## Spatial symbol systems and spatial cognition: A computer science perspective on perception-based symbol processing

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**Abstract:** People often solve spatially presented cognitive problems more easily than their nonspatial counterparts. We explain this phenomenon by characterizing space as an *inter-modality* that provides common structure to different specific perceptual modalities. The usefulness of spatial structure for knowledge processing on different levels of granularity and for interaction between internal and external processes is described. Map representations are discussed as examples in which the usefulness of spatially organized symbols is particularly evident. External representations and processes can enhance internal representations and processes effectively when the same structures and principles can be implicitly assumed.

***The role of spatial relations for cognition.*** Neural representations resulting from perception are often organized in *sensoritopic* representations, that is, according to spatial structure manifested in the perceived configuration. As entities are perceived in spatial relation to one another, a representation that preserves spatial relations is obtained without costly transformations. In linking the external and the internal worlds, perception processes make use of spatial organization principles.

A special feature of structure-preserving representations is that the same type of process can operate on both the represented and the representing structure (Palmer 1978). [See also Palmer: "Color, Consciousness, and the Isomorphism Constraint" *BBS* 22(6) 1999.] Thus, events in the external world can be reproduced internally.

According to Barsalou (sect. 2.4), simulations with perceptual symbols should underlie the same restrictions as their corresponding perception processes, as they share the properties for arrangement and order of occurrence with "real" perceptions. From this perspective, space – similar to time – plays a twofold role for cognitive processes: spatial location may be represented as a perceptual symbol (as a result of perception) and space provides organizing structure for perceptual symbol systems.

As spatial structure is relevant to perception across modality boundaries and as it behaves like a modality with respect to structural constraints, space can be viewed as an *inter-modality* combining the advantages of specificity and generality of amodal and modal representations, respectively. This inter-modality property of space may be essential for multi-modal sensory integration and for cross-modal interaction.

***Specificity versus generality of representations.*** "General purpose computers" have been praised for their capability in implementing arbitrary concepts and processes. This capability has been achieved by breaking up the structures of specific domains and reducing everything to very general primitive principles that apply to all domains. The generality of today's computer systems is achieved at the expense of an alienation of these systems from a real environment.

The computer is a "brain" that is only superficially connected to the external world (cf. Barsalou sect. 4.4). In reasoning about the world and in simulating processes in the world, computers carry out operations that do not structurally correspond to operations in the world. To make computers function properly according to the rules of a given domain, the specific domain structure must be mimicked and described in an abstract way in the general-purpose structure. As the domain-specific structure is not given intrinsically but is simulated through expensive computational processes, certain operations are achieved at much higher computational cost than in a more specialized structure.

Conversely, highly specific modal structures as manifested in sensors can do little but react to the specific stimuli they are exposed to. To be effective, they have to be strongly adapted to their environment. In particular, they are not able to perform cross-modal tasks, unless they have a specific interface to establish this connection.

Thus, spatial structure appears to provide a good combination of the advantages of abstract general and concrete specific levels of representation. In spatial structures, a certain degree of abstraction is possible. At the same time, important relations relevant to our perception, conceptualization, reasoning, and action are maintained.

Spatial structures provide principal advantages for processing information about spatial environments (Glasgow et al. 1995). This can be attributed to the fact that – unlike other information structures – spatial relationships are meaningful on many different granularity levels.

Distinctions that are made on high-resolution levels disappear on lower resolution levels. Preserving spatial structure, different meaningful conceptualization levels can be achieved simply by "looking" more closely or less closely (Freksa 1997).

This property of spatial structure can also be utilized on more abstract levels: conceptual spaces in which small local changes can be ignored in favor of the similarities on a higher level form conceptual neighborhoods (Freksa 1991) with interesting computational properties (Freksa & Barkowsky 1996).

***Maps as external representations for cognitive processes.*** Maps and map-like representations convey knowledge by depicting spatial entities in a planar external medium. Relevant geographic entities are identified and depicted by more or less abstract symbols that form spatially neighboring pictorial entities on the map's surface (Barkowsky & Freksa 1997).

The usefulness of maps depends strongly on the spatial structure of the representational medium and on human spatio-perceptual recognition and interpretation abilities. The symbols in the map are perceived in relation to one another. The pictorial map space is organized in spatial analogy to the world it represents. Hence, the map becomes an interface between spatio-perceptual and symbolic concepts that are integrated in a single representational structure.

Maps as external knowledge representations preserve spatial relations adapted from the perception of the represented spatial environment. Hence they support the conception and use of spatial information in a natural way. The spatial structure of maps extends the cognitive facilities of the map user to the external representation medium (Scaife & Rogers 1996).

The cognitive information processing principles that are applicable to both internal and external spatial representations can be investigated by studying processes on external spatial representation media. This seems especially valid regarding spatially organized knowledge for which the types of relations relevant to both internal and external conceptions of environments can be studied (Berendt et al. 1998). Moreover, as maps combine both spatio-analogical and abstract symbolic information, the relevance of spatial organization principles for non-spatial information can be investigated.

***Extending brain power: External memory and process model.*** The idea of using the same principles for internal and external knowledge organization is computationally appealing. Common structures support the use of internal processes for using externally represented knowledge. Consequently, external knowledge can serve effectively as an extension of internal memory structures.

Furthermore, internal and external processes that strongly correspond to one another can greatly enhance the communication between the internal and the external worlds. A main reason for this is that only a little information needs to be exchanged to refer to a known corresponding process, as the common structures can act implicitly. In anthropomorphic terms we could say that it is possible to empathize with familiar processes but not with unfamiliar ones.