39 Pylyshyn, Z.W. (1980) Computation and cognition: issues in the foundations of cognitive science. *Behav. Brain Sci.* 3, 111–132

40 Federmeier, K.D. and Kutas, M. Meaning and modality: influences of context, semantic memory organization, and perceptual predictability on picture processing. *J. Exp. Psychol. Learn. Mem. Cognit.* (in press)

41 Holcomb, P.J. and McPherson, W.B. (1994) Event-related brain potentials reflect semantic priming in an object decision task. *Brain Cognit.* 24, 259–276

42 Ganis, G. *et al.* (1996) The search for 'common sense': an electrophysiological study of the comprehension of words and pictures in reading. *J. Cogn. Neurosci.* 8, 89–106

43 Nigam, A. *et al.* (1992) N400 to semantically anomalous pictures and words. *J. Cogn. Neurosci.* 4, 15–22

44 McPherson, W.B. and Holcomb, P.J. (1999) An electrophysiological investigation of semantic priming with pictures of real objects. *Psychophysiology* 36, 53–65

45 Bobes, M.A. *et al.* (1994) An ERP study of expectancy violation in face perception. *Brain Cognit.* 26, 1–22

46 Barrett, S.E. and Rugg, M.D. (1989) Event-related potentials and the semantic matching of faces. *Neuropsychologia* 27, 913–922

47 Jemel, B. *et al.* (1999) Event-related potentials to structural familiar face incongruity processing. *Psychophysiology* 36, 437–452

48 Van Petten, C. and Rheinfelder, H. (1995) Conceptual relationships between spoken words and environmental sounds: event-related brain potential measures. *Neuropsychologia* 33, 485–508

49 Chao, L.L. *et al.* (1995) Auditory event-related potentials dissociate early and late memory processes. *Electroencephalogr. Clin. Neurophysiol.* 96, 157–168

50 Grigor, J. *et al.* (1999) The effect of odour priming on long latency visual evoked potentials of matching and mismatching objects. *Chem. Senses* 24, 137–144

51 Sarfarazi, M. *et al.* (1999) Visual event related potentials modulated by contextually relevant and irrelevant olfactory primes. *Chem. Senses* 24, 145–154

52 Domalski, P. *et al.* (1991) Cross-modal repetition effects on the N4. *Psychol. Sci.* 2, 173–178

53 Kutas, M. *et al.* (1999) Current approaches to mapping language in electromagnetic space. In *The Neurocognition of Language* (Brown, C.M. and Hagoort, P., eds), pp. 359–392, Oxford University Press

54 Kounios, J. and Holcomb, P.J. (1994) Concreteness effects in semantic processing: ERP evidence supporting dual-coding theory. *J. Exp. Psychol. Learn. Mem. Cognit.* 20, 804–823

55 Holcomb, P.J. *et al.* (1999) Dual-coding, context-availability, and concreteness effects in sentence comprehension: an electrophysiological investigation. *J. Exp. Psychol. Learn. Mem. Cognit.* 25, 721–742

56 Hart, J., Jr and Gordon, B. (1992) Neural subsystems for object knowledge. *Nature* 359, 60–64

57 Warrington, E.K. and McCarthy, R.A. (1987) Categories of knowledge. Further fractionations and an attempted integration. *Brain* 110, 1273–1296

58 Humphreys, G.W. *et al.* (1999) From objects to names: a cognitive neuroscience approach. *Psychol. Res.* 62, 118–130

59 Martin, A. *et al.* (1995) Discrete cortical regions associated with knowledge of color and knowledge of action. *Science* 270, 102–105

60 Damasio, A.R. (1989) The brain binds entities and events by multiregional activation from convergence zones. *Neural Comput.* 1, 123–132

61 Kutas, M. *et al.* (2000) Language. In *Handbook of Psychophysiology* (Cacioppo, J.T. *et al.*, eds), pp. 576–601, Cambridge University Press

Extending the classical view of representation

Arthur B. Markman and Eric Dietrich

Representation has always been a central part of models in cognitive science, but this idea has come under attack. Researchers advocating the alternative approaches of perceptual symbol systems, situated action, embodied cognition, and dynamical systems have argued against central assumptions of the classical representational approach to mind. We review the core assumptions of the representational view and these four suggested alternatives. We argue that representation should remain a core part of cognitive science, but that the insights from these alternative approaches must be incorporated into models of cognitive processing.

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There is revolution in the air in cognitive science. Since the late 1950s, models of cognition have been dominated by representational approaches. These models posit some kind of internal mechanism for storing and manipulating data as well as processes that act on representations to carry out intelligent behaviors[1–3].

Although the field of cognitive science has made great strides, the early predictions that we would soon have autonomous robots and intelligent computers on our desktops have not yet come to pass. Researchers from a variety of perspectives have suggested that the standard representational assumptions made by cognitive models are to blame for this lack of progress. The suggested remedies range from additional information that should be included in representations to replacement of the dominant paradigm with an alternative.

This article sketches the classical view of representation that is widely employed in cognitive models. Then, four recent approaches to cognitive modeling are examined: perceptual symbol systems, situated action, embodied cognition, and dynamical systems. Each approach has been put forward as a successor to the classical view. We suggest that each of the four alternative approaches has something important to offer, but cannot replace the classical view. We end with a discussion of ways to reconcile the classical view with these alternatives.

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The classical view of representation

Cognitive science uses many kinds of representations, and it would be impossible to provide a complete summary of all of them[4]. On the classical view, all approaches to representation share five key assumptions: (1) representations are mediating states of intelligent systems that carry information; (2) cognitive systems require some enduring representations; (3) cognitive systems have some symbols in them; (4) some representations are tied to particular perceptual systems but others are amodal; and (5) many cognitive functions can be modeled without regard to the particular sensor and effector systems of the cognitive agent. (In this article, we will use the term 'cognitive agent' to include organisms as well as intelligent machines.)

The first assumption is that there are mediating states that are internal to the cognitive system[5]. In order for something to qualify as a mediating state, four conditions must be satisfied[3]. First, there must be some representing world. The representing world consists of the elements that serve as the representations. Second, there must be some represent*ed* world. The represented world is the information (either within the system or external to it) that is being represented. Third, there is a set of representing relationships that determine how elements in the representing world come to stand for elements in the represented world. Finally, there are processes that use the information in the representing world.

As an example, Tversky's contrast model of similarity[6] assumed that objects (the represented world) are represented by sets of features (the representing world). Each feature is a symbol that stands for a particular property of the object, such as the color blue (the representing relationship). Pairs of sets representing two objects are compared by finding the intersection of the sets (a process that acts on the representations). The features in the intersection are the commonalities of the pair, and the features that are not in the intersection are the differences of the pair.

The second assumption is that some representations are enduring states of the system. In particular, agents must use their experience as a guide. Thus, they have internal states that endure longer than the states in the represented world that gave rise to them. To continue the example of the contrast model, an object representation can contain a particular feature (e.g. blue) regardless of whether that property is currently accessible in the environment.

The third assumption is that some representations are symbols. Symbols have two central qualities: their relationship to the represented world is arbitrary[7], and they are discrete packets of information. Symbols are necessary for referring to specific values or properties in the represented world, and mirror the observation that languages consist of words that permit people to fix common reference. In the contrast model, features are symbols in the representing world.

The fourth assumption is that representational elements exist at a variety of levels of abstraction. Some representations correspond directly to aspects of perceptual experience. Other representations are more interpreted, and refer to abstract concepts like truth or justice, which are quite removed from perceptual experience. In the contrast model, there is no necessary connection between the features that describe an object and perceptual information.

The final assumption is that some cognitive models need not be concerned with perceptual and motor representations. On this view, some representations in the cognitive system are sheltered from the particular body of the agent. It is assumed that such processes can be understood without considering the perceptual and effector systems of the agent. For example, the contrast model makes no assumptions about the nature of the perceptual or motor systems of cognitive agents.

Alternatives to the classical view

The four alternative approaches to representation have all taken umbrage with at least one of the core assumptions of the classical view. Each of the new approaches is motivated by some insight or example that suggests a modification of the classical view. In each of the following sections, we describe one of the approaches, starting with its motivating insights and discussing the core assumptions it calls into question. We then argue that none of the new alternatives can replace the classical view. We conclude by discussing possible extensions to the classical view suggested by the alternatives.

Perceptual symbol systems

Cognitive processing is flexible. People are able to recognize when a new situation is like one they have experienced before, but they are also good at handling deviations from normal situations. The classical approach to representation assumes that flexibility requires abstraction. By abstracting away from the perceptual details of specific situations, the commonalities across situations can be preserved. Thus, the classical approach typically assumes that there are abstract *amodal* representations that play an important role in cognitive processing.

Amodal representations are not as flexible as they were initially assumed to be. For example, Schank and his colleagues suggested ways to represent abstract scripts and schemas to enable an agent to comprehend new events[8,9]. These systems had difficulty dealing with the potential variations of simple events. Indeed, later work had to posit both abstract and specific representations in order to account for human-like flexibility in dealing with the variations on events like going to a restaurant[9].

Symbolic models have also had difficulty accounting for differences in the way a property manifests itself across items. People know that the red of a fire engine is different from the red of hair, even though the same color term is used for both. Likewise, the same spatial preposition can describe many subtly different situations[10,11]. For example, the English preposition 'in' normally means that one object is contained inside another, but an apple can be 'in' a bowl, even when it is stacked on other apples such that it rises above the top lip of the bowl. It is difficult to account for this ambiguity using traditional symbolic models[12].

Current research suggests that flexibility in cognitive processing arises from the storage and use of specific episodes in memory and their perceptual content. Barsalou's perceptual symbol system approach proposes that the perceptual system is used to simulate objects and events[13]. For example, representing an apple in a bowl involves simulating an apple on top of other apples using the perceptual system. The connection

Box 1. Cognitive grammar

Cognitive grammar attempts to account for grammatical phenomena using representations and processes that are continuous with those used by other cognitive processes (Ref. a). On this view, grammar facilitates the construction of representations using both perceptual and attentional processes. For example, the representation of the prepositions 'above' and 'below' involves setting up locations in a semantic space, and then focusing attention on one of the objects (see Fig. I) (the top circle in the case of 'above' and the bottom one in the case of 'below').

In this example, the productivity of grammar is accomplished by allowing representations of the arguments of the prepositions to be freely bound to the circles in this representation. Thus, representing the phrase '*the lamp is above the table*' involves binding a symbol for the lamp to the top argument 'above', and a symbol for the table to the bottom argument 'below'.

A variety of grammatical structures can be represented using these principles. For example, temporal events can be represented by extending the representations in time. For example, the concept 'arrive' can be represented by a situation in which one argument gradually gets closer to a second fixed argument over time until they eventually meet. The moving object is the focus of attention in this representation.

Reference

a Langacker, R.W. (1987) *Foundations of Cognitive Grammar*, Stanford University Press

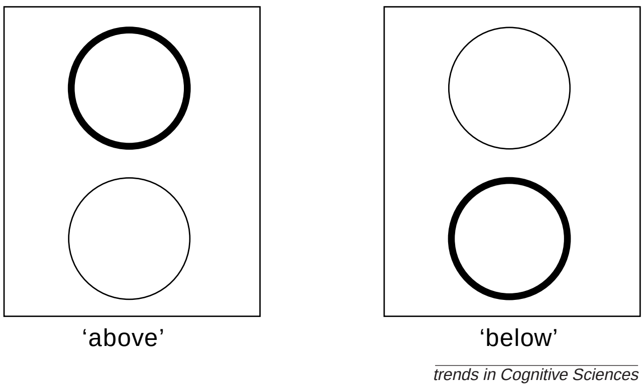

Fig. I. Perceptual and attentional processes in representations. The representation of the prepositions 'above' and 'below' involves setting up locations in a semantic space, and then focusing attention on one of the objects (the top circle in the case of 'above' and the bottom one in the case of 'below').

between perception and language in this case is accomplished using principles derived from cognitive grammar (see Box 1).

Theoretical arguments and experimental evidence suggest that cognitive science should eschew amodal representations. In categorization, Schyns *et al.* point out that most amodal theories assume a fixed feature set[14]. Categorization models then use these features to predict the category to which an instance belongs. Models can calculate similarity to a prototype (i.e. an average member of the category[15,16]), or to various known exemplars[17–19], or they can form rules to describe the categories[20].

People often learn new features, even new perceptual features[14]. Thus, to understand categorization, it is necessary to further understand processes of perceptual feature creation. In one study, Schyns and Rodet taught people perceptual categories each consisting of unfamiliar shapes[21]. What people considered to be the basic perceptual components of the categories depended on the order in which they were exposed to the categories. For example, they might see some items that contained the complex feature XY as one of its components (see Fig. 1). If this was the first category they learned, they treated XY as a whole unit. By contrast, if they first saw some categories with component X, when they later saw XY, they divided this shape up into X and Y. Thus, the set of perceptual features used to construct the categories is learned. Similar demonstrations have been performed with real-world materials. For example, Lesgold *et al.* showed that the features in X-ray films used by expert radiologists to make a diagnosis are different from those used by novices[22].

To summarize, the perceptual approach calls into question the assumption of classical models that there are amodal symbols. This approach suggests that using specific representations derived from perception allows cognitive systems greater flexibility than can be achieved with amodal symbols.

Situated action

The classical approach often views cognition as something that can be modeled by computers. By taking seriously the role of perception in conceptual representations, it becomes difficult to separate cognitive processes from the context in which they occur. The study of situated action (or situated cognition) assumes that cognitive processing cannot be extracted from the environment in which it occurs[23–26].

Two important insights follow from this focus on context. First, all of the information relevant to thinking about a situation may not need to be represented, because a substantial amount of that information is present in the environment. Second, the problem an agent has to solve might be eased by aspects of the environment that would be hard to foresee if the agent had to reason abstractly.

On the first point, when cognition is situated, the agent can rely on the fact that the world is enduring to avoid having to represent the world extensively. As one example, studies of 'change blindness' have demonstrated that people do not store much of the visual world in an enduring fashion[27–29]. These studies find that people have difficulty detecting changes of unattended information in visual images. Although it might seem inefficient to lose this information when a fixation ends, the world typically does not change drastically from moment to moment, so there is little cost to storing only information that is in focal attention.

An agent can also simplify its representation of the world by representing things with respect to itself. For example, Agre and Chapman developed a simulated agent in a video-game world [P.E. Agre and D. Chapman (1987) Paper presented at the Proceedings of AAAI-87, Seattle, WA, USA, 1987]. Rather than forming a detailed map of the world and keeping track of objects by their global coordinates in space, objects were represented by their relationship to the agent. An attacking enemy in the game was represented as something chasing the agent. The agent used this representation for any attacking enemy, because what was relevant was the relationship between the agent and the enemy at that moment.

A second aspect of situated action is that the problem an agent must solve is determined by the environment. For example, Hutchins provides an extensive description of the way navigation teams aboard naval vessels track a ship's position[24]. At a general level, the problem solved by a navigation team involves fixing the position of the ship in the environment and ensuring that the ship maintains a course that keeps it from running aground. However, navigation teams have many specialized tools including two-dimensional overhead perspective maps, protractors, pencils, and devices for measuring the relative location of landmarks with respect to the ship and assessing the depth of the water. These tools turn navigation into a task in which relative locations are drawn onto a map to determine the ship's position.

In summary, because cognitive agents are embedded in environments, they need not form complete representations of their environment at all times. Instead, they can assume that the world is relatively stable. Thus, fewer representations in the cognitive system need to be enduring than has been assumed by classical approaches. Situated action also allows agents to simplify the task they must solve by representing information relative to themselves. Finally, the task environment determines the problem that an agent actually has to solve. Often, what appears to be a difficult problem when cast abstractly is much easier when embedded in an actual situation. The goal of cognitive science, in this view, is to understand how agents structure their environment in order to solve complex tasks.

Embodied cognition

Related to the situated-action approach is embodied cognition, which assumes that it is necessary to *build* agents that actually interact in real environments[30–34]. Building real agents suggests ways that the environment can be exploited to solve difficult problems. Furthermore, although there may be many possible ways of representing information, the space of potential representations might be much narrower when the agent must achieve sensorimotor coordination. Thus, this view rejects the idea that cognitive theories can ignore perceptual and motor systems.

There are many ways that the environment can be exploited to solve difficult problems. Starting with Gibson, research demonstrates that an agent's visual system is sensitive to aspects of the environment that provide information relevant to its goals, where the goals of an agent are constrained by the effectors it has. For example, many species are able to use optic flow to gauge their direction and speed of motion. In addition, the vestibular systems provide information that can be used to augment visual information in the construction of cognitive maps[35–37].

Sometimes building an agent can also lead to simple solutions to potentially difficult problems. For example, Pfeifer and Scheier describe a robot that is able to distinguish large cylinders from small ones[34]. The robot has simple motor routines that allow it to follow walls and therefore to circle around objects. When the robot circles a small cylinder, the ratio of the speed of the outside wheel to the inside wheel is higher than when it circles a large cylinder. By using sensors that provide information about the speed of its wheels, the robot is able to perform a classification task without an elaborate visual system.

Finally, Glenberg suggests that memory research must focus on the function of memory within an organism[33]. Many forms of memory require little effort, such as perceptual priming observed following the presentation of a stimulus, or the ability to point to the location of an object in space when the organism is navigating through that space. Glenberg argues that these forms of memory are what permit organisms to carry out actions in the world. More effortful forms of memory require suppression of current input, which is what makes them difficult to use[38]. He further

Fig. 1. Perceptual symbols. Example of a perceptual feature like the ones used by Schyns and Rodet[21]. Observers who see the feature XY first treat it as a whole unit. However, observers who first see component X, and only later see XY, divide XY into X and Y.

argues that language comprehension involves representing information as if the comprehender were going to act in the situation. In each of these cases, it is assumed that understanding cognition requires focusing on the relationship between an embodied organism and its environment.

The embodied cognition approach has had great success at building simple machines that navigate through environments and avoid obstacles. These agents are able to perform simple tasks like picking up cans or classifying simple objects[32,34]. The claim these researchers make is that all of cognition, including higher cognition, can be successfully modeled using this bottom-up approach.

Dynamical systems

A final challenge to traditional assumptions about representation has come from proponents of 'dynamical systems' explanations of behavior[39–43]. Dynamical systems are systems of non-linear differential equations that can be used to describe aspects of behavior (see Ref. 42 for an introduction, and Ref. 43 for a recent review of the concepts). On this view, a central problem with traditional approaches to representation is that they have discrete and enduring components. Dynamical systems do not involve discrete symbols.

In a dynamical system, there is a current state consisting of the values of some set of control variables. There is also a set of equations that combine the control variables to govern how the system changes over time. Thus, the two key aspects of dynamical systems are that they involve continuous change in the values of control variables, and that this change occurs continuously in time. Hence, dynamical systems assume that representations are time-locked to information in the represented world. As the state of the represented world changes, the representation also changes.

As an example, Kelso describes studies involving the coordination among limbs[39]. For example, people find it easy to flex and extend the index finger of each hand in synchrony regardless of the speed of the movement. In contrast, it is difficult to flex the index finger of one hand while extending the index finger of the other at high speeds, and if they try, they ultimately end up flexing and extending both fingers in synchrony. Kelso is able to describe this movement, as well as many more complex kinds of motor coordination, using dynamical systems. Furthermore, he makes a convincing case that this type of explanation is superior to an explanation of these behaviors involving other types of representations. In this model, the state of the system changes through time as the positions of the fingers change. Thus, this model contains no enduring representations.

Some researchers have argued that this success in describing motor behavior can be extended to all of cognitive processing[40,41]. They suggest that dynamical systems have two advantages over other approaches to cognition. First, by focusing on processes that evolve continuously, they are able to account for the plasticity of cognition. Second, it is assumed that continuous processes allow dynamical systems to account for the fine details of processing, which in turn allows them to account for individual differences. This focus on individual differences contrasts with much research in cognitive science, which focuses on commonalities in behavior across individuals.

Semantics and representation

The four alternative approaches to representation have focused primarily on low-level perceptual and motor processes. They have not had success at explaining higher-level cognition. There is a good reason for this difficulty. To some degree, each of the alternative approaches ties representations to perceptual and motor pathways. On the positive side, this coupling of representation with perceptual and effector systems provides a basis for the semantics of the representation. In particular, one important way that representations come to have meaning is for them to correspond to something external to the agent.

On the negative side, using correspondence as the primary basis for semantics is more likely to be successful for perceptual and motor processes than for high-level cognition. People's ability to represent abstract concepts involves a second aspect of semantics: their functional role. That is, the meaning of a representational element is also determined by its relationship to other representational elements. If a theory of representation focuses primarily on correspondence, then processes that require functional role information will be difficult to explain.

How should the classical view be extended?

None of the problems identified by advocates of the four alternative approaches is fatal to the classical approach to representation. All of the approaches to representation discussed here agree on the fundamental assumption that cognitive processing involves internal mediating states that carry information. Thus, the exploration of representation can be fruitfully described as an examination of the types of properties that must be added to the basic concept of a mediating state in order to capture cognitive processing.

Each of the alternative approaches discussed above highlights particular properties that must be added to mediating states in order to account for cognitive processing[5]. Thus, the remaining assumptions of the classical view all require some change in light of the issues raised by alternative approaches. Not all representations are enduring, not all are symbolic, not all are amodal, and not all are independent of the sensory and effector systems of the agent.

The assumption that some representations are amodal is the one that will require most future scrutiny. The studies supporting perceptual symbol systems suggest that tying representations to specific modalities may provide the basis for considerable flexibility in cognitive processing, and might even account for the use of abstract concepts. Although it is too early to argue that cognitive science can dispense with amodal representations, it may be able to go a long way without them.

The other three assumptions of the classical view are likely to survive intact for most aspects of higher cognitive processing. The assumption that cognitive systems have enduring states was challenged by both the situated action and the dynamical systems approaches. The situated action approach captures the important insight that many aspects of the world remain stable and thus do not need to be incorporated into enduring representations. Classical models will have to focus on ways that agents use the world as a source of information. The dynamical systems view further asserts that representations undergo continuous change in relation to changes in the external environment. This criticism seems less problematic for classical models, as there are many cases where an agent must be able to represent the past in order to be able to reason.

The dynamical systems view also challenges the importance of discrete symbols. This approach has demonstrated that continuous representational states are important for capturing low-level perceptual and motor processes. However, there is good reason to believe that many cognitive processes do require discrete symbols. Many of the aspects of cognition that make perceptual symbol systems attractive argue against dynamical systems as the sole mode of cognitive representation. For example, people's ability to represent spatial relationships in language suggests that there must be discrete components that endure beyond particular sensory stimulation.

Finally, the degree to which perceptual and motor systems must be considered when modeling cognitive processing is an open question. The embodied cognition approach suggests that building real agents is necessary for constructing cognitive models. The perceptual symbol system view requires that representational assumptions must be compatible with what is known about perception. Furthermore, the situated action approach suggests that the environment is an important source of information that is used by agents to solve problems. Thus, models must be able to take advantage of information in the environment.

Despite the clear importance of perception in cognitive processing, cognitive science must continue to develop models of higher cognitive processes; perception is not a purely bottom-up process. Expertise in a domain changes

Outstanding questions

- Are there any amodal symbols in cognition? Models of cognitive processes might be able to go a long way without assuming that there are at least some amodal representations, but it is not possible at present to dispense with them entirely.
- In what ways do lower-level perceptual processes and higher-level cognitive processes place constraints on the form of cognitive representations?
- Can effective models of cognitive processes be developed without first modeling sensory and effector systems?

the way people perceive the basic features of that domain. Thus, without models of how complex reasoning and expertise develops, we will not be able to understand how perceptual representations are constructed. Although cognitive science would ultimately like to have explanations that span from sensation to high-level cognition, these models cannot be developed in a purely bottom-up fashion.

Conclusion

In summary, the classical approach to representation must be extended, but not replaced. The fundamental assumptions that there are internal mediating states and that many of those states are symbolic, enduring and amodal form the core of the computational view of mind. Because these assumptions can be retained, the basic approach to cognitive science remains intact. The core insights of the alternative approaches to representation, however, do require significant changes to the base view. In particular, cognitive models must be more sensitive to perceptual representation. In doing this, we must now address seriously the problem of how high-level concepts are formed from low-level percepts.

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References

1 Anderson, J.R. (1978) Arguments concerning representations for mental imagery. *Psychol. Rev.* 85, 249–277
2 Marr, D. (1982) *Vision*, W.H. Freeman
3 Palmer, S.E. (1978) Fundamental aspects of cognitive representation. In *Cognition and Categorization* (Rosch, E. and Lloyd, B.B., eds), pp. 259–302, Erlbaum
4 Markman, A.B. (1999) *Knowledge Representation*, Erlbaum
5 Markman, A.B. and Dietrich, E. (2000) In defense of representation. *Cognit. Psychol.* 40, 138–171
6 Tversky, A. (1977) Features of similarity. *Psychol. Rev.* 84, 327–352
7 Pierce, C.S. (1897/1955) Logic as semiotic: the theory of signs. In *The Philosophical Writings of Pierce* (Buchler, J., ed.), pp. 98–119, Dover
8 Schank, R.C. and Abelson, R. (1977) *Scripts, Plans, Goals, and Understanding*, Erlbaum
9 Schank, R.C. (1982) *Dynamic Memory*, Cambridge University Press
10 Herskovits, A. (1986) *Language and Spatial Cognition: An Interdisciplinary Study of The Prepositions in English*, Cambridge University Press
11 Landau, B. and Jackendoff, R. (1993) 'What' and 'where' in spatial language and spatial cognition. *Behav. Brain Sci.* 16, 217–266
12 Miller, G.A. and Johnson-Laird, P.N. (1976) *Language and Perception*, Harvard University Press
13 Barsalou, L.W. (1999) Perceptual symbol systems. *Behav. Brain Sci.* 22, 577–660
14 Schyns, P.G. *et al.* (1998) The development of features in object concepts. *Behav. Brain Sci.* 21, 1–54
15 Hampton, J.A. (1995) Testing the prototype theory of concepts. *J. Mem. Lang.* 34, 686–708
16 Reed, S.K. (1972) Pattern recognition and categorization. *Cognit. Psychol.* 3, 382–407
17 Medin, D.L. and Schaffer, M.M. (1978) Context theory of classification. *Psychol. Rev.* 85, 207–238
18 Nosofsky, R.M. (1986) Attention, similarity and the identification–categorization relationship. *J. Exp. Psychol. Gen.* 115, 39–57
19 Porter, B.W. *et al.* (1990) Concept learning and heuristic classification in weak theory domains. *Artif. Intell.* 45, 229–263
20 Nosofsky, R.M. *et al.* (1994) Rule-plus-exception model of classification learning. *Psychol. Rev.* 101, 53–97
21 Schyns, P.G. and Rodet, L. (1997) Categorization creates functional features. *J. Exp. Psychol. Learn. Mem. Cognit.* 23, 681–696
22 Lesgold, A. *et al.* (1988) Expertise in a complex skill: diagnosing X-ray pictures. In *The Nature of Expertise* (Chi, M.T.H. *et al.*, eds), Erlbaum
23 Clancey, W.J. (1997) *Situated Cognition: On Human Knowledge and Computer Representations*, Cambridge University Press
24 Hutchins, E. (1995) *Cognition in the Wild*, MIT Press
25 Suchman, L.A. (1987) *Plans and Situated Actions: The Problem of Human–Machine Communication*, Cambridge University Press
26 Pylyshyn, Z.W. (2000) Situating vision in the world. *Trends Cognit. Sci.* 4, 197–207
27 Grimes, J. (1996) On the failure to detect changes in scenes across saccades. In *Perception* (Akins, K., ed.), pp. 89–110, Oxford University Press
28 Rensink, R.A. *et al.* (1997) To see or not to see: the need for attention to perceive changes in scenes. *Psychol. Sci.* 8, 368–373
29 Simons, D.J. and Levin, D.T. (1998) Failure to detect changes to people during a real-world interaction. *Psychonomic Bull. Rev.* 5, 644–649
30 Agre, P.E. (1995) Computational research on interaction and agency. *Artif. Intell.* 72, 1–52
31 Brooks, R.A. (1991) Intelligence without representation. *Artif. Intell.* 47, 139–159
32 Brooks, R.A. (1999) *Cambrian Intelligence*, MIT Press
33 Glenberg, A.M. (1997) What memory is for. *Behav. Brain Sci.* 20, 1–55
34 Pfeifer, R. and Scheier, C. (1999) *Understanding Intelligence*, MIT Press
35 Golledge, R.G. (1999) Human wayfinding and cognitive maps. In *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes* (Golledge, R.G., ed.), pp. 5–45, Johns Hopkins University Press
36 Golledge, R.G. and Stimson, R.J. (1997) *Spatial Behavior: A Geographic Perspective*, Guilford Press
37 Richardson, A.E. *et al.* (1999) Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Mem. Cognit.* 27, 741–750
38 Glenberg, A.M. *et al.* (1998) Averting the gaze disengages the environment and facilitates remembering. *Mem. Cognit.* 26, 651–658
39 Kelso, J.A.S. (1995) *Dynamic Patterns: The Self-Organization of Brain and Behavior*, MIT Press
40 Port, R.F. and Van Gelder, T., eds (1995) *Mind as Motion*, MIT Press
41 Thelen, E. and Smith, L.B. (1994) *A Dynamic Systems Approach to the Development of Cognition and Action*, MIT Press
42 Norton, A. (1995) Dynamics: an introduction. In *Mind as Motion* (Port, R.F. and Van Gelder, T., eds), pp. 45–68, MIT Press
43 Beer, R.D. (2000) Dynamical approaches to cognitive science. *Trends Cognit. Sci.* 4, 91–99