This is particularly important when we consider the apparent

dual characteristics of cognitive systems. This could, as Sim-

elevsky implies (section 7), be modeled teleologically at the

conceptual level (e.g.; the program could explicitly refer to the

current state of the system to a specific future state). But not a

simpler model (section 11), which is in the same sense reducible to

the sleep state (see Gourley 1958) and the mind, as an evolved

entity, must be viewed at the subconceptual level as teleologism.

(H 89 M p. 6) rather than teleological. An

important strength of the subconceptual approach is that it
could explain the "emergence" of, for example, goal directed-

ness at the conceptual level in terms of subconceptual compo-

nents, the gradual and piecemeal evolution of which would be

relatively easy to understand.

There are two summaries of an evolutionary point of view

which are relevant to the construction of subconceptual models.

The first is that a neurologically consistent subconceptual model of a

complex cognitive process could (should) be built by elaborat-

ing models of simpler processes (inferring evolution). The second is

that at each stage of additional complexity the current

model should be viable in terms of the constraints facing the

simpler models (inferring the development of the nervous

system).

Construction of a model of a subconceptual model of human

cognitive processes would be difficult even if the cognitive

processes were better defined than they now are. But our

knowledge of the structure of the nervous system, which Sim-

elevsky derives as being irrelevant for cognitive modeling, shows

that the brain develops by additions to relatively less changing,

phylogenetically older parts of the system. Whatever the

changes in the emergent properties of the network at each

addition, the subconceptual description of the functioning of the

phylogenetically or developmentally early parts of the system

are unlikely to change greatly. While available data on the

dynamic behavior of human neurons during cognition are

such as to better model building, the same is not true of simpler

organisms or more peripheral parts of the brain. Thus neural

data can be critical for subconceptual (but not conceptual)

models. In particular, subconceptual models of simple neural

systems (where dynamics may be determinable) should be seen

as valid precursors to subconceptual models of more complex

neural systems.

The subconceptual architecture of simple systems (locally

unlike their conceptual architecture) could also provide useful

models for the subconceptual architecture of complex systems.

For example, once the principle and the general telemetry

of "purpose" of lateral inhibition is understood for the receptor

level of a sensory system this not only transfers to the receptor

levels of other sensory systems but also to the higher levels of

the original system. Of course, Smolensky argues (section 2.5)

that perception is exceptional in the extent to which neural

analogies are used. But consider a second exceptional case -

motor control. Current neural models of the cerebellum (e.g.,
Pelisson 1979) border on the subconceptual. The control of

motor activity can be viewed as depending on an "integrated

movement vector" (Linus & Simpson 1981) which is, in effect, a

motor command specified with respect to a sensory coordinate

space. The feedback inherent in this idea is virtually identical to

that embodied in the stretch reflex but the end result is a simple

form of goal direction. As with models of sensory processing,

then, models of movement generation can be built by adding

onto lower order models control processes which have a very

similarity architecture at the neural or subconceptual level but

which generate markedly different consequences at the concept-

ual level.

The unexpected emergent powers of appropriate parallel

neurose net or subconceptual networks, and the extent to

which nature seems in practice to repeat the same tricks at

different phylogenetic levels, suggest that we would not be unac-

table to try to relate subconceptual to neural architecture

directly at this time. Smolensky describes a network which

produces the effect of a schema by settling into a particular final

state on the basis of a specific input and differential connec-

tions. Between modes of the network. A simpler network using similar

connections can solve the global stereopsis problem and settle

into a final solution in a way very reminiscent of one's own

perceptions on viewing global stereoscopic images (see Frisby

1979, p. 150). It is reasonable to search for the neural instanti-

ation of the equivalent of the latter network when found, its exact

form may well have important implications for subconceptual

models such as Smolensky's subnetwork one.

There is an implied scientific connection here between the

neural and subconceptual levels: The subconceptual model can

incorporate neural neurologically general features and, then, through its

capacity to demonstrate a solution to a particular problem at the

conceptual level, can drive the neurophysiologist to look for the

neural equivalent of its components or general dynamics -

dynamics which would have had no meaning in the absence of the

subconceptual model. Thus, Hebb's (1949) subconceptual

speculations about association led physiologists to look for

"Hebbian" synapses - and to find an approximate equivalent in

the hippocampus. This in turn has led to an account of the

hippocampus as a distributed memory system which depends

on the known properties of particular subconceptual associative

systems (McNaughton & Morris 1987).

I believe, therefore, that subconceptual models of cognition

and schemata should use an architecture related to current

models of perceptual systems and that subconceptual models of

goals, intentions, and similar ideas should use architecture

related to current models of motor control. A corollary of this is

that larger subconceptual models should have features which

are consistent with the general architecture of both sensory and

motor neural models. Subconceptual understanding of cogni-

tion may even turn out to be a natural consequence of designing

a single formal system which encompasses our current general

understanding at the neural level of both perception and motor

programming. Available neural information may be highly sug-

gestive even when a direct link to sensory or motor systems is

not possible, as in the specific instance of subconceptual models

of working memory and the known dynamic properties of the

hippocampus.

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NOTE

1. Teleonomy represents purpose in the sense that the eye has the

purpose of seeing (Moor 1974, p. 38). That is, the form of the eye is

limited by the laws of optics and the progress toward advantage

conferrd by small changes in the quality of light sensitivity. However,

teleonomy at no point implies teleology. The eye is merely a conse-

quence and not a goal of evolution.

The psychology of connectionism

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Smolensky (1988) offers a well-reasoned overview of connectionism that helps

guide us in this particular chapter. He settles into a level of description between

the symbolic and the neural - what is in any view an information-processing

level. This is exactly where connectionism belongs; nor is it without much

company at this level. An intermediate level of description is what psychology

has been seeking since, for example, Helmholtz, Donders, and James. In this light,

connectionism is an alternative to symbol systems and modularity, but not to the

information processing systems we're concerned with in this chapter.
Continuing Commentary

mation-processing paradigm. One goal of this commentary is to evaluate several properties of connectionism with respect to the information-processing paradigm currently in use in psychology, and to mention a few precedents of the connectionist approach. Connectionism gives me an appreciation of a continuity of theory development in psychology during the last century. I will conclude with some limitations of current connectionist models as psychological models of mind and behavior.

Evaluating connectionism. Connectionism shares several attributes with information processing even though the primitives and currency of connectionist models are often presented as different from more traditional information-processing models. For example, connectionism has been referred to as parallel distributed processing. However, neither parallel nor distributed appears to be a necessary or sufficient characteristic of either paradigm. Information processing and connectionism contain both parallel and sequential processing. Parallel processing refers to the simultaneous occurrence of two or more processes. Sequential processing exists when one process is dependent on the output of another. Traditional information-processing models have assumed that feature analysis of letters occurs in parallel, and letter recognition is dependent on the output of the feature analysis (e.g., Selfridge's 1959 seminal pantomaton model). In information-processing models, certain processes are assumed to be sequential; for example, a short-term memory search might not begin until the test item is recongnized (Sternberg 1975). There is also sequential processing in connectionist models in that top-down activation of lower-level units might not occur until lower-level units activate higher-level units (Anderson et al. 1977).

Local versus distributed processing does not appear to be a characteristic that distinguishes information processing and connectionism. In connectionism, local representation corresponds to the case in which information about a pattern is stored in the connections of a single unit reserved for that pattern. Distributed representation refers to the information about a pattern being stored in the interconnections of a large number of processing units. The local versus distributed distinction in connectionism parallels the earlier distinctions in information processing between template matching and feature analysis (Neisser 1967) and between feature and code theories of memory representation (e.g., Schvaneveldt & Meyer 1973). Template matching places all the information about a pattern within a single representation whereas feature analysis distributes the information across several representations. Local representation of some concepts exists when all of the information about the concept is represented in a single location, whereas a distributed representation would be distributed across several locations or not located in one place. Selfridge's (1959) pantomaton model also qualifies as distributed because a letter is represented in terms of the features that make up the letter. A distributed model might also represent structural relations among the features (Oden 1970). Local connectionist models have been described, and others contain some local characteristics such as the local representation of the letter in NETTalk (Sejnowski & Rosenberg 1986). It has been proven that a class of distributed models can be mimicked by local models, which perhaps blurs the local-distributed distinction (Sejnowski 1986). It should be stressed that I am not discarding the local-distributed distinction; the thesis is that the distinction is not new and does not differentiate connectionist and information-processing paradigms of inquiry.

Although the processing is assumed to occur among neural-like units, I agree with Smolensky's thesis that connectionist models are not necessarily neural models. If connectionist models were psychological models, then the appropriate test of these models would be at the level of physiology and not at the level of observable behavior (von Mises et al. 1986). However, the current state of the art precludes any tests of connectionism at the neurophysiological level. For example, Marr (1982) a neurobiologist, believes that evaluating the neural bases for phenomena such as word superiority effects is outside the purview of current electrophysiological methods. Connectionist models have been used to explain behavior at a functional level of description by assuming processes analogous to those occurring at a physiological level. This form of explanation is not new. Thorndike (1929) rejected cognitive explanations of cats learning to escape a cage in favor of a neurological explanation. Thorndike's explanation actually assumed that learning resulted from connections being established between neurons. More recently, the feature detectors for letters has been viewed as instances of neural units investigated in electrophysiological research (e.g., Linsley & Norman 1972). Models are metaphors and connectionist models are only less obviously metaphors because the metaphor is glanced neurologically rather than psychologically (Churcher & Grudin 1975). If models are formulated in a connectionist paradigm using "neurological" terms, they might not attract the analytic scrutiny necessary for precision, systematization, and empirical evaluation.

I am impressed by the great affinity between connectionism and stimulus sampling theory (Estes 1950). The latter views behavior in terms of the association of responses and antecedent stimulus events. Association refers to a connection between a stimulus and a response. As Estes (1952) points out, psychological terms such as perception and memory were inadmissible at that time and, strictly speaking, my guess is that reference to anything inside the black box was outlawed. Thus, the connections were established and modified between observable elements such as stimuli and responses. With the "cognitive revolution," it became acceptable to refer to events in the black box, but there events remained at the same functional level as those in behaviorism. Now connectionism offers the hope that the functional level can be replaced by the neurological level, but my belief is that connectionism can be tested only at the functional level and must therefore be evaluated at that level.

In current implementations of connectionism, learning can be simulated by changing the weights of the connections between the neural units. The same outcomes could be implemented in a variety of other ways, as acknowledged by connectionist theorists (Hummel et al. 1986). Rather than modifying existing connections between units, changes in performance might be supported by establishing new connections. There would be some probability of establishing these new connection between units that are active at the same time. This simple learning rule could be formalized to produce mathematical predictions equivalent to those of stimulus sampling theory (Estes 1950). What is important is to note for our purposes is that the several neural possibilities do not appear to inform functional explanations of human performance. Although Thorndike (1898) remained a connectionist throughout his long and productive career, he abandoned the neurological part of his theory (Hilgard 1987). Similarly, current assumptions about neural processing in connectionist models might meet the same fate as the "ether" that was assumed to be the medium of light-wave propagation (Frisbie 1986). The mathematics of light-wave propagation did not change with the demise of the "ether," and some of the mathematics of connectionism might remain with fundamental changes in the current assumptions about neural functioning.

In information processing, we ask to what extent one input system is influenced by processing from another input system or to what extent information from one stage of processing is communicated to another stage of processing. Analogously, information processing addresses the question of the extent to which separate operations must be postulated to describe the relationship between perception and action. In the classic example of signal detection theory, it was necessary to assume separate sensory and decision stages of processing as opposed to simply assuming a direct mapping between stimulus and re-
Continuing Commentary

want. Connectionist models, on the other hand, have blurred
the distinction between sequential operations or states of pro-
cessing. They tend to assume a direct mapping of connections
between inputs and outputs. The assumption of sequential
stages of processing appears to be necessary for mapping
categorical information into action, even in connectionist models.
The sensory input features are not sufficient to determine
the appropriateness of responses. For example, visual features
of the letters do not predict the pronunciation as well as the
latter names do (e.g., coperis).

Sensitively it makes clear that connectionism offers an alter-
native to the physical-symbol-system paradigm (see also Douth-
te and Plato 1986). The latter often uses symbols to embody
sensory experience and project symbolic representations
involving categorization, familiarity, memory strength, and
even activation and inhibition among representations. In fact,
Massaro and Cohen (1987) pointed that a specific connectionist
model with only input and output layers is sometimes mathem-
atically equivalent to a specific process model called the fuzzy
logistic model of perception (Massaro 1987).

Connectionism also contrasts with the fundamental principles
of modularity (Fodor 1983; Gardner 1985). Modularity has its
basis in the assumption that the so-called decomposition assumption
as in information processing. Complex behavior can be decomposed into a
variety of simpler processes, and these processes might be further
decomposed into yet simpler processes. The strong claims of
modularity involve the lack of communication among input
systems and the impossibility of a functional "middle-level"
representation of cognition. Modularity assumes some isolation
among processes because input processes occur relatively inde-
pendently of one another. Although the modularity assumption
is not inconsistent with information processing, it is inconsistent
with the high interconnectivity among the units from the ear-
liest until the latest processing in connectionist models. Both
modularity and connectionism make assumptions that are con-
sidered empirical questions within the information-processing
paradigm. Given this observation, the issue concerns not
whether connectivity or modularity is the better descriptor of
human performance and task. However, the paradigm of in-
formation processing dictates an empirical test between these
alternatives.

Constraints on psychological inquiry. It is important to con-
sider three constraints on psychological inquiry. First is that
the phenomena of interest are highly complex, but they do not
necessarily constrain psychological boundary (Massaro & Secord 1985).
For example, the acquisition of the basic tone is a highly
complex affair and can be loosely described by the categorically
opposed native-based and instance-based theories. A second con-
straint on psychological inquiry is that scientists have a confirma-
tion bias and seek to generate reality to support their pet
theory (Tversky et al. 1981). The third constraint on psychological
inquiry is that there is a plethora of different theories for the
phenomena of interest. As made transparent by the history of
specific phenomena (e.g., memory search and progress in
mathematics psychology, there are many ways to explain or
describe a particular observed phenomenon.

Strategies for psychological inquiry. Faced with these three
constraints, what are the implications for psychological inquiry?
In my view, four strategies can overcome these constraints.
First, it is necessary to develop highly simplified experimental
studies in order to reveal fundamental regularities or laws
related to the phenomena in interest. These regularities or laws
cannot be tested in highly complex situations. A complex exper-
imental setup is influenced by multiple causes, the regularities of
each will not be easily disentangled. The second strategy for psychological inquiry is the requirement to test
between alternative models of performance using the research
strategy of falsification (Popper 1959) and setting limits (Platt
1964). The investigator is required to develop opposing models
and to devise an experiment that tests the differential predic-
tions of these models. Simply comparing existing evidence that is
consistent with a given model is not an ideal strategy because
the data might be equally consistent with a diametrically op-
opposed model. Third, it is necessary to carry out inclusive
experiments and to perform a fine-grained analysis of the results
to distinguish among competing models. Only by thorough,
systematic, and single-minded analyses can an investigator elimi-
nate alternative models. Only this elimination will reduce the
set of models consistent with the observations of human
performance.

Good scientific inquiry dictates that we avoid actively
attempt to eliminate alternative models. Given the power of
physical systems and connectionism, however, the ob-
served data often fail to be sufficient to decide among alter-
native models. The fourth strategy is that only discriminating
models are permitted to survive. To be discriminating is to predict only
the actual results, not the universe of possible results. The
investigator therefore eliminates not only observed results but
also a range of potential results that do not necessarily occur.
Collier (1985) has made a significant point that although a more
complex model might be more accurate than a less complex
model, the more complex model should not necessarily be
preferred. The more complex model would be less preferable if it
also predicted results that did not occur.

Empirical tests of connectionist assumptions. Taking the task
of non-trained tasks, I tested the assumption of interactive
activation (i.e., two-way connections between units) of specific
connectionist models (Massaro 1986, submitted). Interactive
activation was shown to be both unnecessary and inconsistent
with empirical results. Both the interactive activation model of
written word recognition (McClelland & Rumelhart 1981) and
the TRACE model of speech perception (McClelland & Elman
1986) have been falsified (Massaro 1986, submitted), which
tests against human performance. Interactive activation is not
necessary to account for the integration of multiple sources
of information in language processing. In addition, interactive
activation is inconsistent with the finding that the representa-
tion of bottom-up information remains independent of top-
down context. This research demonstrates that it is possible to
test assumptions of specific connectionist models in the same
way that assumptions of information-processing models can be
test.

Superpower of hidden units. I have used the fourth strategy to
assess connectionist models with hidden units. As anticipated
by Minsky and Papert (1969) in their critique of perceptrons
(Amendt 1986), connectionist models with more than two
layers of units might be too unconstrained to be informative.
Models of this type might be Turing-equivalent that are capa-
bles of mimicking any computable function. As previously
formulated, many of the connectionist models with two-way
connections among different levels of units and connectivity among
units at a given level appear to be too powerful (superpowerful).
They appear to be capable of predicting not only observed
results but also results that do not occur (Massaro 1985; 1986).
I have demonstrated that some connectionist models simulate
results that have not been observed in psychological investiga-
tions and results generated by incorrect process models of
performance (Massaro 1985).

Both the framework of psychophysics specifying the envi-
ronmental characteristics used by subjects and information
processing specifying the processing these characteristics under-
derstand are necessary for progress in the field. Apparantly,
Level of analysis is not a central issue

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In Smolensky’s (1988) thoughtful and stimulating essay and the accompanying commentary, a major emphasis is placed on the importance of the level of analysis for a “proper treatment of connectionism” (e.g., section 2.3). Specifying the level of analysis at which one is working is certainly important. However, it is largely irrelevant and even misleading to identify the fundamental differences between connectionist models and “traditional” models in engineering science and artificial intelligence and their respective contributions. The salient distinction presented in more detail elsewhere (Reggia, 1988) lies in the nature of the information processing involved.

1. Connectionist networks are self-processing. Traditional AI-like models typically consist of a passive data structure (connectionist network, sensory apparatus, etc.), which is manipulated by an active external processor/procedure (oblivious inference mechanism, rule interpreter, etc.). In contrast, the nodes and links in a connectionist model are themselves active processing agents; there is typically no separate external agent that operates on them, either during “problem solving” or during network modification (self-organization).

2. Connectionist models exhibit global emergent systemic behaviors derived from concurrent local interactions of their numerous components. The external process that manipulates the underlying data structures in traditional AI-like models typically has global access to the entire network’s state, and processing is strongly and explicitly sequentialized (e.g., conflict resolution in rule-based systems).

These restrictions hold regardless of “level of analysis.” The two approaches are sufficiently distinct to permit substantive analysis and comparison. Smolensky’s “proper treatment of connectionism” almost equates connectionist models at the sub-symbolic/supraconceptual level with connectionist models of relevance to cognitive science in general. In contrast, the viewpoint offered here, connectionism as well as traditional models, are both example systems that are potentially relevant at all levels of analysis.

To see this, it is useful to consider an example where both a connectionist model (Peng & Reggia, 1989; Wieland et al., 1988) and a traditional model (Peng & Reggia, 1989) have been developed at the same level. The specific task is to learn a simple, two-input two-output model. Both models are trained with back-propagation and tested on the same data. Despite being at the same level of analysis, however, the two models can be distinguished by features (1) and (2), described above. This provides a clear counterexample to the claim that level of analysis is a fundamental distinction between connectionist and traditional models.

This observation also bears on the distinction between sub-symbolic connectionist models and neural network models. Smolensky and others have correctly emphasized that a sub-symbolic cognitive model is not necessarily a neural model. But holding this emphasis primarily on the level of analysis confuses rather than clarifies the role of connectionism in mind and brain modeling. For example, consider the statement that “the sub-symbolic level of analysis is higher than the neural level” (Smolensky, 1988, p. 10, point 1). The sub-symbolic level is part of the “supraconceptual, conceptual, subconceptual, sub-mental” . . . ” that describes nondisjunctive cognitive mechanisms. Neural systems involve a corresponding list of brain-center-pathway . . . cell group, individual neuron neurotransmitter . . . ” that describes biological mechanisms. Smolensky (section 4) appears to suggest that there is only one poorly-identified level of connectionist modeling relevant to neural systems. In contrast, the viewpoint presented here is that there are many levels at which connectionist models of brain function can be conceived, how they correlate with the levels of connectionist models of cognitive mechanisms remains to be determined at all levels. For example, neurologists often analyze patients in terms of a “connectionist model” at the level of abnormal “centers.” The brain is viewed as consisting of various . . .