Understanding Cognition through
Synthesis and Analysis

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Abstract. This article discusses the interdisciplinary research area of cognitive science. It presents methods and approaches to investigating cognitive processes. Spatial cognition as a subfield of cognitive science is used to show how mental processes are connected with the physical realm through perception and action. These bridges between physical and mental permit a variety of rather distinct approaches that contribute to the investigation of the cognitive processes involved. Particular attention is given to the role of artificial intelligence approaches to help discovering cognitive processing principles. The article discusses the interplay between synthetic and analytic approaches to cognitive science and emphasizes the complementary strengths of these approaches. It shows how the environment, the context of the specific situation, and the task can reduce the cognitive effort to be taken. The trade-off between general abstract representations and specific concrete representations is shown. The power of virtual environments for testing and understanding models of cognition is demonstrated. Numerous examples are given.

Key words: cognitive science; spatial cognition; synthetic approach; artificial intelligence; knowledge representation; virtual reality; empirical studies

1 Introduction

Cognitive Science is concerned with information processing in humans, animals, or robots, jointly called cognitive agents.

Spatial cognition is concerned with cognitive agents in space with the nature of that space (spatial environment), and with the knowledge of the agents about their spatial environment (knowledge representation). This article describes how Artificial
Intelligence (AI) research makes use of empirical findings from field and laboratory studies on cognition; I will show in which ways AI approaches can be useful for researchers designing empirical studies with human participants in the field or in the laboratory. In essence, I will argue that AI provides the missing link between empirical research and theoretical models that will help to understand the functions of cognition. I will use examples from spatial cognition to illustrate my points; this does not mean, however, that the arguments are restricted to spatial cognition.

2 Cognitive Science – a Brief Sketch

Philosophers have been interested in questions regarding the nature of knowledge and thought at least since ancient Greek times (e.g. Socrates, Plato, Aristotle). During the last centuries, insights into the physiology of thought processes (e.g. Refs. [9, 12]) provided a foundation for the study of perception and for the systematic investigation of human behavior. Many insights into the psychophysics of perception and the anatomy and electrophysiology of the nervous system were acquired during the last two centuries (e.g. Refs. [14, 40]). Psychology moved from the observation of stimulus-response behavior to the functional explanation of cognitive processes[53]. At the same time, linguists developed an interest in the structure and the semantics of language (e.g. Refs. [15, 31, 32]), neuroscientists and computer scientists started to understand neural circuitry on the cell assembly level[26,39,46], and cognitive anthropologists and ethnologists investigated characteristics and differences in the conceptualization of the world in different cultures[3,54,34].

Philosophers in the field were interested in fundamental issues of thinking, for example the mind/body problem[12], the possibility of the existence of an ‘artificial intelligence’[47], or the existence of a free will[45]; the empirical disciplines observed and described relationships between physical, psychological, or social situations and people’s response to them, each with their particular research agenda in mind; AI developed models for problem solving and decision making[36] and built systems for automated reasoning (e.g. Ref. [49]) and machine learning[35].

Deep human desire to understand the nature of cognition over centuries combined with human reasoning power did not suffice to get a handle at the mysteries of cognition; it required the availability of computers as artificial brains and of problem solving paradigms from AI as artificial minds to bring together the more traditional disciplines that investigated various aspects of cognition. The new interdisciplinary research area cognitive science was established in the late 1970s[38].

Why did it take the formal and technical discipline of AI as a catalyst for a joint interdisciplinary search for the understanding of cognition? The reason is that computers and computation provided a suitable metaphor for cognition that all the disciplines involved could relate to. The fact that computers are concrete devices that perform specific functions in a primitive way helped establish a reference language that is anchored in accessible technological artifacts. In addition, these dull machines that appeared to perform similar functions as human minds provoked humanists and religious people who took it for granted that thinking and intelligence are exclusively reserved for human kind[13,47,51]. This provocation combined with shared concepts of intelligent behavior created an excellent foundation for exciting debates and scientific
investigations into the nature of cognition and the notion of intelligence.

Computer scientists understand the principles of computers and AI programs as they have synthesized these artifacts from elementary building blocks, whose basic functions and interactions are well understood. On a certain level of abstraction, these building blocks and their functions sufficiently resemble the substrates of natural cognitive processes (neurons and neural networks) that we can treat them as replicas of their natural role models. This level of abstraction has been identified as the level of information processing which forms the common ground for cognitive science. In their Physical Symbol System Hypothesis (PSSH), Newell and Simon hypothesized that intelligence is the work of symbol systems. Stated more formally, the hypothesis is that a physical symbol system has the necessary and sufficient means for general intelligent action. Essentially this means that intelligence of any sort can be implemented on a symbolic computer, in principle. Such a computer implementation would not only simulate intelligent behavior (weak AI) but it would actually generate true intelligence (strong AI).

The computer-inspired PSSH put forward by psychologists and AI pioneers provided a level of abstraction and provocation that would stimulate rather different disciplines to contribute. Philosophy of mind had been discussing thought processes in terms of abstract symbols for quite some time; viewing symbols as physical entities on one hand and adding a symbol processing model (the computer), on the other hand, has made philosophical theories testable. The language of computer components and operations has become available that allows us to question concepts like ‘intelligence’ or to refine the notions behind such concepts.

In the 1980s, the focus of interest in cognitive processing shifted from the symbolic level of computation to the sub-symbolic level, from toy examples to real-world applications, and from explanation to performance. The embodiment of the computational process and the interaction between body and environment were recognized as more urgent issues than the question of the epistemological status of representations. Nevertheless, as sub-symbolic embodied computational processes are still implemented on symbolic computers, the Physical Symbol System Hypothesis has not yet been abandoned through alternative explanation models.

Productive research paradigms provide substantial overlap with existing theories; but they must be provocative and must leave space to be refuted. Some researchers were annoyed by the strong claim expressed in the Physical Symbol System Hypothesis and/or sensed a degradation of the special status of human beings. Thus, research was initiated with the goal of disproving the validity of the hypothesis. This led to a more refined view on notions like ‘intelligence’ and helped enhance the mutual understanding of different research communities considerably.

Psychology, linguistics, and cognitive anthropology are able to express concepts and notions in terms of formal symbols and their relations; these can be directly transformed into corresponding notions of the computer metaphor and tested procedurally by means of running computer models. These models inevitably will exhibit differences in behavior in relation to their natural counterparts. Differences between the new artifacts and their natural role models open up interesting new areas for further research into the nature of cognition.
3 Spatial Cognition

In the context of interdisciplinary cognitive science, spatial cognition is of interest in at least two different ways: (1) from an empirical and an analytical perspective, spatial cognition is concerned with the ways in which humans, animals, or machines ‘think’ about real or abstract space; space is here an object of cognition; (2) from a formal and a synthetic perspective, spatial cognition is interested in the ways in which spatial structures can be employed to represent and realize cognitive processes; space is viewed here as a means of cognition.

The first perspective considers cognitive agents, how they interact with their spatial environment, how they localize themselves in space, how they localize other entities in their spatial environment – independent of the internal structures and processes that may be involved. The second perspective is concerned with implications of the fact that cognitive agents and their internal processes are immersed in spatial structures and are themselves spatially structured.

As a consequence of the immersion of cognitive agents and their information processing structures in space, spatial structures in the environment must be in some way reflected in the spatial structures of the cognitive agents – otherwise they could have no knowledge about their environment. These internal structures are of particular interest to neuroscientists, cognitive psychologists, and AI researchers. The role of the internal structures has significant implications for the cognitive processes operating on the agents, including perception, reasoning, interaction through language and gestures, and actions in space.

Spatial cognition is a particularly interesting domain for the study of cognitive processes, as many spatial concepts are grounded in physical structures – this is not necessarily the case for more abstract concepts. As a consequence, we can employ rigorous scientific methods to physically, mathematically, or logically validate our theories when we apply them to concrete physical environments. The challenge for AI then is to establish adequate correspondence relations between abstract spatial concepts and concrete spatial environments as well as representations of these concepts and computational procedures that operate on them.

Thus, although spatial cognition is concerned with mental processes, it connects the mental realm with the physical realm. This is done by means of perception processes on one hand and by means of action processes, on the other hand. Interactions (e.g. by language or gestures) between cognitive agents involve both, perception and action processes (e.g. Ref. [56]).

Perception organs (or technical perception devices) transform specific physical stimuli into more general information signals. Although these signals still have a physical nature, they are dealt with on a more abstract information processing level (the physical substrate then becomes arbitrary). For actuators (e.g. muscles, glands, and motors) transformations take place in the reverse direction: physically insignificant information signals are transformed into physical actions of a specific modality, where the physical substrate matters.

In other words, perception organs and actuators act as interfaces between the physical and the mental worlds. They illustrate that the transition from physical to mental need not be reflected in a transition from material to spiritual; the important point is that different aspects of an entity are relevant on the physical and on the
mental level, different abstractions is what counts (cf. Ref. [18]).

As representation of knowledge is a central theme in cognitive science and knowledge is information about the world, suitable abstractions from the real world for reasoning about this world are of central interest for psychologists and AI researchers in cognitive science. Studying abstract representations of concrete entities is particularly appealing as we know quite well what is required to solve tasks in the concrete physical world; learning about abstraction principles in a concrete (i.e. spatial) domain that we know much about should help us develop suitable representations for more abstract domains later on.

4 Empirical Studies on Natural Cognitive Systems

Natural systems provide existence proofs of functioning cognitive mechanisms. Such existence proofs are suited for rejecting pessimistic hypotheses regarding cognitive functions; these hypotheses may result from theoretical research that uses specific assumptions which are useful from a formal point of view but not adequate from a cognitive perspective.

For example, complexity theory – a subfield of theoretical computer science – teaches us that the computation of an optimal solution of a wayfinding problem requires ‘exponential time’; this means, the amount of time required for solving the problem increases exponentially with the size of the problem. An empirical study, on the other hand, may tell us that humans find an answer to a complex wayfinding problem more quickly than this theory would predict\(^4\). This discrepancy raises the question whether natural cognitive systems transcend the theoretical limits determined by complexity theory or whether there are simpler explanations, e.g. the theory may be wrong, the empirical results may be invalid, theory and empirical investigation may have considered different problem-solving tasks – or at least different conditions under which the task has been carried out. Most likely, certain assumptions about the problem are wrong – for example, the assumption that the solution to the wayfinding problem must be optimal\(^5\).

Now assume the empirical investigation showed that the participants of a study actually produced optimal solutions. Does this finding justify the assumption of an optimal wayfinding procedure? By no means. The natural cognitive system under investigation may merely have been ‘lucky’ in finding optimal solutions – this does not imply that the procedure used guarantees optimal solutions.

There may have been good reasons though why our cognitive system found high-quality solutions even without an optimal algorithm: the representation of the spatial environment and the cognitive processes operating on them may favor good solutions for other reasons; alternatively, the particular problems to be solved by natural cognitive systems may make it particularly easy to find good – or even optimal – solutions. In other words, the structure of our particular problems may not require a generally optimal procedure; a simpler – and more efficient – procedure may suffice in our specific problem domain. Thus, the empirical findings may guide us in identifying suitable specialized representations and procedures that may be cognitively more adequate than those developed by purely theoretical considerations.

Proof-of-concept studies need only one instance that demonstrates a certain
principle; they do not require statistical evaluations over populations of cognitive agents. Case studies of cognitive performance actually may provide a clearer picture of the specific representations and procedures an individual cognitive agent employs. Unfortunately, the value of case studies is not generally appreciated in the empirical sciences, as there has been a traditional interest in ‘normal behavior’ rather than in the mechanisms underlying cognitive functions that may lead to rather diverse high-level cognitive procedures and decisions.

AI researchers in cognitive science, on the other hand, are primarily interested in studying specific capabilities to understand computational and cognitive principles; it is only of secondary interest how these capabilities distribute over agent populations. Empirical case studies could provide valuable information for modeling and understanding cognitive principles and for understanding the origin of individual differences in cognitive processing.

5 Formal Theories and Abstract Models

Formal theories allow computer scientists to derive answers to certain questions much more effectively and efficiently than other methods do. In particular, formal methods serve to investigate the soundness of models (will the model only produce correct answers?) and the completeness of models (will the model produce all answers?). In addition, formal theories are used to investigate resource requirements of computational procedures: how much memory and how much time does a given process require? How do these requirements vary with various parameters? What is the worst-case performance of a given process under adverse conditions? What is the average performance under typical conditions? Formal theories also can provide important insights into the crucial cases to be tested and thus help reduce the empirical effort required.

The formally derived answers to the questions concerning the computational properties relate to the internal structure of a given model; they cannot respond to questions about the cognitive adequacy of the model. They can, however, point to crucial issues that can be tested empirically. For example, if a computational model predicts that it will take four times as long to solve a given wayfinding problem than it would take for a problem with only half the number of decision points, then we can empirically refute or support this model by confronting people with the respective problem and measure the time they need to determine the solution.

We can prove models to be wrong by refutation, but we can never prove a model to correctly explain a cognitive mechanism by confirmation; there may be a large number of alternative models that exhibit the same behavior. We can only support the plausibility of a model through confirmation. In general, the simplest model that is consistent with empirical findings will be preferred as long as there are no good reasons to believe that a more complex model is needed\cite{43}. As a refutation of a hypothesis is stronger than a confirmation of a hypothesis, it is scientifically more rewarding to formulate ‘risky’ hypotheses, i.e. hypotheses that are not bound to be true but which carry a potential for being refuted\cite{42}.

The rigor required by formal theories and models frequently helps to sharpen the awareness of factors that are easily overlooked in informal models. Formal theories and models also allow hypothesizing cognitive performance under extreme conditions
that cannot be easily observed empirically. In interaction with empirical studies, formal theories help provide hypotheses about the dimensions and degrees of freedom of a cognitive system and about their interrelationships. Formal models of cognitive systems help to develop theories that can be tested according to the standards of the natural sciences.

6 Simulation in Virtual Environments

Once an abstract model of cognitive processes appeals to us on the basis of its formal properties, we may want to know how an implementation of the model actually performs. Paper and pencil investigations can tell us about desirable static properties; however, cognition can not be adequately described in terms of static properties, as it involves complex dynamic processes, and the limited human imaginative capabilities usually do not permit us to foresee all implications of a model describing complex processes; we seem to be cognitively biased to conceive of one or very few possible interpretations of a model, neglecting other alternatives (‘preferred mental models’ – Ref. [29]).

AI researchers like to implement their models in a ‘running’ computer program and observe the compounded effects of the intentionally provided formal properties in order to overcome limitations in the human interpretation of formal models of cognitive processes. For problems of spatial cognition, for example, this means that we must run our programs in spatial environments. As this may be difficult to do, we also may have to simulate spatial environments, i.e., we design formal structures that are supposed to behave like physical space when cognitive processes interact with them (‘virtual spatial environments’). We now can investigate spatial cognitive processes in simulated action. We can compare the behavior of simulated cognitive agents with the behavior of the original cognitive agents that we modeled and we will discover that our cognitive agents exhibit behavior that was not foreseen or intended.

As we know the architecture of our simulated cognitive agents in detail, it is not very difficult to analyze and explain the reasons behind the observed behavior and to improve the model to get closer to the desired behavior.

7 Artificial Cognitive Agents in Physical Space

A simulated virtual environment is not the real physical spatial environment. As in the case of the artificial cognitive agent, only the obvious and well-understood properties of the real spatial environment will have been conceptualized and implemented in the virtual environment. The challenge for a spatial cognitive agent will be the confrontation with the physical spatial environment itself. This requires that we connect (or ‘interface’) the cognitive model of our agent with the physical spatial environment.

Interfacing a cognitive model with the physical environment means: we must provide sensors that perceive certain aspects of the physical space and map the perceptions to the representation language of our model. Thus, physical space is transformed into a representation that models physical space. Conversely, we must provide actuators that will map models of spatial actions into physical actions in the spatial environment.
As interfaces between the physical spatial world and the mental representational world, sensors and actuators must be adapted to both worlds to communicate between them effectively and appropriately. Consequently AI researchers and cognitive roboticists typically will start with spatial environments for which it is easy to interpret sensor output and to control the actions, e.g. worlds with flat horizontal ground surfaces, straight walls, etc.

In these idealized worlds, we employ “autonomous” robots as spatial cognitive agents. They are equipped with sensors of various types (e.g. cameras for vision, ultrasound and touch sensors for sensing obstacles, laser range finders for measuring distances), actuators (e.g. motors and wheels or legs to move the robot, arms to grasp), and a computer (the robot’s brain) to interpret the sensor output, to make spatial inferences on the basis of sensor information and background knowledge, and to control the actuators[2].

We may now ask what these artificial cognitive agents have in common with human beings who grew up in a rich social and cultural context and who developed concepts of their environment in a tradition of many centuries. Of course not too much - and we are quite aware that we are creating culturally deprived artifacts. But we are interested in necessary and sufficient conditions to perform specific cognitive spatial tasks. To study complex cognitive interactions empirically, we have the choice of controlling the spatial environment ('laboratory conditions') or controlling the cognitive agent, or both – otherwise we will not be able to test research hypotheses scientifically.

The different options all have their specific advantages and shortcomings. Controlling the environment has the advantage that we can study natural cognitive agents – in particular humans; the drawback is that we cannot be sure they behave under controlled conditions in the same way as under natural conditions. Controlling (natural) cognitive agents has a long tradition in the neurosciences: we can study the cognitive abilities of patients or animals with specific known neurological deficits; this helps us to link cognitive deficiencies to neurological conditions and allows us to reason about the functionality of the corresponding fully functional neurological structures. Obviously, we cannot (and we do not want to) reduce the functionality of our cognitive agents in such experiments to elementary levels on which we could study the role of specific neural modules in the cognitive performance individually. Besides incurring ethical problems with such experiments, we also would lose the interactions between different neural modules, which are crucial for cognitive processes.

Artificial cognitive agents provide a way out of this situation: the agent is controlled, as we know the functionality of its components and its architectural structure. We can work towards employing artificial agents under relatively natural conditions (being fully aware that conditions are bound to become less natural when we introduce a robot - or an ethnologist, for that matter - into a natural environment).

As artificial cognitive agents are rather specialized ‘low performers’ in comparison to neurological patients with specific deficits, we have the additional advantage that we will observe differences in the characteristics of problem solving processes between artificial and natural cognitive agents. To reduce these
differences, additional explanations and mechanisms will be typically required. It is much easier to find such explanations incrementally through system synthesis than decrementally through system analysis[5].

In summary, we hope to be able to narrow the knowledge gap in our understanding between spatial performance on one hand and the underlying functional mechanisms, on the other hand.

8 Empirical Investigations in Unnatural Worlds

In the previous section I suggested that empirical studies with artificial cognitive agents might be a valuable supplement to empirical studies with natural cognitive agents. While this discussion focused on agents in real or simulated natural spatial environments, I want to go a step further in the present section and plead for empirical studies in unnatural environments.

In section six I discussed virtual spatial environments for cognitive agents that are designed to be as close as possible to natural spatial environments – with the advantage that they can be manipulated more easily and more systematically than natural environments (e.g. [57]). Here I want to discuss the design of environments in which intrinsic properties of physical space that are taken for granted in natural environments are distorted on purpose.

Natural cognitive systems are adapted to their natural environments. If we study environment and adapted agents as strictly connected units, we are not able to find out about the adaptation parameters and the adaptation mechanisms. To test whether our cognitive processing model will behave under different boundary conditions as our theory would predict we must dissociate a cognitive agent from its environment. Thus, just as physiologists need zero gravity or enhanced gravity to study the effects of gravitational forces on the human body, we can make use of space that has different properties than our familiar physical space. In this way, we will be able to test cognitive process models with regards to built-in assumptions on the structure of the environment.

For example, we take for granted that certain geometrical and topological properties hold in space and we make use of these properties to navigate and to find our way; in particular, we can rely on metric properties of space which are manifested in the triangle inequality: the distance between two points A and C is at most as large as the sum of the distances between point A and point B and the distance between point B and point C. Or, when we are on one side of a river, our topological world knowledge tells us that we have to cross the river to get to the other side.

Virtual reality technology enables us to create spatial environments with geometries and/or topologies that cannot exist in physical reality[59]. What happens with our spatial reasoning abilities, when we change geometric or topological laws of our spaces? Are our mental structures flexible enough to adapt to hypothetical properties of the space or are they intrinsic parts of our physical environments and their genuine properties that restrict them to the very properties of physical space?

Empirical studies in unrealistic or even physically impossible spatial environments can provide clues about the level of abstraction and generality employed in the underlying representation and reasoning mechanisms. If we or our
artificial cognitive agents can easily adapt to new types of space, then there is some evidence that these agents represent their knowledge on a rather abstract level; if, on the other hand, they cannot adapt (i.e. they make specific mistakes or the performance does not measure up to normal levels), this is an indication that spatial knowledge is represented on a rather concrete level, making use of the specific structures and properties of natural physical space.

9 Context

In cognitive systems, much of the information available to cognitive agents is contained in the environment rather than in explicit mental representations and explicit communication[19]. Various types of context are used to communicate and interpret the environment and other cognitive agents efficiently. From a cognitive engineering point of view, this is a clever way of dealing with the complexity of the world; the method has been called ‘cognitive offloading’[33,58].

In section three I discussed environment-inherent spatial structures that reflect possible configurations of objects in the environment and thus make it an easier and less complex task to deal with the environment[17,20]. Besides the inherent spatial structures, perception, reasoning, action, and interaction processes can take advantage of a number of additional structuring mechanisms. These mechanisms emerge from the interrelationships of the entities that cognitive systems deal with on various levels of cognitive processing. I want to describe specifically three such contexts here, the situation context, the language context, and the task context[24].

Situation context is a structure that emerges on top of the inherent spatial structures of a physical environment through the ways entities in the world are arranged. For example, furniture in a building may be arranged in such a way that chairs are distributed all over the room or they may be located around a table. Such types of arrangements create situation contexts that form the background for cognitive events in the environment. For example, sitting down actions will be interpreted and understood with reference to the actual arrangements of the chairs rather than with respect to all possible arrangements of chairs in our spatial environment.

Similarly, we interpret route instructions with reference to the actual road layout; consequently, route instructions need to be only specific enough to select routes in the environment they are provided for; they need not be specified to an extent that would allow reconstructing that route or a precise map of that route in an empty environment. In other words: most of the information for taking a route is contained in the situation context of the environment rather than in the route description for the route; by making explicit very little information regarding the route I can imply many details about that route from the situation context.

Language context applies similar principles on a more abstract level: language expressions structure our conceptualization of the world. When I say ‘x is tall’, I classify the world into at least two categories, entities that are tall and entities that are not tall. Implicitly I also express that x is not short, as ‘tall’ is an antonym of short. Furthermore, by saying that x is tall, I do not say all sorts of other things that might be said about x or about other entities; by selecting what I say I implicitly decide on all the things I do not say[52]. In other words, language context establishes
a cognitive agenda that tremendously constrains cognitive processing.

Finally, task context establishes a reference framework for interpreting what is going on in an environment: cognitive agents understand what is going on in terms of intentional or accidental forces or tasks that are performed. When I believe that animals pursue the task of surviving, I can interpret all sorts of events that I observe with reference to this belief: moving from one place to another, ingesting objects, quickly running to other animals, etc. In fact, my high-level descriptions for such actions like ‘searching food’, ‘eating’, ‘chasing animals’ that lump together sets of elementary events require such a conceptual framework of what is going on. In other words, task contexts restrict the interpretations of the world to a tractable meaningful subset of conceivable interpretations.

In summary, contextual organization of the world into phenomena that are considered with reference to a background structure is an omnipresent mechanism that can be exploited by cognitive processes on many different levels. From a modeling point of view, a cognitive system is much easier to model than the environments and contexts they operate in; but the contexts are as important!

To get a good sense of the influence and relevance of various contextual factors, it is extremely helpful to gain experience in situated field studies. At the same time, artificial contexts synthesized by computer scientists may provide interesting test fields for studies of natural cognitive agents, as they may help to distinguish between genuine cognitive system factors and contextual factors.

10 Task-Oriented Processing

Independent of the constraints on cognitive processing provided by the task context as described in the previous section, there may be big differences in the cognitive processing required for a given spatial representation, dependent on the target task to be performed. This concerns on one hand the type of task to be performed (in particular: is it a recognition / identification task or is it a construction task) and on the other hand the quality of solution required (for example: is it better to have an approximate solution to a problem quickly or is it better to have a carefully worked out solution later on?).

An example for the difference between recognition and construction tasks was already given in connection with the discussion about the situation context in the previous section: a route description may be provided to identify and select an existing street in the context of the specific environment or to construct a map that precisely reflects the layout of an environment in the absence of the context of that environment.

11 Level of Abstraction / Schematization

A particularly interesting issue in spatial cognition is the level of abstraction at which knowledge about the spatial world is represented or should be represented. In computer science, abstract representations are popular as they are more general than concrete representations. Knowledge that we can abstract from the specific context in which it has been acquired can be applied to other contexts as well. More abstract knowledge tends to be less complex and computation is restricted to a specific relevant subset of aspects. On the other hand, knowledge that is very general may have to
be constrained to fit the requirements of specific situations; this adds computational
effort and cost for solving specific tasks; thus, there is a trade-off between abstract
and concrete representations[23].

The issue of abstract vs. concrete representation can be illustrated in discussing
the question which types of representations are more useful for wayfinding: realistic
depictions of the environment or schematic representations. At first sight, a realistic
depiction of the actual environment, e.g. a photographic image, appears to be more
suitable than an abstract map, as it will be easier to match this to the environment.
However, matching the map to the environment is only one part of the task that we
have to solve; the other part is the reasoning process that finds a suitable route on
the map. The reasoning process is facilitated if only information is depicted that is
relevant for the decision making process. This is the case, for example, in a schematic
map of a city transportation system that abstracts from many details like shape
information. In other words, different parts of the overall task are performed more
easily on different types of representations; cognitive effort is required to accomplish
the transition from one type of representation to the other.

The answer to the question which representation is best suited will thus depend
on the relative distribution of subtasks that the representation is needed for: if the
map is exclusively needed to determine a suitable route, a schematic map will be more
helpful; if, on the other hand, the route to take has already been determined and the
map is needed to match this route to the perceived environment, a more concrete
map will be more helpful.

Frequently it pays off to use different representations for different subtasks and
to convert from one representation to the other to relate them to each other. If one
map has to serve both purposes and in effect becomes an interface between the more
abstract reasoning and the concrete perceptual matching part, a suitable balance
between abstractness and concreteness of representation must be found. Different
people may distribute the subtasks differently, depending on individual abilities and
preferences. To relate this issue of abstractness vs. concreteness to the discussion
about different types of context, we can see that different tasks depend on different
contexts: the criteria for the best route to be found may be specified in such a way
that they do not depend on the specific situation context while the route to be taken
obviously depends on it.

12 Space-based vs. Language-based Internal Representations

As we have cognitive abilities both to think in concrete terms and to think and
speak abstractly, cognitive scientists are confronted with the question, on which of
the levels knowledge can be maintained better or more easily. ‘Concrete’ means
here that concepts are anchored in specific situations that are directly perceived or
vividly imagined; ‘abstract’ means that concepts are related to other concepts whose
semantics is not immediately related to real world phenomena. In this sense, we can
speak about ‘space-based’ (concrete) and ‘language-based’ (abstract) representations,
respectively.

As with external representations like the maps for localization or wayfinding
discussed in the previous section, more concrete and more abstract mental – or
computer-internal – representations both have their advantages and draw-backs: as
concrete representations can be instantiated in terms of perceptions and experiences; in this way, they become associated with other aspects that can support but also distract reasoning processes, depending on whether these other aspects are helpful for the task at hand, or not.

A reasoning approach that makes use of concrete representations is case-based reasoning[1]. More abstract representations are more suitable for associations on the semantic level and allow for more general inferences that do not depend on specific instances and on additional knowledge that may be associated with them; on the other side they are not as easily integrated into event-related representations. From human memory research we know that over time concrete representations persist more easily than more abstract ones and abstract knowledge might be remembered later in terms of concrete episodes[4].

13 Thesis and Conclusion

The availability of computers and knowledge representation formalisms from artificial intelligence research triggered the formation of cognitive science as an interdisciplinary research field in the mid 1970s. Disciplines studying natural systems in real environments (cognitive psychology, linguistics, cognitive anthropology, neurosciences) started a joint enterprise with disciplines investigating formal systems in abstract worlds (philosophy, logics, mathematics) and disciplines constructing artifacts in virtual or physical environments (artificial intelligence, computer science). In this way, methodological shortcomings from one discipline can be compensated by methodological strengths of the partner disciplines. The aim of generating synergies between the disciplines calls for a generalization of notions of agents, environments, systems, and science to include natural and artificial; physical and virtual; concrete and abstract; pure and applied, respectively.

In this extended research domain we can study relations and interactions between natural and artificial agents, correspondences and interplays between sensory and imaginary worlds, relationships between formal models and concrete implementations, and the difference between value-free and goal-oriented interpretations.

Computers have added a new dimension to the study of cognitive systems. Not only do they enhance analytical capabilities for the evaluation of models and theories, but they also provide ways for creating new cognitive species that help investigate the cognitive abilities of existing species. Spatial cognition is a particularly good domain for the interaction between classical analytical and the newer synthetic approaches, because the same physical / spatial reference world may be used for relating different approaches.

In his inspiring book ‘Vehicles’ Braitenberg[5] convincingly demonstrated that ‘synthetic psychology’ has considerable advantages over analytic psychology. The reason is that an infinite number of models may be compatible with a single pattern of performance while a specific model generates only one type of behavior. Thus, the synthetic approach yields great explanatory power.

Computer programs provide a means of implementing and testing hypotheses and abstract theories in a rigorous way and point to issues that are not found by paper and pencil investigations or by empirical studies. Thus, insights from theoretical and
empirical investigations can be cast into a running model that should exhibit the predicted characteristics; furthermore, an operational model can make predictions about the outcome of empirical experiments on the basis of a theory and thus provide interesting questions for empiricists to validate. In this way, a cognitive theory can be iteratively refined and modified.

To build a running computer model of a cognitive theory, assumptions must be made about issues that seem to lie outside the scope of the theory. There are two options regarding these assumptions: either they really lie outside the theory - then their choice should not affect the pertinent behavior of the computer model; or these assumptions do affect the pertinent behavior of the computer model - then they should be incorporated into the theory. In this way, the computer approach forces certain questions to be answered to resolve open issues.

The most important contribution artificial intelligence can provide for interdisciplinary research is to help avoid terminological confusion and to help bridge communication gaps between disciplines. This is because in AI models, concepts must be made precise by definitions. For example, in spatial cognition, we may use concepts like ‘cardinal direction’ assuming everyone knows what I mean by ‘north’. For a computer program, I will have to decide whether ‘north’ means compass direction 360 degrees with respect to a given point, or the 90 degree sector 360 degrees plus and minus 45 degrees, or compass direction 360 degrees from any point on an imaginary East - West line through the given point, or ...[10]. Such requirements can help recognize relevant terminological differences in the interdisciplinary community that have not been detected previously.

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