension successive utterances by a speaker are to be placed, by a listener or a reader, in a coherent semantic context according to rules that allow internal and external reference to be preserved and that also enable the listener, or reader, to recognize the speaker's intention. Both speakers and listeners apply these rules, perhaps unwittingly, and the rather strict adherence to such rules in normal forms of discourse has led to the idea of discourse as a form of social contract. This contract includes first of all a number of pragmatic rules holding, among other things, that the speaker is supposed to tell the truth, that he or she will speak literally or else indicate clearly the use of metaphor, irony, and other figures of speech. Also the speed and level of complexity should be adapted to the knowledge level and the processing capabilities of the listener. The latter should signal any departures from the accepted level (by raising eyebrows, verbal objections, or even by becoming distracted or falling asleep).

Several attempts have been made to extract so-called ‘story grammars’ from spoken and written text. These are modelled after one or another syntax for single sentences but instead apply to whole utterances or sets of utterances. The basic structure of a story might thus consist of rewrite rules specifying a story as a canonical sequence of a number of discourse particles (Setting, Theme, Plot, Resolution). The Plot-particle in turn might consist of any number of Episodes, each Episode being composed canonically of a particle sequence (Subtheme, Attempt, Outcome).

Another rule-governed aspect of discourse are the rhetorical illocutions, including attribution, identification, comparison, etc. Their expression is assisted by the frequent occurrence of so-called cue phrases (‘similarly’, ‘incidentally’, ‘however’, ‘as a matter of fact’, etc.), as well as by non-verbal means (gestures, etc.). None of these are strictly required for comprehension, but they facilitate the process tremendously, and appear to be subject to rather strict rules or conventions.

3.5 Thinking

In real life situations, thinking involves a complex mixture of deductive and inductive reasoning, as well as problem solving strategies. In psychological research on thinking, on the other hand, broad divisions have typically been made between several main types of thinking such as problem solving, reasoning, and decision making.

While such artificial divisions have made the subject more tractable for study, they have also invoked strong criticisms which claim that such research has failed to capture much of the dynamic qualities of everyday thought.

3.5.1 Thinking and reasoning

Theories of skill or expertise have been concerned with the acquisition and application of schematic knowledge. Another branch of research, much of it descriptive rather than explanatory, has explored how people produce creative solutions to solve unfamiliar or novel problems. For example, Gick and Holyoak (1980, 1983) have explored the phenomenon of analogical thinking which involves mapping the conceptual structure of one set of ideas (called a base domain) onto another set of ideas (target domain). In these laboratory studies, however, unless explicitly instructed to use the analogous story, subjects often failed to notice, and therefore to use, the analogy in solving the problems. In studies which have explored more everyday problem situations, subjects have been found to use their own ‘naive theories’ or ‘mental models’ to understand the world (e.g., Norman, 1983).

Mental models, as proposed by Johnson-Laird (1983), can be viewed as being a special type of analogical representation which can be characterized as incomplete, explanatory theories which are used by Subjects to generate predictions and explanations of complex situations.

Mental models are also been invoked to account for human reasoning. Psychology has accepted the basic philosophical idea that humans are rational even if their behaviour does not always conform to the laws of logic. Deviations are explained in terms of misunderstanding the reasoning task; after the initial misunderstanding, however, further reasoning is logical. This basic idea has been elaborated in several psychological theories and has been modelled computationally. For example, abstract-rule theories assume that subjects have a set of rules which resemble those of propositional calculus, such as modus ponens. These rules are applied to premises in order to make valid deductive inferences. This theory has been successful in propositional reasoning tasks and has been shown to generate precise predictions about both subjects' judgments of validity and their reaction time on tasks (Braine, Reiser, & Rumain, 1984). The theory also accounts for inter-subject differences on tasks (Rips & Conrad, 1983). As yet, however, it is still unclear how this theory would generalize to other types of reasoning tasks. The theory of mental models on the other hand, has been successfully applied to many different areas of reasoning, including syllogistic reasoning (Johnson-Laird, Byrne, & Tabossi, 1989) and propositional reasoning (Byrne, 1989). The rules of this mental-model theory do not resemble the rules of propositional calculus; they are procedures for constructing models, for searching alternative models, and for reading off conclusions. Within the model, reasoning is assumed to occur in three stages: initially, the premises are comprehended and a model of them constructed; secondly, a putative conclusion is drawn from this model; and finally, attempts are made to find alternative models of the premises in which this conclusion is not the case.

3.5.2 Problem solving

Much of the psychological research on problem solving can be traced back to the pioneering efforts of Newell and Simon (1972). Their problem space theory of problem solving involves a constrained and guided search through a problem space comprising different alternatives. The search is guided by various heuristics (or strategies) which co-ordinate the application of various operators. The task of the operators is to transform the present (initial) state into another, more preferred (goal) state.

All of these processes are carried out by a cognitive system which is subject to various constraints such as a limited working memory system; or limits on the speed with which information can be stored in or retrieved from long term memory.

Problem-space theory has been very successful. It does predict human problem solving behaviour in puzzles such as Tower of Hanoi or Missionaries-and-Cannibals in considerable detail. In the second place, more generally speaking it brings out the extent to which production-system based computational models do indeed parallel a variety of human cognitive behaviours.

A further advance that has been made in the area of problem solving relates to the understanding of human expertise. Empirical studies have explored the differences between experts and novices in many diverse fields, such as chess playing, computer programming or solving physics problems. Anderson (1983) has implemented a general computational theory of skill acquisition which can be applied to skill learning in many such domains of expertise. He views skill acquisition as proceeding from the use of declarative knowledge (knowledge that can be reported and is not tied to specific situations) to procedures that can be used quickly and automatically in specific situations (procedural knowledge). In the final stage, the procedure tuning stage, existing procedural knowledge is either strengthened, generalized or discriminated.

Another example of a general theory of cognition is Soar, an architecture for intelligence that was developed by Newell and his associates (Laird, Newell, & Rosenbloom, 1987). Soar is essentially a parallel production system architecture which is in essence an implementation of the theory of human problem solving as it was initially put forward by Newell and Simon (1972). Soar consists of a limited set of default production rules (if-then relations), plus a working memory that can temporarily hold the information to which these rules are applied. When the if-part of a rule is true—which is the case when it matches the contents of the working memory—then the rule will become active. It will ‘fire’, which means that it will execute its then-part, thereby changing the information content of the working memory. This then will allow the match-and-fire process to continue with other rules whose if-part is matching the new situation. Soar is a parallel architecture in the sense that all rules are tested simultaneously for their truth value. When several rules are true at the same time, they execute their then-part in parallel.

A problem space is in some respects synonymous with what we usually call a task domain. It incorporates all task-specific knowledge that a system has about a particular task. Formally we may consider a problem space as a collection of states and operators. Operators are data structures—one might say: knowledge—that can modify certain states. The game of chess is a typical example; its states are the positions that can arise from the game by applying an operator, that is by making a legitimate move. Problem solving consists of finding a chain of operators that transform an—undesired—initial state in a problem space into a desired end state or, in other words, finding the steps that lead to a goal. Problem solving induces sub-problems. Only trivial actions and problems that have already been solved on a previous occasion immediately reveal the path from initial state to goal state. Usually, however, the problem solver, on his way to the goal state, will be confronted with impasses. An impasse is itself a genuine problem: it is a situation at which the next action to be taken is not immediately evident and therefore requires problem solving. There is a whole taxonomy of impasses, but the most important types are the no-change impasse and the tie impasse. An operator no-change impasse, for example, is said to occur if there is no operator that can be applied to the present state of the problem solver; a tie-impasse ensues if there are several, equally attractive, operators that can be applied to the present state.

An impasse implies that momentarily not enough knowledge is available to allow further progress in the direction of the goal state. The solution in Soar is the principle of Universal Subgoaling. For each and any impasse a new problem is automatically created that is formally represented as a sub-goal. The system must first reach this lower level goal, before it can continue solving the principal problem. The new problem—reaching the sub-goal—must be solved in a new problem space. If, in turn, yet another problem occurs in this subsidiary problem space, the system will again create an appropriate sub-goal. It will continue to do so until at a sufficiently deep level a solution is found for the then prevailing impasse. Alternatively the system may find that it has not enough data available to reach a solution, upon which it will halt, leaving the problem unsolved.

A system that operates in this fashion may be considered a recursive problem solver. A special feature of the technique described here is that the problem space in which a solution is attempted may be different from the original problem space, and indeed may be a different one at each subsequent level.

3.6 Creativity

Creativity can be studied either from the perspective of its behavioural manifestations or from that of its underlying mental processes and mechanisms. An example of the former would be a comparison between the works of Johannes Brahms with those of Arnold Schönberg, or between a novel of Saul Bellow with one of bestseller author Tom Clancey. Results of these analyses may amount to a series of arguments explaining why Bellow’s work is more creative than Clancey's. Very often these arguments run in terms of styles of working or they may be related to personality typologies suggesting that Bellow, as a person, is more open, innovative or inspired than Clancey. More interesting from a cognitive psychologist's point of view is a description of the processes and mechanisms than would account for perceived differences in creativity. If successful, such a description should provide insights with respect to the question as to whether and how creativity can be implemented in artificial systems. The most elaborate attempt to deal with creativity within an overall cognitive framework has been undertaken by Boden (1991, 1994). Her starting point are the four stages in the process of creation that were identified by the French mathematician Poincaré as early as 1914: *preparation*, *incubation*, *inspiration* and *verification*. These Boden translates into the cognitive framework of symbols, representations and operations. Because creativity implies thinking and problem solving, this means that an analysis of the creative process should begin with the concept of problem space or conceptual space within which the creative solution is to be searched. Creative products, however, are *novel*, that is unpredictable and consequently surprising. Two kinds of novelty should be distinguished, the first consisting of original combinations of familiar ideas, the second consisting of a transformation of the initial conceptual space. The former implies that combinations are found that are improbable, the latter that combinations are formed that are impossible (at least within the consisting problem space). It is the latter kind of novelty is most often understood as truly creative. It is the distinction between science and engineering, between composing and performing. It is also what Koestler called it 'a bisociation of matrices'. Matrices, in this context, are the mental representations in a cognitive system, which may consist of stories, icons, texts, images or schema's. And bisociation means that habitual structures or conventional combinations are dissolved and that new combinations may arise, by processes such as analogy and metaphor. In this sense removing existing constraints lie at the heart of creativity: removing constraints may result in new ideas and new thoughts. It should be emphasized, though, that Boden's theory doesn't say anything about the content of a creative product or idea. It is only an attempt to analyze the processes that underlie the generation of the creative product, much as the linguist's analysis of grammar has very little to say about the wonderful books that get written by Saul Bellow or, for that matter, Tom Clancey.

3.7 Emotions

Emotions are traditionally not associated with cognitive processes. Emotions are considered as physiological responses, or as part of one's personality structure, but in any case they stand in stark contrast to cognition. Frijda (1986) was one of the first to explicitly formulate a theory of emotions that is essentially cognitive in nature: his theory provides a functionalist perspective and employs an information processing approach. Frijda's defines emotion in the following way:

> "Emotions are changes in readiness for action as such (we called these changes in activation), or changes in cognitive readiness (they have come under investigation as attentional arousal), or changes in readiness for modifying or establishing relationships with the environment (we called these action tendencies), or changes in readiness for specific concern-satisfying activities (we called these desires and enjoyments)" (o.c., p. 466).

Under this definition a large part of the literature on emotions can indeed be subsumed. Frijda has indeed taken all varieties of emotional behaviour into consideration—from fear and anger to surprise and wonder. He also has dealt in detail with the physiology of emotions and emotional experiences.

Central in every theory of emotions is the notion—to which Frijda's theory does not take exception—that emotion is a response indicating a relation between subject and object or environment. Theories may differ, however, as to where the focus of theoretical interest lies; this may be may be peripheral or central. An example of an early theory representative of the former position is the James-Lange theory which posits that we are afraid because we are running away, and grieve because we are crying. By contrast a subject-oriented approach will hold that we flee because we are afraid and cry because we grieve. Examples of the latter are personality trait theories and cognitive theories (Mandler, 1976).

Frijda's theory of emotions is indeed a cognitive theory. It is operationalized as a processing model in which the various functional elements of the emotional process are made explicit. Beginning with the reception of a stimulus event a sequence of processing stages follows, including an analyzer, a comparator, a diagnoser, an evaluator and an action proposer. The latter input to physiological change generators, resulting in covert responses, or it will propose overt behavioural responses. The various stages in this process are controlled by executive processes and basic physiological mechanisms. In the process also a 'relevance check' is performed that may lead to a dismissal of the signal or an integration of the signal at the various stage positions. Frijda's theory of emotions is easily the most elaborate model of emotion to date. It subsumes a processing model, a 'meaningful' environment, and a semi-independent physiological level of description.

3.8 Action

Cognitive activities are initiated by signs or signals from the environment. By a process of transduction they are translated into internal symbols and subsequently processed in various ways. In the preceding sections we have covered some of these processes. Towards the end of the processing cycle, a reverse transformation must be made. If the human organism is not to be left "buried in thought" (Guthrie, 1935, p. 172) the ultimate internal symbols, representing the outcome of the process, will have to be translated back into signs and signals, actions that can have a physical impact on the external world.

Under most circumstances the body has many more options than it requires to express itself. Given the flexibility of the human anatomy the same effect can be obtained in a great many, perhaps infinite number of different ways. This is known as 'constancy of effect' or 'motor equivalence'.

Generally speaking the question to be answered by the investigator of a particular kind of action pattern is to find out how these possibilities are effectively constrained and how these constraints are effected. There appear to be two major constraining factors. The first is to reduce the number of degrees of freedom, the second is serial order.

(a) *Degrees of freedom*. One of the first questions is how many of the degrees of freedom derive from the task at hand, and how many from the organism. If the system is richer than the task, then there are more ways to perform the same action. Fingerings for musical instruments are a case in point; it is, for instance, possible to produce the 40-odd tones that can be played on a bassoon by means of some 120 different fingerings. Vertebrate anatomy allows a great many degrees of freedom. As an example consider a study by Raibert (1986) which showed that the movement pattern during running is based on an algorithm that keeps net acceleration equal to 0; in other words it leads to constant speed and stable posture. Extensive research has been carried out to determine what motor-coordination programs are active in particular task conditions. This research found its inspiration in the time-honoured principle of reafference proposed by Von Holst and

Mittelstaedt (1950) and in Bernstein's (1967) idea of coordinative structure. These ideas concern the integration of simple actions into a coherent pattern so as to keep the computational complexity of action patterns within bounds. The reafference principle can easily be seen at work if we move our eyes from one fixation point to the other. Some internal mapping function will compute the loci of details in the field of view as they will be projected onto the retina after the intended eye movement has been executed. This results in a stable visual environment, irrespective of the activity of the eyes. If, however, the eyeball is moved passively (e.g., by pressing it gently from one side), no reafference signal is received and the world will appear to be in motion (Wertheim, 1979). Saltzman & Kelso (1987) have carried this idea further by integrating it with the concepts of Newtonian dynamics, considering the body as a complex system of masses and springs. By describing a particular task in terms of motion equations, mass, and force, one generates as it were a competence theory, describing the action pattern without reference to a moving system, viz. the body. The problem then is to find a description of the ways a human body can, in fact, instantiate this abstract representation.

(b) *Serial order*. Thus far we have considered only the description of single actions. Normally, however, behaviour takes place in a temporal context. This brings up the problem of serial order as it was initially formulated by Lashley (1951). In the behaviouristic tradition serial behaviour was thought to consist of context-sensitive chains of elementary actions, or ‘primitives,' each being triggered on the basis of the prevailing situation (Wickelgren, 1969; Estes, 1985). This assumes, in essence, that complex behaviour can be described in terms of a finite grammar. However, the same arguments that Chomsky (1959) used to defeat Skinner's views of verbal behaviour apply in the general case of complex action. Consequently more recent discussions about action involve more complicated, richer structures. These include scripts, or scenarios, extensions of the schema theory discussed in section 3.3.4 (Schank & Abelson, 1977; Schank, 1982). Knowledge is assumed to be stored in memory in the form of scripts or schematized sequences of actions. Thus a script for travelling by train would involve going to the station, buying a ticket, looking for the right platform, and boarding the train. Each of these actions is subdivided into smaller episodes. Buying a train ticket would involve going to a ticket counter, asking for a specific kind of ticket, paying, checking the stated destination, etc. Further refinement eventually leads to more and more automated elementary actions that, unlike the higher level actions are not open to cognitive control and modification (Pew, 1974; Schmidt, 1975, 1982; see also Georgeff & Lansky, 1987).

Schemata for motor activity may be conceived as programs for doing the right thing at the right time. Frequently adaptive behaviour is not so much a matter of deciding what to do, but when to do it (Michon, 1967). Again this introduces the problem of constraining degrees of freedom of action. In this context the human organism has been conceived as an intricate combination of time keepers—clocks and regulators, physiological, mechanical, and cognitive. For any particular activity requiring external or internal timing an appropriate time keeper is set up, selected from the available clocks (Gibbon & Allan, 1984; Michon, 1985; Richelle & Lejeune, 1980). Such time keepers may persist over time, as in the case of the circadian rhythm. For many complex tasks, however, they provide only a medium for temporal adaptation or tuning: their use is entirely opportunistic and they will differ from one person to the other, or even from one occasion to the other in the same person. Here, like in the case of spatial aspects of movement we need to be able to explain how the organism avoids a combinatorial explosion of its behavioural options. Further progress may be in the direction suggested by the work of Jordan (see Jordan & Rosenbaum, 1989) using the independent descriptions of task space and articulation space in the context of a richly connected network, searching for equilibrium. The promising aspect here is particularly the clear distinction that is made between the formal description of the task space, and the implementation-oriented description of the articulation space (see section 2.1.3).

Vera & Simon (1993) have recently tried to relate the cognitive symbol system to the external environment, more in particular to action. This has become known as the ‘situated action’ debate. The first rather vague formulation of ‘situated action’ can be found in Winograd & Flores (1986). In taking sides—somewhat naively—with Heidegger, they reproach cognitive psychology and its computational offspring artificial intelligence for neglecting the real world and the ‘being in the world’ (*Dasein*). Suchman (1987) and Clancey (1993) have followed up on this criticism, by arguing that cognitive psychology has no answer or theory to deal with the interface between minds in the head and actions in the world. The world is dynamic, requires talent for adaptation, is social in nature, and asks for learning capacities. Subsequently Vera and Simon (1993) have countered these attacks by admitting that cognitive psychologists had, thus far

> “[...] brushed over one important point. If the physical symbol system hypothesis is to embrace systems that interact with the real-world environment, then the patterns of motor movements (of hand and feet as well as lips) and patterns of light on the retina or of sound on the ear should be regarded as symbols. [...] The case for regarding sensory inputs and motor outputs (whether they come from computer or human) as symbol structures is that they are patterns and they do denote. [...] One is skilled in hammering when the senses deliver symbols that denote accurately the location of a nail, and the associated motor symbols denote actions that cause the hammer to descend squarely on the nail's head.” (o.c., p.121-123).

Simon acknowledges that the relation with the external dynamic world is a neglected part of cognitive psychology. Action is, indeed, just as much part of the computational approach as is cognition itself and the fact that ready-made answers are not available yet, is no reason to get rid of the symbolic framework. Recent developments in robotics and autonomous systems have, moreover, demonstrated the validity of Simon’s position.

4. CONCLUSION

4.1 Psychology as intelligent behaviour

Psychology, from the perspective adopted in this chapter, deals with the behaviour, broadly conceived, of intelligent systems. As a scientific activity, psychology itself belongs inherently to the class of behaviours studied by psychologists. Consequently a final question to be addressed is whether the theoretical tenets of the computational stance do indeed apply to psychology itself. In other words, to what extent is scientific psychology a computational theory of mind and behaviour in the sense of this chapter. The answer is, clearly, that not nearly all of psychology qualifies as such. The computational approach works by virtue of the fact that it builds representations (models) of mental structures and processes which can be manipulated by well defined operations. Theorists’ concerns, as we have seen, focus on defining computational architectures, subject to constraints that enable these architectures to generate realistic behaviours, while excluding unrealistic behaviours as much as possible. In other words, these concerns closely focus on the decidability issue of computation.

The computational approach, however, does not in principle exclude other possibilities for acquiring valid scientific knowledge about intelligence, although it seems to be, indeed, the only possibility we know to be successful.

To what extent does such a stance disqualify other inroads to the study of mind and behaviour? In so far as theory construction proceeds strictly at the intentional (rational) level—as is the case in much of social psychology, economics, management studies and anthropology—there is no problem. As a matter of fact many theories and models in these realms are computational (e.g., (Carley & Newell, 1994; Oaksford & Chater, 1998).They differ from regular psychological theories and models only in the sense that they refrain from detailed processing assumptions. In this sense they may be conceived as rational or competence theories of complex behaviour (Dennett, 1978,1987). Thus, for instance, the rational man of classical economics and the decision maker of operations research resemble the ideal observer of signal detection theory, or the ideal communicator of linguistics. The point we wish to make, however, is that since psychology should ultimately be dealing not with competence but with performance, theorizing at the intentional level falls one step short of the program of psychology as a science, although it is a prerequisite for such a program.

4.2 Extending the computational view

The strength of the computational approach as a medium for theories about intelligent behaviour is presently being placed in yet another context. The question is here if it is feasible to view natural species as intelligent systems, and if we can therefore apply the computational view to the behaviour of species rather than individual organisms. In other words, is it meaningful to define goals for species, or to ask how they represent their environment, what cognitive processes they employ, or what the constraints are under which these operate?

This approach to “cognitive morphogenesis’ has a tradition going back at least to Von Driesch and Waddington in biology, and Piaget in psychology, but it has been gaining strength during the last decade (Donald, 1991). Schull (1990) initiated a discussion about the question whether species should be considered intelligent. The issue here is whether a theory of evolution of cognitive systems can be based on the computational approach. Can a species be said to search a problem space, and does it do so heuristically? It is not yet clear how far the analogy can be stretched in this case. However, Schull's question could eventually lead to an extension of the claims for a unified theory of cognition made by Newell (1990). Extending the computational approach to this high level of complexity appears a daring exercise, but it is certainly worth trying.

4.3 Semiotics and psychology

The final point brings us back to semiotics *per se*. We have discussed some of the major domains of psychological investigation. For each of these domains one or more plausible computational theories are available. This means that symbol systems have been designed that are rich enough (but not too rich) to express acceptable levels of representation plus a sufficient set of constraints to account for the phenomena in each domain. A question that has not been addressed in detail, however, is what the formal properties are of these symbol systems are, more importantly, whether the symbol systems that have been adopted can indeed do the things they are supposed to do. One such issue that we considered in some detail concerned the formal power of connectionist models. Presumably the level of formalization of psychological theories is still, by and large, not advanced enough to admit such analyses. Theoretical psychology could become more powerful by specifying what features symbol systems must have in order to constitute a computational theory of cognition (or intelligence, or mind).

From our present perspective there appear to be various interesting ideas hovering on the horizon. These ideas or approaches show an ‘adaptation’ of cognitive psychology on the one hand and a deepening insight of the relevance of semiotics for psychology on the other hand. They include the semiotic testing of cognitive theories (Jorna,1990), the evolutionary perspective on psychology and semiotics (Bouissac, 1998; Daddesio, 1995; Cunningham, 1998), a cognitive semiotics (Dölling, 1998) and, finally, a psychology of sign-handling (Jorna & Van Heusden, 1998). We will briefly review these developments.

(a) *Semiotic testing*. A clear step towards a semiotic ‘bench mark test’ for cognitive theories was taken by Jorna (1990) by comparing several prominent cognitive theories, including ACT* (Anderson, 1983), Kosslyn's theory of mental imagery (Kosslyn, 1983), Tulving's theory of episodic memory (Tulving, 1983) and Soar (Laird, Newell, & Rosenbloom, 1987). He compared these theories with respect to three characteristics: the levels of explanation they address for their description of mental representations and symbol manipulation, the extent to which they distinguish propositional, pictorial and episodic information, and the logical (notational) properties of the symbol systems in which they are stated. This approach has resulted in a semiotically well-founded way for classifying cognitive theories, even though it does not yet provide the apparatus to decide which particular combinations of characteristics determine the epistemological (un)acceptability of a theory of cognition. As such, however, it is a distinct step on the difficult road to a semiotics of psychology.

(b) *Evolutionary perspective*. The evolution of cognition and the dynamics of representations (Van Gelder, 1998) are rapidly gaining prominence in psychological theory. Some authors (e.g., Wuketits, 1984; Bouissac, 1998) go as far as envisaging an evolutionary epistemology as the road on which cognitive psychology and semiotics have to proceed: the key concept for both is adaptation, in the sense of the selection of a genetic variation by the environment. For cognitive psychology the ‘functionalist’ question is by what mechanism such adaptation is taking place. It cannot be the biological interpretation, because that involves a cycle of (hundreds of) thousands of years. Consequently it must be dependent on the way human cognition creates, adjusts and transforms symbols. This process already starts with the way children learn to work with increasingly complex sign systems and learn to change these sign systems by their aggregating patterns in actions and perceptions. Daddesio (1995) takes the same route by integrating perspectives of Piaget, Vygotsky and, more recently, Katherine Nelson (1986). We would like to argue that Vera and Simon’s (1993) argument for a slightly modified version of the symbol system hypothesis closely related to ‘situated action’ seems to move in the same direction.

(c) *Cognitive semiotics*. Dölling (1998), after semiotically examining the computational, the connectionist and the ‘situated action’ approaches, proposes a cognitive semiotics. This cognitive semiotics on the one hand has to integrate the various empirical results of cognitive psychology and on the other hand has to integrate the various existing semiotic frameworks. The emphasis of cognitive semiotics will lie in the semiotic analysis of all kinds of signs in media (texts, pictures, icons, sounds, bodily gestures, smell and taste) and its influence on the human representational system. According to Dölling, cognitive semiotics should eventually be theoretical as well as empirical. What direction cognitive semiotics will take, however, is less than clear. Perhaps semiotics will eventually develop into a computational theory *sensu* Marr, underlying cognitive science (see section 2.1.3 above), but it may also turn out that human beings as semiotic systems will prove to be rather different from the information processing systems that figure so prominently in present-day cognitive science (Fetzer, 1990).

(d) *Psychology of sign-handling*: Our future environment may be less prominently physical and become more virtual and representational instead (Jorna & Van Heusden, 1998). On this assumption the relevance of semiotics for psychological research will increase because of the predominance of presentations and representations in such a world. Signs, sign handling and sign understanding are essential constituents of this new environment. Although we are familiar with the fact that we have internal representations, the outside world is also becoming more and more a *digital* world. The way humans, *qua* information processing systems, interact with ‘natural’ environments will be different from their interaction with ‘representational’ environments. Two problems may illustrate what we have in mind. In the first place, many people are currently complaining about information overload. Apparently they are forced to process too much badly structured information in very little time. The question is therefore how can we select relevance in the representational devices at our disposal, the ‘semiotic’ interface, rather than in our own information processing system. As a second example consider the automatic ticket-buying machines (for example for buses or trains) and telephone devices that handle questions of people to be informed require fast and precise actions. Many people have problems in correctly operating these devices and they often are the cause of frustration. Both questions have been central to the concerns of applied psychologists, ergonomists and industrial designers for many years. But, since the information overload and mismatch may indeed be the result of design mistakes concerning hardware and of misunderstanding user possibilities and limitations, it seems relevant also to consider the semiotic aspects of the human-device interface. This may help in explaining and designing novel forms of representation that support optimal semiosis. Interestingly, such new research questions appear to be in sight. These include questions about what forms of semiosis will occur in a virtual reality or a virtual community; what are the effects of different sign structures on various kinds of ‘intelligent’ behaviour; what are the logical and empirical relations between information processing, knowledge, semiosis and meaning; what other kind of tools can be developed to analyze and judge emerging sign structures; does the cognitive architecture itself has a semiotic nature; what equipment, devices and designs are excluded from semiotic analysis and why; how can abduction be implemented in artificial devices and are these devices semiotic in nature? In all these questions psychological research may be stimulated and guided by a semiotic framework.

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