Increases in cognitive flexibility over development and evolution: Candidate mechanisms

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Abstract

When chimpanzees, monkeys and rats are disoriented, they reorient themselves using geometrical features of their environment (Tinkelpaugh, 1932; Cheng, 1986; Margules & Gallistel, 1988) In rats this ability appears to be modular, impervious to nongeometric information (e.g. distinctive colors and odors) marking important locations (Cheng, 1986; Margules & Gallistel, 1988) I tested young children and adults in an orientation task similar to that used with rats (Hermer & Spelke, under review) Whereas adults readily used both geometric and nongeometric information to orient themselves, young children, like rats, used only geometric information. These findings provided the first evidence that humans, like many other mammals, orient by using environmental shape; that the young child's orientation system, like that of rats, is informationally encapsulated (Fodor, 1983); and that in humans the apparent modularity of this system is overcome during development.

Rozin (1976) has proposed that during evolution, such increases in the flexibility of putative adaptive specializations stem from duplication within one system of another system's processing mechanisms. I argue that this contradicts standard adaptive theory, and that any such increase in flexibility over the course of evolution or development more likely results from more domain-general processing within a logical system with access to disparate systems' outputs. I discuss candidate mechanisms for providing this organization, based on my research in progress.

Modularity, and spatial orientation as an adaptive specialization common to many mammals

Though sometimes in conflict over the underlying mechanisms they suggest, several investigators have proposed that most fundamental systems of information processing are modular, or informationally encapsulated (e.g. Fodor, 1983). Nevertheless, what may be most striking about human cognition is its flexibility: Human adults appear able to overcome the limits of modular processing in their reasoning, at least partially (Carey, 1991; Townsend & Bever, 1992; Carpenter & Just, 1992; Cosmides, 1989). Thus a central problem for cognitive psychology is to reveal the nature and limits of natural modular systems and the processes by which they are overcome. I have made substantial progress toward this goal for the case of spatial orientation, particularly with respect to the mechanisms underlying this ability in human adults and young children, and the mechanisms allowing communication among the foundational and supporting information-processing systems for it in human adults.

Spatial orientation, an ability found in nearly every tested member of a terrestrial species, is accomplished similarly in a variety of adult mammals. After losing their sense of position and heading, chimpanzees and monkeys (Tinkelpaugh, 1932), rats (e.g. Cheng, 1986), and young children and human adults (Hermer and Spelke, under review) all reorient themselves by using environmental shape. In rats and young humans this ability is modular (for rats, Cheng, 1986; for young children, Hermer & Spelke, under

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using environmental shape. In rats and young humans this ability is modular (for rats, Cheng, 1986; for young children, Hermer & Spelke, under review), even when the use of salient nongeometric information, which subjects perceive and remember (Hermer and Spelke, under review) would allow for more successful orientation. In contrast, human adults can use both geometric and nongeometric information during the same orientation task (Hermer and Spelke, under review).

Spatial orientation in young children and adults

Although children's use of landmarks has been extensively studied (e.g. Pick et al., 1988; Newcombe, 1988) no previous study had examined children's ability to orient themselves by using environmental shape versus environmental landmarks (features of surfaces that do not alter the macroscopic shape of the environment). In my experiments, subjects saw an object being hidden in a corner of a rectangular room, and then were disoriented, after which they were asked to locate the hidden object. Orientation (and hence object location) was partially specified by the room's geometry, and fully specified in some conditions with the addition of salient nongeometric landmarks.

In experiment 1, 16 university students (8 males and 8 females) completed 4 object-search trials in an all-white room, and 4 trials in a room with one blue wall (Fig. 1). Unlike rats, human adults used both nongeometric information (wall color), when it was available, and geometric (sense) information to locate the object. In the all-white condition, the proportion of searches at either geometrically-correct corner (.93) far surpassed the chance expectation of .50 ($t(15)=11.35$, $p=.0001$), with absolute search accuracy (henceforth "search accuracy," the proportion of searches at the actual object location) close to the maximum of 50% (with successful disorientation and with only geometric cues, because of the axial symmetry of the room). These results indicate that the adults perceived and used the metric and sense properties of the room. In the blue-wall condition, subjects exclusively searched the geometrically-correct corners (sign test, $p<.001$), with accuracy levels approaching 100% ($t(15)=15.89$, $p=.0001$). Human adults' absolute search accuracy improved reliably with the addition of the blue wall ($t(15)=7.10$, $p=.0001$), their use of this landmark vastly exceeding adult rats' use of olfactory and visual landmarks in a corresponding study (Margules & Gallistel, 1988) ($t(19)=10.33$, $p=.0001$). No sex differences were found, in contrast to the results of a prominent study of other aspects of human navigation (Bever, 1992).

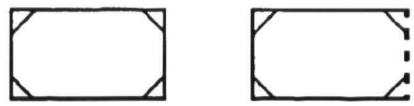

Fig. 1: Top view of the two experimental environments used in experiments 1 and 2. Pillars in the corners behind which an object could be hidden are represented by the triangles, and the blue wall, by the heavy dotted line in the second room's representation.

In experiment 2, 32 children (16 males and 16 females) aged 19-24 months (mean age 21.1 months) completed the same task. In the all-white condition, subjects primarily searched the geometrically-correct corners, with search accuracy over 40% ($t(31)=6.38$, $p=.0001$). In the blue-wall condition, however, accuracy did not increase (paired-$t(35)<|1|$), despite the fact that the absolutely-correct corner looked strikingly different from its rotational equivalent. At the end of the disorientation procedure and before each search trial, each subject was made to face a randomly determined direction. There was no effect of "final facing position" on corner choice in this experiment, in either the all-white or the blue-wall condition ($t(15)\text{s}<|1|$). Young children's search accuracy in the landmark condition differed significantly from that of the adults (unpaired-$t(46)=-9.62$, $p=.0001$) but not from that of the rats ($t(35)<|1|$). Once again, no sex differences were found.

Experiment 3 was undertaken to investigate whether young children could use solid objects as landmarks and to attempt to ensure that subjects represented the landmarks' identity and location. Sixteen new subjects, mean age 21.9 months, participated in two search sessions. Before the first session, the experimenter pointed out the landmark(s) to be used in that session (either the blue cloth comprising the blue wall or two distinctive toys, Fig. 2). Before the second session, the child and experimenter played with the second set of landmarks, and then placed them in the room together to be used for that session. Each search session was followed by a test of memory for the landmarks. The results of the two search tests were similar to those of the previous experiments. Young children reliably chose the geometrically-correct locations but did not choose the absolutely-correct location more often than its rotational equivalent, *despite the fact that most subjects remembered the landmarks' identity and location.* Again there were no sex differences and no effect of "final facing position" on corner choice.

Fig. 2: The two environments with nongeometric landmarks used in experiment 3. The room at left contains a blue wall, indicated by the heavy dotted line, and the room at right contains a red and yellow toy dump truck and a brown teddybear, filling roughly equal volumes and with similar shape, indicated by the T and B.

Finally, I assessed young children's performance in a "direct landmark" task in either the rectangular room or in a room whose shape did not allow any distinction among hiding places (Fig. 3). Separate groups of 8 children were tested in a rectangular room (mean age 21.8 months) versus a cylindrical room (mean age 21.3 months). In one session the chamber was entirely white, and the object was hidden behind one part of the chamber wall. In the other session a blue cloth covered the portion of the cylindrical wall directly in front of the object hiding place.

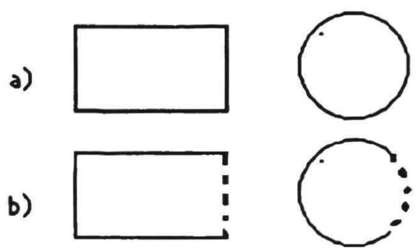

Fig. 3: The rectangular and cylindrical experiment rooms for the "direct landmark" task, experiment 4. a) Rooms for the all-white condition. b) Rooms for the blue-wall condition.

In the cylindrical room, search accuracy was at chance with no landmark (defined as the proportion of wall surface area and circumference occupied by the blue cloth, = 1/6). However, it rose to nearly 90% with the addition of the blue wall. In the rectangular room, in contrast, search tended to be geometrically-correct but was evenly distributed, in the landmark condition, between the blue wall and the opposite white wall. Landmark-guided search in the cylindrical room exceeded that in the rectangular room (unpaired-$t(14)=-2.54$, $p=.024$), suggesting that to determine orientation, children used a direct landmark only when the "geometric module" (Cheng, 1986) was inactive.

These findings show that when young children were unsure of their position and heading, they reoriented themselves and continued with goal-directed behavior by finding a location congruent with their representation of the shape of the environmental layout. Children oriented by such geometric information alone, even though most of them detected and remembered the potentially useful nongeometric landmark information. These findings provide evidence for a common shape-based orientational mechanism in humans and other mammals (or, more likely, land-dwelling polygynous mammals), and for modularity in the young child's mechanism.

In contrast to young children and mature rats, adults conjoined geometric and nongeometric information to orient themselves. Because these two types of information appear to come from anatomically and functionally separate processing systems (Ungerleider & Mishkin, 1982; Farah et al., 1988) adult performance suggests that these systems' outputs become more accessible (Rozin, 1976) over the course of both development and evolution.

Examination of the child's mechanism

I am currently conducting experiments to isolate the mechanisms underlying children's and adults' performance in these tasks, as well as the mechanisms responsible for the striking developmental change from the child's orientation mechanism to the adult's. The first experiment probes whether children's inability to use nongeometric information in the above tasks results from a true exclusion of nongeometric information during orientation, or from a salience hierarchy making geometric information inherently more noticeable to subjects this age. If the former possibility is correct, subjects should exclude nongeometric information from reorientation, but use it in navigation and object-search tasks that do not involve disorientation. If, on the other hand, the latter possiblity is correct, subjects should fail to use the nongeometric information in the test environment (which is identical in the two conditions) whether or not they are disoriented. Preliminary findings for this experiment suggest the former outcome. This in turn suggests a true double dissociation in the child's mechanism for use of geometric and nongeometric information in object search, as shown in tasks identical except for whether subjects were disoriented prior to search.

Another study is designed to distinguish between two possibilities underlying children's failure to use geometric and nongeometric information together in the above tasks. Children may have a logical mechanism allowing them to use the two types of information together, but which cannot operate in the rectangular room indirect landmark tasks because it is suppressed by the function of the geometric module. On the other hand, at this stage of development children may not possess a mechanism for joining these two types of information. In this study I am therefore testing whether young children can solve an indirect landmark task (involving the conjunction of geometric and nongeometric information, e.g. with the object hidden opposite the blue fabric) in the cylindrical room, in which the geometric module appears not to operate.

The developmental change and the "language production hypothesis"

I suspect that children this age cannot conjoin geometric and nongeometric information, because of evidence that a specific linguistic ability, which does not develop until well after age 2, is required for conjunction of information from two separate and encapsulated domains. First, 9 out 10 adults in my first experiment, when asked how they chose a corner to search in the blue-wall condition, immediately responded that they had used the location of the blue wall. However, when the same subjects were asked, after completing the all-white condition, why they only searched in two of the chamber's four corners for the hidden object (the two corners of correct sense relations), only one was able to respond with the correct answer immediately, and only one other subject, given substantial time to think, also mentioned the shape of the room (Hermer, unpublished data). This suggests that orientation in the two conditions drew on two separate systems, only one of whose outputs were accessible to language. Second, I conducted a Child Language Acquisition Database (MacWhinney, 1990) search of children's production of spatial descriptions, and found that only children beyond the age of 5 years could describe spatial relations corresponding to the information necessary for success in the original task (e.g. "the toy is in the corner with blue on the right and white on the left"; Hermer, unpublished data). In piloting the original experiment, I found that no child under age 5.5 years used the nongeometric information when it was available (see below). Third, some evidence suggests that encoding spatial relations with respect to a nearby landmark is more effective with the use of language (Kosslyn, 1988). Fourth, many aspects of problem solving are known to improve with the onset of language (Premack, 1983), whether this results from the development of language itself or from the development of the resources supporting it. And finally, an obvious difference between subjects succeeding at the original task (adults) and those failing it (children aged 19-24 months) was a fluency with language.

My specific hypothesis relies on the fact that language often has access to visually-perceived properties of surfaces (e.g. color, size, shape and texture). When language is used as a way to recode such information, language-based propositions about the spatial relations in question, particularly if they are present in access consciousness (Block, 1992) may be used to override the more automatic function of the geometric orientation system. For this mechanism to operate, the subject must be able to produce the propositions in question. I am now running studies to test this hypothesis, one to determine the ages at which the transition from childlike to adultlike performance (across a variety of tasks) takes place, and another to test specifically the validity of this language production hypothesis. These studies have also been designed to test alternative hypotheses about what mechanism underlies success in the tasks, involving, for example, the myelination of certain fiber tracts (White & White, 1980) or the more general advances in children's concrete reasoning associated with the onset of formal schooling (Cole & Cole, 1991). Even if the "language hypothesis" is sustained, however, it will remain unclear whether the mechanism responsible for success in the tasks is spatial language production per se, or some other logical capacity supporting language (some research suggests the latter possibility, e.g. Premack, 1983). Further studies would be needed to address this.

The adult's mechanism

Human adult spatial orientation may rely on the same mechanisms as those allowing for the developmental change. Alternatively, it may rely on another set of mechanisms, regardless of what mechanisms are found to underlie the developmental change. One adult study I am running addresses whether the processing of geometric information (in an environment containing no useful nongeometric information) and of nongeometric information occur separately, and whether either kind of processing occurs automatically, i.e. quickly and without drawing on significant cognitive resources. Another study of adults addresses both this automaticity issue and whether language is necessary for adults' performance in the original task. Preliminary evidence suggests that orientation by geometric information occurs automatically, without much strain on cognitive resources, while orientation by nongeometric information occurs more slowly and effortfully (Hermer, unpublished data).

The future of this approach

The importance of this research may transcend the study of human spatial orientation. We may find a similar developmental increase in flexibility in other processes for which humans start with adaptive specializations shared by many mammals. For example, aspects of foraging behavior or of interacting with physical objects may initially depend on highly encapsulated mechanisms. After sufficient maturation, however, these processes may operate less automatically and with more integration of information. Furthermore, if the language hypothesis is correct, I would expect linguistic mechanisms to aid in other such increases in flexibility. At least one other line of research supports these hypotheses, that by Gallistel and Gelman (1992) on developmental changes in numerical reasoning. Also, it has been proposed that the formation of isomorphisms between domains of knowledge partly drives conceptual growth (Carey & Spelke, in press; Gentner, 1983). The underpinnings of adults' conjunction of information from disparate systems in my tasks may become a candidate for the mechanism allowing such conceptual change.

Finally, this research will likely contribute to the emerging field of evolutionary psychology. At least one researcher (Rozin, 1976) has suggested that, in tightly constrained circumstances over the course of evolution, previously hardwired adaptive specializations for cognitive function become more flexibly used to solve problems posed by the environment. In proposing a mechanism for this, however, Rozin did not deal with the issue of how selective pressures lead to a more flexible, more domain-general use of information that had been rigidly encapsulated; standard adaptive theory predicts that such systems should only become more refined within the domain for which they evolved (Williams, 1967). If the results of my ongoing research correlate increasing flexibility with language (or with another logical capacity with access to outputs from several different domains), they will suggest that a more domain-general process is "imposed on" the adaptive specializations leading to their more general use. If, on the other hand, no such logical capacity is implicated, they will suggest a widening of the specializations' earlier domains, warranting a modification of adaptive theory for the evolution of brain and behavior.

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