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# Sources of Flexibility in Human Cognition: Dual-Task Studies of Space and Language

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Under many circumstances, children and adult rats reorient themselves through a process which operates only on information about the shape of the environment (e.g., Cheng, 1986; Hermer & Spelke, 1996). In contrast, human adults relocate themselves more flexibly, by conjoining geometric and nongeometric information to specify their position (Hermer & Spelke, 1994). The present experiments used a dual-task method to investigate the processes that underlie the flexible conjunction of information. In Experiment 1, subjects reoriented themselves flexibly when they performed no secondary task, but they reoriented themselves like children and adult rats when they engaged in verbal shadowing of continuous speech. In Experiment 2, subjects who engaged in nonverbal shadowing of a continuous rhythm reoriented like nonshadowing subjects, suggesting that the interference effect in Experiment 1 did not stem from general limits on working memory or attention but from processes more specific to language. In further experiments, verbally shadowing subjects detected and remembered both nongeometric information (Experiment 3) and geometric information (Experiments 1, 2, and 4), but they failed to conjoin the two types of information to specify the positions of objects (Experiment 4). Together,

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the experiments suggest that humans' flexible spatial memory depends on the ability to combine diverse information sources rapidly into unitary representations and that this ability, in turn, depends on natural language. 

Although the neural mechanisms subserving perception, action, memory, and problem solving are substantially conserved across mammals, the functional cognitive capacities of humans show striking unique features. Only humans develop elaborate patterns of tool use, art, ritual, and culturally transmitted bodies of knowledge about the physical and living worlds. How do these abilities emerge from the foundational cognitive systems that all mammals share?

Studies of the phylogenetic and ontogenetic development of spatial representation may shed light on this question. A rich body of behavioral, anatomical, and physiological research has revealed considerable similarities in navigation and spatial representation across all mammals, including humans (e.g., Gallistel, 1990; McNaughton, Knierim, & Wilson, 1995; O'Keefe & Nadel, 1978). For example, all mammals maintain and update representations of their allocentric position and heading through processes of ''dead reckoning'' (e.g., Loomis, Klatzky, Gollege, & Cicinelli, 1993; Mittelstedt & Mittelstedt, 1980) and construct representations of the environment allowing travel along novel paths (e.g., Landau, Spelke, & Gleitman, 1984; Tolman, 1948). Humans and rats even show comparable sexual dimorphisms and seasonal changes in spatial abilities (Bever, 1992; Kimura & Hampson, 1994; Williams, Barnett, & Meck, 1990). Anatomically and physiologically, the structures in the hippocampus and parietal cortex that appear critical for the formation of allocentric spatial representations show strong commonalities over different species of mammals (e.g., Miller, 1991; Seifert, 1983). This body of comparative work suggests that what one learns about navigational processes in any mammal will apply to a first approximation to other mammals, including humans.

Despite these similarities, human navigation shows at least two unique features. First, all people appear to be capable of dead reckoning, but the use of this process is highly variable across different circumstances, individuals, and cultures (Gladwin, 1970; Levinson, 1996b). The errors and variability in human navigation contrast with the accuracy and consistency of navigation in other animals tested in their natural environment (Gallistel, 1990). Second, people typically navigate with great flexibility, using verbal directions, maps, compasses and other devices, and they solve new navigational problems in one or a small number of trials (Hermer & Spelke, 1994; Hermer-Vazquez, 1997). In contrast, nonhuman mammals show more limited flexibility in their navigation and may require hundreds of trials on the tasks that humans quickly master (Cheng, 1986; Biegler & Morris, 1993, 1996). The greater flexibility and speed of human navigation can be seen particularly well in a situation studied extensively both in rats and in humans, in which subjects are disoriented and then reorient themselves in order to find a stably located object. Because this situation forms the basis for all the present experiments, we describe it in some detail.

Cheng (1986) developed a paradigm in which rats searched for food within a closed rectangular chamber, such that the food's location was partly specified by the shape of the chamber and fully specified by the brightness of its walls and the patterns and odors at its corners. After rats were familiarized with the location of a single food source, they were removed from the chamber and disoriented, and then they were returned and allowed to search for the now-hidden food. The investigators assumed that the oriented rats initially stored a representation of the food location (for example, representing the food as buried in the northeast corner of the chamber) and that the disoriented rats had to reorient themselves in order to find it (Gallistel, 1990, and McNaughton et al., 1995, discuss the evidence supporting these assumptions). The position at which rats searched for the food therefore indicated the information that they used to reorient themselves.

In these experiments, rats showed high rates of search both at the correct location and at the geometrically equivalent location on the opposite side of the chamber, despite the many salient cues—including strong and distinctive odors and large differences in contrast and luminosity—that distinguished these two locations (Cheng, 1986; Fig. 1a). Search rates at the two geometrically appropriate locations were indistinguishable when great care was taken to disorient the animals fully so that they had to rely on spatial memory, rather than dead reckoning, to guide their search for the food (Margules & Gallistel, 1988). These findings and similar findings by other investigators (Biegler & Morris, 1993, 1997; Dudchenko, Goodridge, Seiterle, & Taube, 1997) provide evidence that rats reoriented in accord with the shape of the environment but not in accord with the chamber's varied and salient nongeometric properties. Because rats notice and remember nongeometric properties of the environment and use them to solve other tasks, Cheng concluded that the failure to reorient by this information stemmed from limits specific to the reorientation process. Reorientation in rats depended on a task-specific, encapsulated system: a ''geometric module'' (Cheng, 1986; see Fodor, 1983).

The concept of a modular system for reorientation is controversial, for both neurophysiological and behavioral data can be interpreted as evidence against full modularity in rats (e.g., Suzuki, Augerinos, & Black, 1980; Taube, Miller, & Ranck, 1990; Dudchenko et al., 1997) or other animals (e.g., Vallortigara, Zanforlin, & Pasti, 1990). There is broad agreement, however, that geometric information is especially important for reorientation. Reliance on geometric information for reorientation is likely to be adaptive in natural settings, where the macroscopic shape of the environment seldom contains deceptive symmetries. Moreover, the shape of the layout tends to be enduring, whereas snowfall and plant growth, new scent markings, and

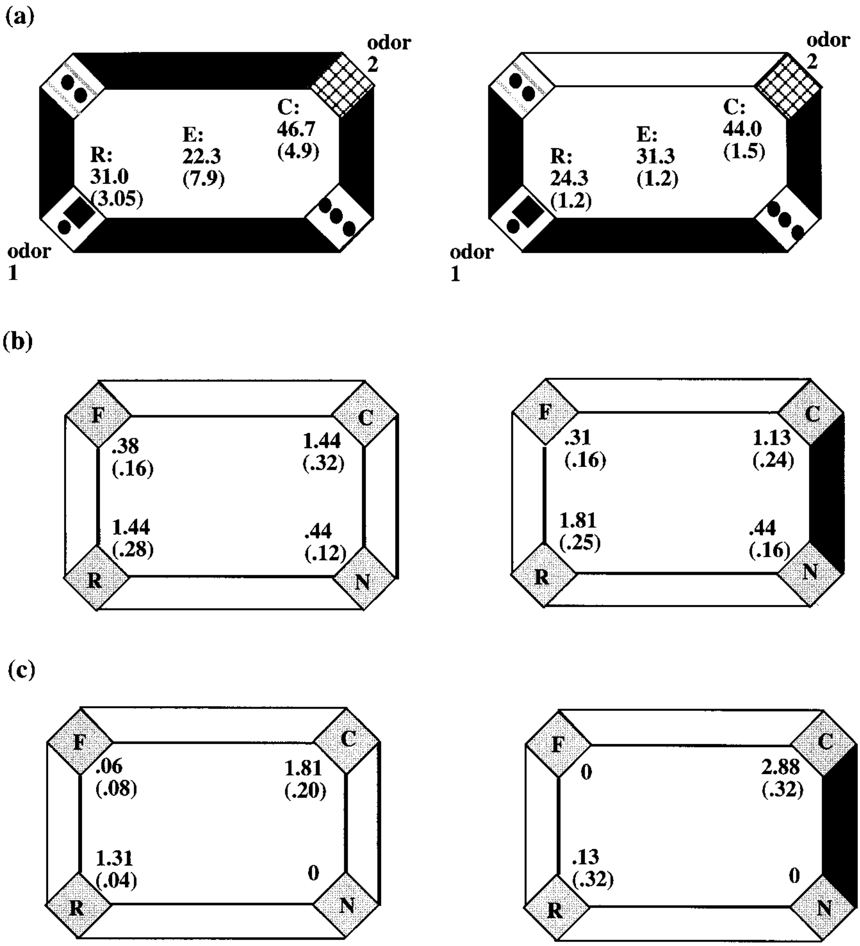


**FIG. 1.** Search rates at the correct location (C), the geometrically equivalent opposite location (R), and other locations (E, N, and F) by (a) adult rats (after Cheng, 1986) and by (b) human children and (c) adults (after Hermer & Spelke, 1996).

displacements of movable objects make the environment's nongeometric properties unreliable cues to orientation. Consistent with this ecological analysis, a wealth of research suggests that geometry provides the primary information for reorientation processes in a wide range of animals (e.g., Dudchenko et al., 1997; O'Keefe & Burgess, 1996; Tinkelpaugh, 1932).

A recent series of studies extends this generalization to human children (Hermer & Spelke, 1994, 1996). In Hermer and Spelke's studies, children aged 18–24 months were brought into a rectangular experimental chamber where they witnessed the hiding of an object in one corner and then were lifted and turned slowly by a parent, with eyes covered, to induce a state of disorientation. In one condition, the chamber was rectangular and contained no distinctive landmarks. In a second condition, the chamber contained a unique, nongeometric feature (a blue wall) that broke the environment's symmetry. As in Cheng's experiments, children's abilities to reorient in accord with both the shape and the coloring of the room were assessed by their search for the hidden object. In the entirely white room, children searched the two geometrically appropriate corners equally, and they searched those corners reliably more than the other corners (Fig. 1b). These search patterns provided evidence that the disorientation procedure was effective and that children remembered the object's location and were motivated to find it. In the room with a blue wall, children again searched the two geometrically appropriate corners with high and equal frequency: like rats, they failed to use the room's nongeometric property to break its symmetry and reestablish their orientation. Subsequent experiments showed that this pattern of performance is quite general over variations in the environment (like rats, children fail to reorient in accord with the distinctive texture or patterning of surfaces or the placement of landmark objects) and specific to reorientation (like rats, children use nongeometric properties of the environment to locate movable objects when they are oriented; Hermer & Spelke, 1996). Young children's reorientation therefore shows detailed similarities with that of adult rats.

Although these findings provide further evidence for homologous navigation processes in humans and other mammals, they raise a puzzle. Intuition and everyday experience suggest that human adults do *not* rely exclusively on environmental geometry to restore their sense of orientation. Rather, disoriented people appear to use of wealth of information to determine their position and heading, including maps, compasses, verbal descriptions, and landmarks of all sorts. Experiments using a variant of Cheng's method confirm these suggestions. When Hermer and Spelke (1994) tested adults in the same task and environments used with children, adults searched the two geometrically correct corners of the white room with equal frequency (evidence for disorientation and for reorientation in accord with environmental shape) but searched only the correct corner of the room with the blue wall (Fig. 1c). Unlike rats and young children, adults appeared to use a nongeometric property of the environment to specify the unique position of the hidden object.

These initial studies suggested that young children reorient by a process that is encapsulated, task-specific, and common to other mammals, whereas adults reorient in a more flexible manner. To explore the sources of this flexibility, Hermer-Vazquez (1997; Hermer, 1994) investigated developmental changes in children's reorientation in a rectangular or square room with one blue or red wall. In three experiments, the transition from encapsulated to flexible performance was associated with advances in the productive use of spatial language.

In an initial study (Hermer, 1994), disoriented children aged 3 to 7 years searched for an object hidden either directly behind a distinctively colored wall or to the left or right of the wall. Success in the former condition first occurred at about age 4, at about the time that children in the study began spontaneously to describe the hidden object's position as ''at the blue side'' or ''in back of the wall.'' Success in the latter condition first occurred at about age 6, when many children in the study began spontaneously to describe the environment with expressions containing the terms ''left'' and ''right.''

To explore this association further, Hermer-Vazquez (1997) measured a variety of cognitive abilities in 5- to 7-year-old children given a reorientation task in a square room with one red wall, and she used regression analyses to investigate which abilities were associated with successful search for an object hidden to the left or right of the colored wall. Success was not related to age or to measures of nonverbal IQ, verbal working memory capacity, vocabulary size, comprehension of spatial language, or production of spatial expressions involving the terms ''above,'' ''below,'' ''front,'' or ''back.'' In contrast, success was related to production of expressions using ''left'' and ''right'' in a separate set of problems involving referential communication: Partialing out the (small) effects of the other measured variables, there was a significant association between performance in the reorientation task and spontaneous production of expressions conjoining spatial sense information with object color information (e.g., ''Put it [a green ball] left of the orange one.''). Furthermore, the reorientation performance of children who showed no ability to produce the relevant phrases was at chance level, suggesting that more flexible reorientation was linked to the emerging spatial language abilities.

In a final experiment, Hermer-Vazquez (1997) investigated whether the improvement in children's spatial performance that was associated with the acquisition of spatial language was specific to the task of reorientation. A new group of 5- to 7-year-old children were given a problem, based on experiments by Biegler and Morris (1993, 1997), that required them to encode the left/right position of a hidden object in relation to a movable visible landmark while they remained oriented. Spatial memory performance followed two qualitatively different patterns: Some children succeeded at the problem after one or a few trials, searching for the object in the correct geometric relation to the nongeometric landmark, whereas other children, like rats, learned to search in the vicinity of the landmark but not in the correct geometric relation to it. To investigate correlates of these different patterns, the children were given tests of production of phrases involving ''left'' and ''right'' as well as other spatial terms. Once again, spatial memory performance was related to the production of verbal expressions involving the terms ‘‘left’’ and ‘‘right,’’ and this association remained when effects of age and other variables were partialled out.

Hermer-Vazquez’s (1997) findings provide evidence that the acquisition of spatial expressions such as ‘‘left of the blue wall’’ is associated with enhanced abilities to represent the spatial relationship of a hidden object to a nongeometric landmark, both when children are disoriented and when they are oriented. For familiar reasons, however, the existence of this correlation does not clarify the nature of the relation between developments in language and spatial performance. It is possible that advances in spatial language and spatial memory are functionally independent but developmentally linked, because they depend on structures that mature at similar times. As a second possibility, developmental changes in spatial language and spatial memory might both depend on a common factor: perhaps the increasing accessibility or explicitness of spatial representations. As a third possibility, the development of spatial language may produce a change in children’s spatial representations, enhancing their ability to locate themselves or objects in relation to nongeometrically specified landmarks.

Concerning the third possibility, the acquisition of a specific, natural language may enhance children’s spatial representations because of two general properties that all natural languages share. First, the lexicon of any language contains terms that refer to entities from different cognitive domains: e.g., spatial terms such as ‘‘east’’ or ‘‘left,’’ color terms such as ‘‘red’’ or ‘‘bright,’’ and object terms such as ‘‘truck’’ or ‘‘wall.’’ Second, the grammar of any language allows terms to be combined irrespective of their domain-specific content: for example, one can describe one’s location as ‘‘left of the red truck,’’ ‘‘in the group with the odd number of players,’’ or ‘‘on the spot where the great injustice took place.’’ A natural language therefore could provide speakers of the language with a medium of representation in which multiple sources of information can be combined flexibly.

The present research was undertaken to investigate this last possibility. Four experiments used a dual-task method with adult subjects to test a set of predictions from the thesis that language provides a medium for flexibly conjoining geometric and nongeometric information. The experiments depended on the assumption that one cannot use language processing mechanisms to perform two tasks at once (e.g., Broadbent, 1971; Brooks, 1968; Cherry, 1957). Experiment 1 investigated whether concurrent verbal shadowing would impair disoriented subjects’ ability to conjoin geometric and nongeometric information so as to locate an object to the left or right of a blue or white wall, while sparing subjects’ ability to locate the object on the basis of geometric information. When these effects were obtained, Experiment 2 investigated whether they were specific to verbal interference by assessing subjects’ reorientation performance while engaged in a nonverbal rhythm shadowing task of equal or greater difficulty. The last experiments investigated the nature of the spatial processes impaired by verbal interference by assessing whether verbally shadowing adults detect and remember nongeometric information (Experiment 3), and whether they can conjoin geometric and nongeometric information when they perform a variant of the moving object search task of Hermer-Vazquez (1997) while in a state of orientation (Experiment 4).

## EXPERIMENT 1

In Experiment 1, college student subjects were given the Cheng reorientation task in the white rectangular room and in the rectangular room with one blue wall. Subjects were tested in each environment with no secondary task (a replication of Hermer & Spelke, 1994), and they were tested in the room with the blue wall while repeating continuously a tape-recorded prose passage that was played throughout the session (Broadbent, 1971; Cherry, 1957). Their search for the hidden object was assessed in each session in order to determine (a) whether nonshadowing adults used the shape of the environment to locate the object in the white room, (b) whether they used the blue wall to locate the object in the room with the blue wall, and (c) whether simultaneous verbal shadowing impaired either of these abilities.

### *Method*

*Subjects.* Participants were 11 male and 5 female university students ranging in age from 18 to 21 years (mean, 18.8 years). Students were recruited through announcements in department courses and were given extra credit for their participation. Additional subjects were omitted from the original sample and replaced because they had gaps of more than 2 s in their shadowing, as judged by a coder of the video record of the session (3), because they maintained their sense of orientation despite the disorientation procedure, as indicated by a pattern of perfect search performance in the white room (3), or because they terminated the experiment before its completion (1).

*Apparatus.* Subjects were tested in a $1.92 \times 1.23 \times 1.92$ m rectangular chamber, housed within a larger experiment room with no windows or obvious sources of noise. The chamber was composed of white felt fabric stretched onto a concealed wooden frame and a padded floor (Fig. 2). A curtained opening to the left of one of the long walls (as one faces it from the outside) permitted entry into the room without breaking its symmetry; when not in use, this opening was sealed with Velcro. Four indistinguishable $23 \times 123$ cm red panels, composed of felt on a concealed wooden frame with a loose fabric curtain at the bottom, stood in the room's four corners. In the nongeometric landmark condition, a bright blue $1.23 \times 1.92$ m piece of fabric was attached to one of the two shorter walls of the chamber by Velcro, such that it covered the wall completely. The room was illuminated from above by four 25-W lights, one in the top center of each wall. A video camera, suspended from the center of the room's ceiling, provided an overhead view of the experiment. During the shadowing session, a central overhead tape recorder with overhead speakers in symmetrical locations toward the two short walls played a tape recording of the experimenter reading political articles from a newspaper. During the noshadowing conditions, a central overhead white noise generator prevented subjects from maintaining their orientation through the use of any sound beacon. A ring of keys served as the object for which subjects searched.

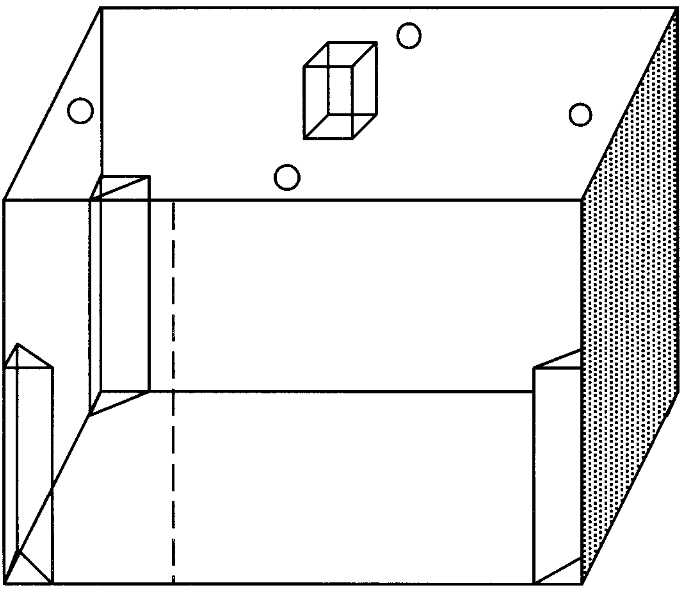

**FIG. 2.** Schematic diagram of the chamber used in the present experiments.

*Design.* Each subject first completed 4 search trials in the room with the blue wall while shadowing, then completed 4 trials in the same environment with no secondary task, and finally completed 4 trials in the white room. On each trial, the object was hidden in a different corner of the room. The facing position of the subject at the end of disorientation varied from trial to trial and was randomly determined with the restriction that approximately equal numbers of trials ended with subjects facing each wall.

*Procedure.* Before the experiment, subjects were told that they would ''see something happening that [they] should try to notice'' during the experiment and that they would be asked about what they saw. They were instructed to allow themselves to become disoriented rather than to attempt to maintain their orientation. Subjects then were trained to repeat verbal material as it was being spoken, syllable by syllable or word by word, rather than waiting for larger syntactic constituents and repeating them as phrases, until they were fluent enough that they could shadow for about 2 continuous min without pausing for more than 2 s at any time. Once they reached this training criterion, they began shadowing continuously and then were led into the testing room with one blue wall and were given the reorientation task.

On each reorientation trial, a subject first saw the object being hidden in one corner and then began rotating slowly with eyes closed. The subject was made to turn at least 10 full rotations, changing direction on cue from the experimenter, who walked around the subject at varying speeds so as not to serve as a landmark herself. The subject was stopped and turned to face in the predetermined direction by the experimenter, who continued walking around slowly so as not to cue the subject to any possible location. Then the subject opened his or her eyes and was asked: ''Where did we hide the keys?'' Subjects either pointed spontaneously to where they thought the object was or were told to ''point'' if they hesitated. At all times if the subject hesitated while shadowing, the experimenter encouraged him or her to continue.

Four reorientation trials were given while the subjects shadowed continuously, and then the subject was led from the room and allowed to stop shadowing. After a 1-min break, the subject returned to the room with the blue wall for four trials without shadowing. After a second break, the blue wall was removed and the subject was given four trials in the entirely white room.

*Coding and analyses.* All searches for the object were coded from the video record by two assistants unaware of the purpose of the experiments. Coders considered a subject to have searched for the object whenever s/he was judged to have pointed to a panel after disorientation, regardless of whether the object was retrieved at that corner. To make this judgment, one experimenter cued the videotape to the point immediately after the hiding of the object, and the other experimenter judged the direction in which the subject faced at the end of disorientation and the location of each of the subject's searches for the object. This procedure ensured that the coder of subject search was blind to the hidden object's location.

The analyses focused on the location of the subject's first search on each search trial. Search was coded in three ways (see Fig. 3): as ''correct'' if the subject searched at the correct corner C, as ''geometrically appropriate'' if he or she searched at C or at the rotationally equivalent opposite corner R, and as ''landmark-appropriate'' if he or she searched at C or at the corner closest to it (N), which had the same distinctive coloring as C in the room with the blue wall. For the first search trial in each condition, binomial tests assessed subjects' tendency to search at the correct corner (chance = .25) and at geometrically appropriate and landmark-appropriate corners (chance = .5). For all the search trials in a condition, we calculated for each subject the percentage of trials with search at correct, geometrically appropriate, and landmark-appropriate corners; single-sample $t$ tests compared these percentages to chance levels (25 or 50%).

Further analyses compared subjects' patterns of correct, geometrically appropriate, and landmark-appropriate search across the different experimental conditions. $\chi^2$ tests compared performance during the first search trial, and analyses of variance, with Gender as the between-subjects factor and Condition as the within-subjects factor, compared performance across trials.

## *Results*

Figure 3 presents the principal findings of this experiment. In the white room, nonshadowing subjects searched for the object with high and equal frequency at the correct corner and at the rotationally equivalent opposite corner. These findings indicate that adults were disoriented and that they used the shape of the room to reorient themselves and find the object. In the room with the blue wall, nonshadowing subjects searched for the object with high accuracy at the correct corner, indicating that they used the conjunction of geometric and nongeometric information to reorient themselves and find the object. When subjects engaged in verbal shadowing in the same environment, however, their search accuracy declined and they searched with high frequency at both the correct corner and the rotationally equivalent opposite corner. Shadowing subjects appeared to use the shape of the room but not the color of the walls to reorient themselves.

Analyses of performance in the white room revealed that nonshadowing subjects tended to search at geometrically appropriate corners on the first trial (binomial $p < .001$) and across all four trials ($t(15) = 13.00$, $p < .001$). Subjects did not show landmark-appropriate search in this condition, in which no landmark was available, either on the first trial ($p > .3$) or across trials ($t < 1$). The use of room geometry produced a significant tendency to search the correct corner at above-chance levels, both on the first trial ($p < .05$) and across the session ($t = 4.39$, $p < .001$).

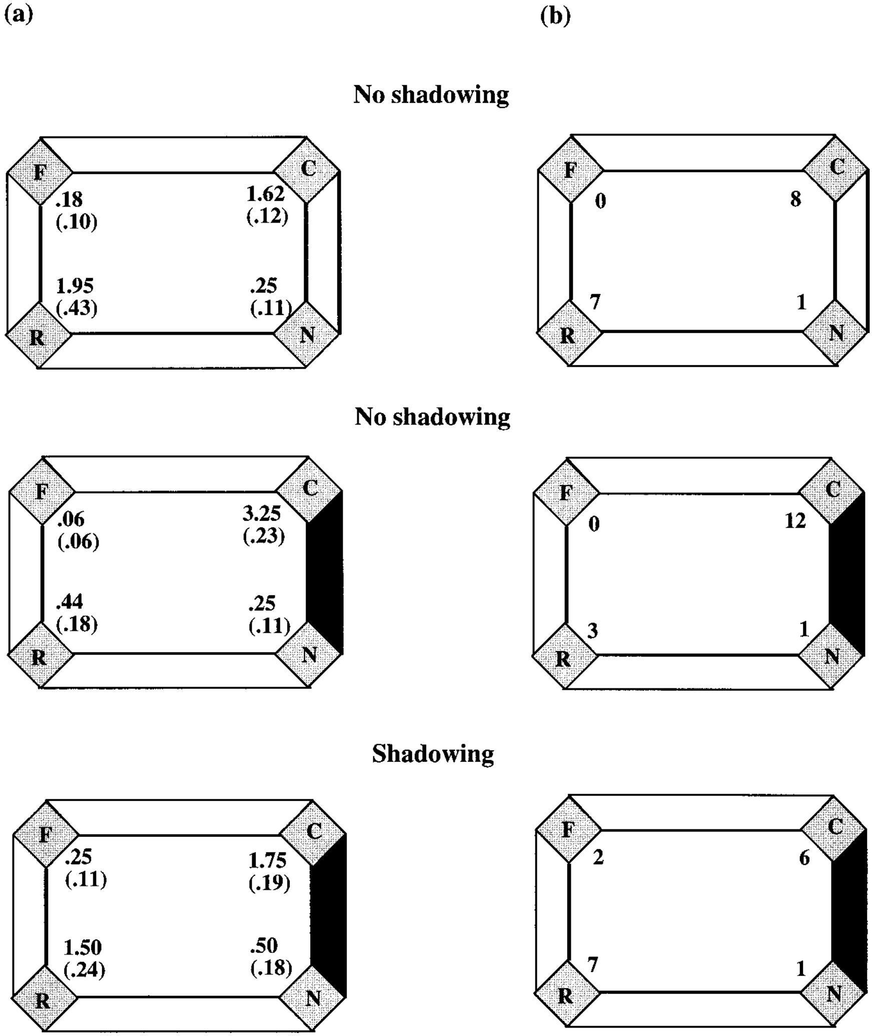


**FIG. 3.** Search rates at the correct location (C), the geometrically equivalent opposite location (R), and the adjacent corners (N and F) in the three conditions of Experiment 1. (a) The mean number of searches at each location (with standard errors in parentheses). (b) The number of subjects searching at each location on the first trial of the experiment.

In the room with the blue wall, nonshadowing subjects showed both geometrically appropriate search (first trial, $p < .001$; across trials, $t = 14.10$, $p < .001$) and landmark-appropriate search (first trial, $p < .02$; across trials, $t(15) = 6.21$, $p < .001$). These effects combined to produce a strong tendency to search the correct corner (first trial, $p < 001$; across trials, $t = 8.45$, $p < .001$).

Finally, shadowing subjects in the room with the blue wall also focused their search on geometrically appropriate corners (first trial, $p < .01$; across trials, $t = 5.84$, $p < .001$), but failed to focus on landmark-appropriate corners (first trial, $p > .3$; across trials, $t = 1$). The use of room geometry led to above-chance search at the correct corner both on the first trial ($p < .02$) and across trials ($t = 3.87$, $p < .001$).

Comparing across conditions, subjects searched geometrically appropriate corners at equivalent rates in the three conditions (in the ANOVA, all $F$s < 1). In contrast, subjects showed different rates of landmark-appropriate search in the three conditions (for the main effect of Condition, $F(2, 28) = 12.64$, $p < .001$; other $F$s < 1). Follow-up tests revealed that subjects showed greater landmark-appropriate search in the blue wall, no-shadowing condition than in the blue wall, shadowing condition, both on the first trial ($\chi^2$ $p < .02$) and across trials ($t(15) = 5.37$, $p < .001$). Subjects also showed greater landmark-appropriate search in the blue wall no-shadowing condition than in the white no-shadowing condition (first trial, $p < .10$; across trials, $t = 4.99$,$p < .001$). Landmark-appropriate search rates did not differ between the blue wall, shadowing condition and the white, no-shadowing condition (first trial, $p > .3$; across trials, $t = 1.28$, $p > .2$). The landmark effects were reflected, as well, in the analysis of search at the correct corner. Subjects searched correctly at different rates in the three conditions ($F(2, 28) = 21.09$, $p < .001$; other $F$s < 2.1). They searched the correct corner in the blue wall, no-shadowing condition more than in either the blue wall, shadowing condition (first trial, $p < .02$; across trials, $t = 5.48$, $p < .001$) or the white no-shadowing condition (first trial, $p < .10$; across trials, $t = 5.93$, $p < .001$), and the latter conditions did not differ (first trial, $p > .3$; across trials, $t = 1.14$, $p > .20$).

*Discussion*

In the conditions of this experiment involving no secondary task, adults who were disoriented in a rectangular room used both the shape of the room and the color of one wall to guide their search for a hidden object. These findings replicate those of Hermer and Spelke (1994) and provide further evidence that human adults, unlike human children or adult rats, use both geometric and nongeometric properties of the environment to reorient themselves and locate objects. In contrast, adults who engaged in verbal shadowing searched for the object only in accord with information about the shape of the environment. They searched geometrically appropriate locations reliably more frequently than geometrically inappropriate locations, but they failed to search the correct location more frequently than the rotationally equivalent, but incorrectly colored, location on the opposite side of the room. Comparing these findings to adults' performance when not shadowing, it appears that the secondary task substantially impaired adults' ability to use the color of the wall to guide their search but had little or no effect on adults' ability to use the shape of the room for the same purpose.[1]

These findings suggest that human adults have a geometric reorientation process similar to that found in young children and rats. Ontogeny and phylogeny do not appear to alter the geometric system but to overlay it with further abilities. The latter abilities appear to be highly vulnerable to verbal interference, moreover, whereas the geometric reorientation process is not.

What properties of the verbal shadowing task interfered with disoriented adults' flexible search for the object? Because verbal shadowing involves language, it may have interfered with appropriate object search by preventing subjects from producing spatial expressions, such as ''left of the short white wall,'' that would specify the object's location in a form that can survive disorientation. Because verbal shadowing also involves working memory and attention, however, it may have diminished the attentional and memory resources available to our subjects (see Baddeley, 1990). If object search based on nongeometric landmarks requires greater resources than geometry-based search, then any interference task that places significant demands on attention and memory might have the same effect on subjects' performance. The next experiment was undertaken to distinguish these possibilities.

Experiment 2 was conducted in three phases. First, we developed a nonverbal analog to the verbal shadowing task used in Experiment 1, we modified the verbal shadowing procedure to improve its effectiveness and its comparability to the nonverbal shadowing procedure, and we compared the difficulty of the two shadowing tasks by assessing their effects on performance of a third task involving no reorientation or spatial memory (Experiment 2a). Next, we replicated two conditions of Experiment 1 with the modified shadowing procedure, assessing disoriented subjects' search for a hidden object in the rectangular room with the blue wall both with and without verbal shadowing (Experiment 2b). Finally, we assessed disoriented subjects' object search in the same environment, both with and without nonverbal shadowing (Experiment 2c). We describe each phase of the experiment in turn.

## EXPERIMENT 2A: VERBAL AND RHYTHMIC SHADOWING

Experiment 2 made use of a new nonverbal shadowing task in which subjects listened to a complicated rhythm and reproduced it continuously. To

[1] The sessions with no shadowing were always run after the shadowing session, but adults' greater success in those sessions is not likely due to any order effect, because no such order effects appeared in the original adult reorientation study, which was conducted with a counterbalanced ordering of conditions in the same environment and with the same procedure, except for the absence of any interference task (Hermer & Spelke, 1994, 1996).

compare the attentional demands of the rhythm and verbal shadowing tasks, we studied three groups of subjects as they participated in a conjunctive visual search experiment (Treisman & Gelade, 1980; see Dosher, 1998, for review). One group of subjects performed the visual search experiment while engaged in verbal shadowing. Two further groups of subjects performed the visual search experiment while engaged in rhythm shadowing with a nonverbal response (tapping) or a verbal response (repeating a single nonsense syllable). The difficulty of each shadowing task was assessed by comparing the speed and accuracy of subjects' performance on the visual search experiment while they performed each interference task.

## *Method*

*Subjects.* Participants were 15 Cornell undergraduate volunteers, 6 males and 9 females, recruited as in previous studies. The subjects ranged in age from 18 to 24 years (mean age, 20.5 years). One additional subject was omitted from the sample and replaced because she failed to engage in continuous rhythmic shadowing.

*Apparatus and materials.* Subjects performed the visual search experiment in a room with 10 Power PCs. Each subject sat at a computer, while other students engaged in the same tasks on other computers. The visual search experiment was programmed in VSearch 2.0. On each of a total of 96 trials, subjects first viewed a fixation point and then saw a field of alphanumeric characters, presented in random locations on a 12 × 12-in. grid and at randomly chosen orientations of 0°, 180°, and 270°. On half the trials, the field consisted of 3, 7, or 11 ''T''s. On the remaining trials, the field consisted of 2, 6, or 10 ''T''s and a single ''L'' (the target). Subjects terminated a trial by hitting either the ''1'' (target present) or the ''2'' (target absent) key of the computer. Termination of the trial was followed by a blank screen for 2 s and then by the fixation point that started the next trial.

While subjects performed the visual search experiment, they heard the verbal or rhythmic interference tape recording played from the front of the room and projected back throughout the room on the same sound system as was used in the other experiments. The verbal interference tape was the same as in Experiment 2. The rhythmic interference tape was a recording of a sequence of hand-clapped rhythms in 4/4 time, which occurred at a rate of about 90 beats per minute and that changed to a new rhythm every 8 beats (two measures). The task was similar to verbal shadowing, because subjects heard continuous input and gave continuous output, and both the input and output were only partly predictable over short time intervals.

*Design.* Two male and three female subjects were assigned to each of the three shadowing conditions. All subjects participated in the same visual search test, in which they received four blocks of 24 trials, half with a target present and half with the target absent. For each type of trial in each block, 4 trials were presented with each of three set sizes.

*Procedure.* Subjects were run in groups of two or three at a time in the same shadowing condition. They were trained simultaneously, sitting at a table. One group of rhythm shadowers was trained to tap out the rhythm on the table with one hand, with the knowledge that they would be entering their responses for the visual search experiment with the other hand concurrently. The other group of rhythm shadowers was trained to give verbal output, by repeating the syllable ''na'' for each beat they were shadowing. Subjects were trained to the same criterion of shadowing performance as in Experiment 1: 60 s of continuous shadowing with no breaks longer than 1 s. Attainment of the criterion was monitored by three experimenters who walked around subjects as they shadowed.

After training, subjects were seated at a computer and read a short list of instructions, and then the shadowing tape recording began. During the experiment, subjects shadowed continuously while searching for the target. Trials were organized into four subject-initiated blocks of 24 trials. After subjects completed each block, they received feedback about their accuracy through an automatically generated summary that appeared on the screen.

As each subject performed this task, he or she was monitored by an experimenter who sat next to the subject and encouraged him or her to continue if shadowing slowed or stopped. The experimenter carried a stopwatch and made a note of any stops longer than 1 s, noting the approximate times of the stops. Subjects were omitted from the sample and replaced if they made any stop longer than 2 s during the search experiment.

*Coding and analyses.* Both reaction time and accuracy were coded for each trial, so that for each block, accuracy and reaction times for each of the two target conditions and each of the distractor numbers was generated. Mixed-factor ANOVAs were performed on the mean reaction times and the percentage of correct data per block. Due to the small number of subjects in each condition, we included subject as a random factor for this experiment.

### *Results*

Figure 4a presents the mean reaction times for each shadowing condition, broken down by whether a target was present or absent and by the number of distractors. Preliminary ANOVAs revealed no effects of gender or block, so these factors were omitted from subsequent analyses. A mixed-factor ANOVA with the factors subject (15), shadowing condition (3, for each type of interference task), trial type (2, for target present vs. target absent), and set size (3, for each number of characters in the display) revealed significant main effects of subject ($F(12, 45) = 7.45$, $p < .001$), trial type ($F(1, 45) = 37.05$, $p < .001$), and set size ($F(2, 90) = 50.52$, $p < .001$) and significant interactions between subject and trial type ($F(12, 45) = 3.37$, $p < .005$), subject and set size ($F(24, 90) = 3.05$, $p < .001$), trial type and set size ($F(2, 90) = 10.15$, $p < .001$), and subject, trial type, and set size ($F(24, 90) = 2.10$, $p < .01$). There were no effects involving the factor of shadowing condition.

Figure 4b shows the accuracy of visual search performance for each interference condition, broken down further by whether a target was present or absent and by the number of distractors. In five of six cases, the subjects engaged in verbal shadowing had the highest accuracy rates, again suggesting that this task may have been the least demanding of subjects' visual attention. Preliminary analyses revealed no effects of the factors sex or block, so these factors again were omitted. The resulting 3 (shadowing condition) $\times$ 15 (subject) $\times$ 2 (trial type) $\times$ 3 (set size) ANOVA showed main effects of subject ($F(12, 45) = 4.08$, $p < .001$) and trial type ($F(1, 45) = 11.36$, $p < .005$) and a significant interaction between subject and trial type ($F(12, 45) = 2.86$, $p < .01$). Again, no effects involving shadowing condition were significant.

### *Discussion*

On the visual search experiment, subjects' reaction times varied as a function of both the number of distractors and the presence of a target, as expected from earlier visual attention studies (Dosher, 1998; Treisman & Gelade, 1980). Reaction times were similar in the three dual-task conditions, with

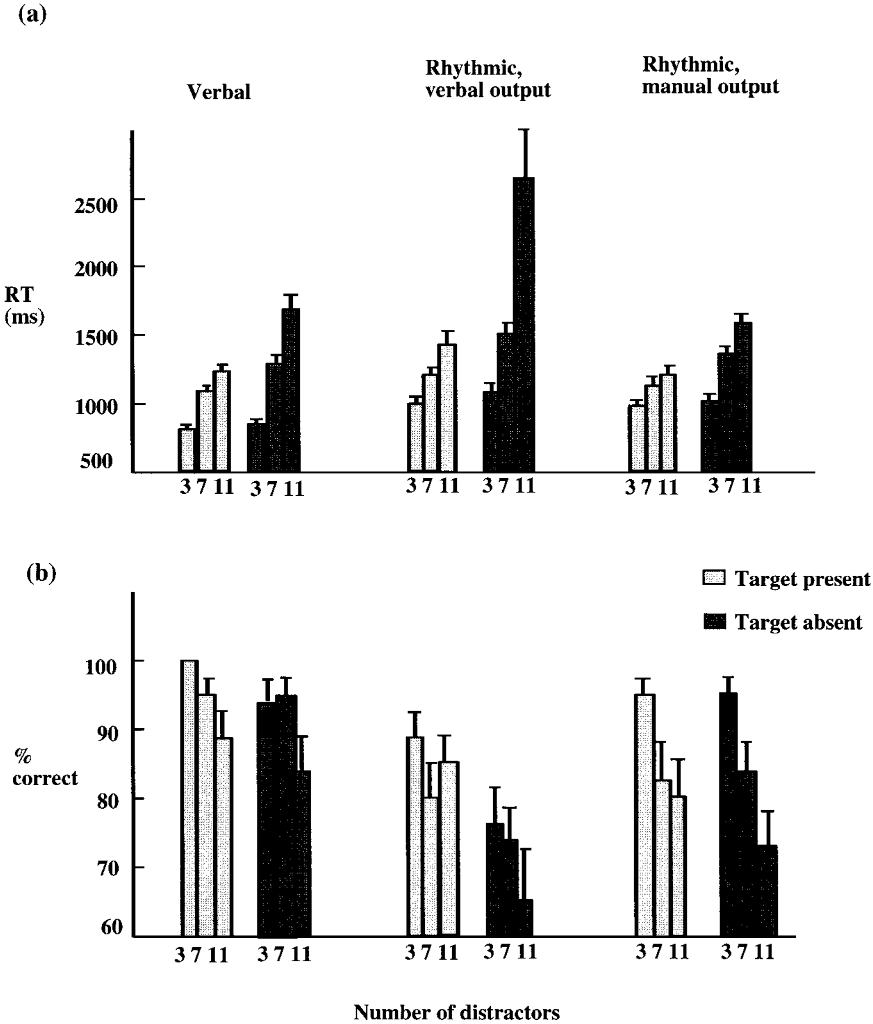


**FIG. 4.** Mean response latencies (a) and percentage of correct responses (b) for the three interference conditions of Experiment 2a.

nonsignificantly faster performance, suggesting less interference, in the verbal shadowing condition. Error rates also were nonsignificantly lower in the verbal shadowing condition, indicating that the reaction time effects do not stem from a speed–accuracy trade-off and again suggesting that rhythm shadowing is at least as demanding as verbal shadowing. Informal reports by the subjects supported this suggestion, for rhythm shadowers commented more often than verbal shadowers on the difficulty of the task.

One might ask whether the (nonsignificantly) larger interference produced by rhythm shadowing stemmed from the greater demands of rhythm shadowing on general attentional or memory resources or whether it stemmed from interference of a more specific kind. In the shadowing task with nonverbal input (rhythm) and output (tapping), in particular, the tapping response might have caused specific interference with the key press response required for the visual search experiment. The findings from the rhythm shadowing condition with verbal output (repeating the syllable ‘‘na’’) cast doubt on this possibility. Although responses in this condition should not interfere with the key press response any more than responses in the verbal shadowing condition, interference was as great in this condition as in the other nonverbal shadowing condition and nonsignificantly greater than interference in the verbal shadowing condition. Rhythm shadowing therefore appears to place demands on attention and memory that at least equal the demands of verbal shadowing. If verbal shadowing shows greater interference with blue wall reorientation, that finding likely would stem from specific effects of verbal shadowing on language processing.

## EXPERIMENT 2B

This experiment was a replication of Experiment 1 with the improved verbal shadowing training procedure, conducted in a larger rectangular room than that used in Experiment 1 and with a modified reorientation procedure designed to call subjects’ attention to the nongeometric landmark. Subjects were tested only in the room with one blue wall, first with verbal shadowing and then with no secondary task. Because use of the blue wall precludes assessment of the effectiveness of the disorientation procedure (in Experiment 1, disorientation was assessed by comparing searches at the correct vs. opposite corners in the white room), a subset of the subjects was given a brief assessment of their state of orientation on a final trial.

### *Method*

*Subjects.* Participants were 10 male and 6 female university students ranging in age from 18 to 23 years (mean, 20.0 years), recruited as in previous experiments. Two additional subjects were omitted from the original sample because of failure to shadow continuously (1) or misunderstanding of the directions (1).

*Apparatus and materials.* Subjects were tested in a $2.31 \times 1.69 \times 1.85$-m rectangular chamber composed of brown pegboard fastened to a concealed wooden frame, with white acrylic fabric stretched over each internal wall and the ceiling and carpet on the floor (Fig. 5). The concealed door, corner panels, illumination, audiotape recordings, and video observation were as in Experiment 1. The shorter walls were removable for future experiments (see below). A plastic frog which emitted a sound when squeezed served as the object for which subjects searched.

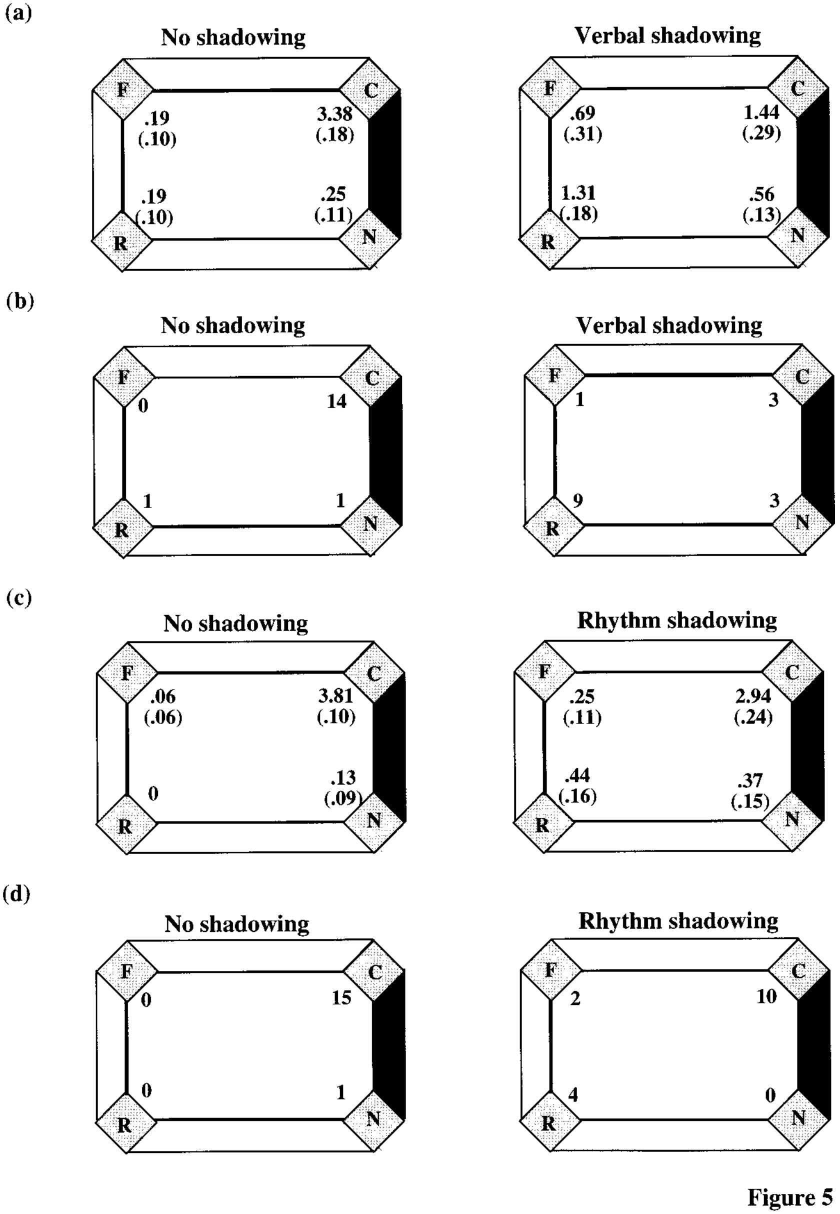


**FIG. 5.** Search rates at the correct location (C), the geometrically equivalent opposite location (R), and the adjacent corners (N and F) in Experiment 2b (a and b) and Experiment 2c (c and d). The mean number of searches at each location (with standard errors) appears in (a) and (c). The numbers of subjects searching at each location on the first trial of the experiment appear in (b) and (d).

*Design.* Each subject completed four codable trials with verbal shadowing and four codable trials without shadowing. In addition, the last eight subjects received one disorientation assessment trial (see below). The design was otherwise the same as that in Experiment 1.

*Procedure.* Two experimenters conducted the study. Subjects were trained on verbal shadowing as in Experiment 2a, until they could shadow continuously for 60 s with no pause longer than 1 s. Then a second phase of training was given, in which shadowing proceeded as before except that subjects also were instructed by the first experimenter to ''notice what [the second experimenter] was doing'' as she walked around the room pointing at various objects. While they observed the second experimenter, subjects continued shadowing until they could shadow continuously for 60 s without stopping at any time for longer than 1 s. Finally, subjects learned a set of nonverbal commands the experimenter would give them for starting or stopping rotation during the disorientation procedure. The shadowing training was otherwise the same as that in Experiment 1.

For the disorientation test, subjects were led with their eyes closed into the experiment room, the shadowing tape was turned on and adjusted in volume to the subject's liking while the subject waited with eyes closed, the subject began shadowing, the first experimenter reentered the room and sealed the door, and the experimenter tapped on the subject as a signal to open his/her eyes. The experimenter then drew the subject's attention to the short blue and white walls by motioning toward each wall and tapping on it until subjects had clearly fixated it; she tapped first on the white wall for half the subjects and first on the blue wall for the others. The experimenter then picked up the plastic frog which had been resting on top of one of the corner panels, moved it into the subject's field of view, squeaked it loudly several times, and with large motions moved it toward its first hiding location and placed it behind the panel in that corner. The experimenter motioned that the subject should begin turning in place with eyes closed. After 30 s of turning with two reversals of direction, the experimenter stopped the subject with a tap and said loudly, ''Where was the frog hidden? And please keep shadowing!'' Subjects nearly always looked around the room and pointed or searched at a corner. If a subject hesitated and appeared confused, the experimenter repeated, ''Where's the frog? Point or touch where.'' After the subject pointed or touched a corner, the experimenter signaled him to begin the disorientation procedure for the next trial.

At the end of four search trials with shadowing, the experimenter told the subject to stop shadowing and she turned off the shadowing tape. Four more search trials in the room with one blue wall, similar to the trials with shadowing, commenced. For four subjects, the experiment ended after the last search trial. For the remaining subjects, these trials were followed by an assessment of the effectiveness of the disorientation procedure. The object was hidden, the subject turned as before, and then the subject stopped turning with eyes still closed and pointed to where s/he thought the object was.

*Coding and analyses.* All searches for the object were coded from the video record as in Experiment 1. To assess whether subjects were disoriented, the coder measured the angular deviation between the true location of the hidden object and the direction of blindfolded pointing at the object degrees between 0 and 180° (clockwise or counterclockwise, whichever way the deviation was 180° or less).

The principal analyses were the same as those for Experiment 1. For the assessment of the effectiveness of the disorientation procedure, subjects' mean angular deviation of eyes-closed pointing to the object was analyzed by a single-sample $t$ test against a population mean of 90°. Note that if subjects as a group were disoriented, we would expect a uniform distribution of scores between 0 and 180°, with a mean of 90°.

## *Results*

Figures 5a and 5b present the findings of this experiment. As in Experiment 1, subjects located the object with high accuracy when they were not engaged in shadowing. When shadowing, accuracy declined and subjects searched with high and equal frequency at the correct corner and the rotationally equivalent opposite corner.

The analyses confirmed these findings. In the no-shadowing condition, subjects showed geometrically appropriate search on the first trial (binomial $p < .001$) and across trials ($t(15) = 9.93$, $p < .001$), and they showed landmark-appropriate search as well (first trial, $p < .001$; across trials, $t = 10.50$, $p < .001$). These effects combined to yield a strong tendency to search the correct corner (first trial, $p < .001$; across trials, $t = 13.22$, $p < .001$). In the verbal shadowing condition, subjects searched geometrically appropriate corners (first trial, $p < .05$; across trials, $t = 2.54$, $p < .025$) but not landmark-appropriate corners (first trial, $p > .3$; across trials, $t < 1$). Because subjects tended nonsignificantly to search more at corners with the inappropriate coloring, the tendency to search the correct corner was not significant either on the first trial ($p > .3$) or across trials ($t = 1.52$, $p > .10$).

Comparisons across the two conditions revealed that the rate of search at geometrically appropriate corners did not differ on the first trial ($\chi^2$ $p > .1$) but did differ across trials (for the main effect of Condition, $F(1.14) = 12.59$, $p < .005$; other $F$s $< 1$). Subjects searched landmark-appropriate corners and the correct corner at higher rates in the no-shadowing condition, both on the first trial (both $p$s $< .001$) and across trials (for the main effect of Condition, respective $F$s $(1.14) = 30.44$ and $60.89$, $p < .001$; for all other effects, $F < 1$).

A final set of 2 (Experiment) $\times$ 2 (Gender) $\times$ 2 (Condition) ANOVAs compared performance in Experiment 2b to that in Experiment 1 for each of the three search measures. None of these factors significantly affected subjects' geometrically appropriate search, although search at geometrically appropriate corners was marginally higher in the no-shadowing condition ($F(1.28) = 3.15$, $p < .10$). Landmark-appropriate search and correct search rates were higher in the no-shadowing condition (respective $F$s$(1, 28) = 51.22$ and $76.76$, $p < .001$), but no other effects were significant. Performance in the two experiments therefore was very similar.

In the disorientation assessment, the average angular deviation from the correct pointing direction was 84° (SE = 14.6°). This did not differ significantly from 90° ($|t| < 1$) and indicated that the disorientation procedure was effective.

*Discussion*

The present experiment replicated the principal findings of Experiment 1. Disoriented subjects who engaged in verbal shadowing located a hidden object correctly in relation to room geometry, but they failed to locate the object in relation to a nongeometric landmark. In contrast, the same subjects located the object in relation to both geometric and landmark information when they were not shadowing. Success on the disorientation task without shadowing cannot be attributed to the decreasing effectiveness of the disorientation procedure, because the final disorientation assessment trial provided evidence that subjects were effectively disoriented throughout the study. Rather, nonshadowing subjects appeared to locate the object in the search test by encoding and remembering its relationship to the blue wall, and verbal shadowing appeared to interfere with this process.

When the subjects in Experiment 2b were shadowing, they showed reduced search at geometrically appropriate corners. This effect, however, could be an artifact of the effect of shadowing on subjects' use of the nongeometric landmark: Because the correct location in relation to the blue wall was also one of the two geometrically appropriate corners, any use of the blue wall to guide search will inflate the measure of geometrically correct responding. To test whether shadowing interfered specifically with the use of geometric information, therefore, it is necessary to compare the rates of geometric responding during shadowing to the rates of geometric responding by nonshadowing subjects in a room with no nongeometric landmarks. This comparison was made in Experiment 1 and provided no evidence for an effect of verbal shadowing on use of geometric information. It is noteworthy, moreover, that the rates of search at geometrically appropriate corners were as high in the shadowing conditions of Experiments 1 and 2b as in previous experiments with adult rats (Cheng, 1986) and young children (Hermer & Spelke, 1994).

Having found again that verbal shadowing impaired disoriented subjects' use of a nongeometric landmark to locate a hidden object, we next asked whether rhythm shadowing would have the same effect.

## EXPERIMENT 2C

Experiment 2c was identical to Experiment 2b except for the shadowing procedure. Subjects shadowed a rapidly presented and frequently changing sequence of rhythms by clapping out a rhythm as they heard it.

### *Method*

*Subjects.* Participants were 11 females and 5 males between the ages of 18 and 21 years (mean age 19.1 years), recruited as in previous experiments. No subjects were eliminated from the sample.

*Materials, design, and procedure.* These were identical to those used in Experiment 2b, except that the subjects were trained and tested with the nonverbal shadowing task of Experiment 2a using a clapping response.

### *Results*

Figures 5c and 5d present the search results from this experiment. Subjects tended to search the correct corner more than any other corner both when they were shadowing the rhythmic sequence and when they were not shadowing. The accuracy of search at geometrically appropriate corners was about as high on rhythmic shadowing trials as on the verbal shadowing trials of Experiment 2b. In contrast, the accuracy of search in relation to the nongeometric landmark was higher on the rhythmic shadowing trials than on the verbal shadowing trials of that experiment.

The analyses support these findings. Subjects showed geometrically appropriate search both in the no-shadowing condition (first trial, binomial $p < .001$; across trials, $t(15) = 17.99$, $p < .001$) and in the shadowing condition (first trial, $p < .005$; across trials, $t = 6.21$, $p < .001$). Subjects also showed landmark-appropriate search in the no-shadowing condition (first trial, $p < .001$; across trials, $t = 31.00$, $p < .001$) and, except for the first trial, in the shadowing condition (first trial, $p > .10$; across trials, $t = 7.46$, $p < .001$). These tendencies combined to yield high search rates at the correct corner in the no-shadowing condition (first trial, $p < .001$; across trials, $t = 27.91$, $p < .001$) and in the shadowing condition (first trial, $p < .002$; across trials, $t = 7.77$, $p < .001$).

Comparisons across the two conditions revealed no difference in subjects' tendency to search geometrically appropriate corners when shadowing vs. not shadowing, either on the first trial ($\chi^2$ $p > .30$) or across trials ($F(1, 14) = 2.75$, $p > .1$). In contrast, subjects showed higher rates of landmark-appropriate search and of correct search in the no-shadowing condition, both on the first trial (respective ps $< .02$ and $< .01$) and across trials (respective $F$s $= 9.95$ and $9.33$, $p < .001$). There were no main effects or interactions involving gender in these analyses (all $F$s $< 1.4$).

Further 2 (Experiment) × 2 (Gender) × 2 (Condition) ANOVAs compared subjects' search patterns across Experiments 2b and 2c. The analysis of geometrically appropriate search revealed no interaction of Condition by Experiment ($F(1.28) = 1.56$, $p > .2$): Verbal and rhythm shadowing had equivalent effects on geometrically guided search. The analyses of landmark-appropriate search and of correct search, in contrast, each revealed a significant interaction of these factors (respective $F$s $= 7.32$ and $7.61$, $p < .02$): Verbal shadowing had a greater effect on landmark-guided search and on correct search than did rhythm shadowing. All three analyses revealed better performance overall in the no-shadowing condition (for geometrically appropriate search, $F(1, 28)=12.34$, $p < .002$; for landmark-appropriate search and correct search, respective $F$s $= 38.85$ and $53.89$, $p < .001$) and marginally or significantly better performance in Experiment 2c (for geometrically appropriate search, $F(1, 28) = 3.79$, $p < .10$; for landmark-appropriate search and correct search, $F$s $= 11.42$ and $13.78$, $p < .001$). Subjects' gender did not influence search (all $F$s $< 1$).

On the disorientation assessment trial, the mean pointing deviation was 84°, which did not differ from the population mean for a disoriented population ($t < 1$) or from that of the eight subjects who received the disorientation assessment in Experiment 2b ($t < 1$).

*Discussion*

Disoriented subjects who engaged in nonverbal shadowing searched the correct corner substantially more than they searched the rotationally equivalent corner. This search pattern provides evidence that the subjects were able to use a combination of geometric and nongeometric information to locate the hidden object. The subjects engaged in rhythm shadowing searched the correct corner more than did those who engaged in verbal shadowing in Experiment 2b, who used the room's geometry but not its coloring to locate the object. This difference provides evidence that the language demands of verbal shadowing impaired performance.

Several alternative explanations for the difference between the two shadowing conditions can be eliminated. First, subjects did not perform better during rhythmic shadowing because that task led to more frequent gaps and pauses in shadowing performance during the spatial memory experiment. Although subjects reported that rhythm shadowing was very difficult, monitoring of their performance from the video records indicated that they performed continuously during reorientation trials. Second, subjects did not perform better during rhythmic shadowing because they were less disoriented: The final disorientation assessment trial indicated that subjects were equally disoriented in the two shadowing conditions. Finally, rhythmically shadowing subjects did not perform better than verbally shadowing subjects because rhythmic shadowing was less difficult. The findings of Experiment 2a indicated that subjects were at least as impaired on a concurrent visual search task by rhythm shadowing as by verbal shadowing, even when the shadowing procedures used similar responses. Although the two shadowing tasks had similar effects on visual search and on use of geometric information in the disorientation test, verbal shadowing caused a specific impairment during the blue wall reorientation task.

These findings could be explained in two ways. First, adults may use language to combine geometric and nongeometric information, and verbal shadowing may interfere with this combination process. On this view, verbally shadowing adults are able to detect and remember both geometric and nongeometric information but not their conjunction. Second, adults may combine geometric and nongeometric information independently of language, but verbal shadowing may interfere with their ability to detect or remember the nongeometric landmark. Although verbal shadowing largely spared adults' abilities to represent and remember geometric information, it may distract adults from noticing or recalling the nongeometric landmark. Reports by the subjects in Experiments 1 and 2b favor the first explanation: 12 of 16 subjects reported that they noticed the blue wall before or during the first search trial, and 13 of 16 subjects reported that they had noticed it by the middle of trial 2. Several subjects reported that they had seen the blue wall and had tried to use it to remember the hidden object's location, but that they were unable to do so. Because these reports were given post hoc, however, the next experiment was undertaken to distinguish between the two potential explanations.

## EXPERIMENT 3

In Experiment 3, we presented verbally shadowing subjects with a simplified version of the search task. The experiment was conducted in a rectangular room with one blue wall, as in Experiments 1 and 2b, with two changes in method. First, the object was hidden directly behind the top of the short blue or white wall rather than to the left or right of the wall. Because the distinctively colored wall served as a direct cue to the object's location, subjects did not have to conjoin geometric and nongeometric information to locate the object. Instead, they could learn a direct association between the nongeometric cue and the goal object: a strategy available both to animals (see O'Keefe & Nadel, 1978; Gallistel, 1990; Vallortigara et al., 1990) and to young children (Hermer & Spelke, 1996).

A second modification was made to encourage subjects to adopt the associative strategy and not rely on their sense of orientation to locate the object. The environment used in Experiments 2–4 was constructed so that the two short walls with attached corner boxes were removable. After the subject was disoriented and while he or she continued shadowing with eyes closed, both short walls and the hidden object were brought outside the chamber. The subject then was led from the chamber with eyes closed, opened his or her eyes while continuing to shadow, and was asked to find the hidden toy. Because the wall covering the hidden object now appeared in a different environment, a reorientation strategy for finding the object in its previous geocentric position was now irrelevant. Indeed, research with children and rats provides evidence that displacing a hidden object and visible landmark from their original locations causes a redefinition of the search task and allows use of a direct nongeometric cue to solve it (Hermer & Spelke, 1996; Biegler & Morris, 1993).

Experiment 3 therefore investigated whether adults would use the nongeometric property of wall coloring to locate the object. If verbal shadowing impaired subjects' ability to notice or remember the blue wall in Experiments 1 and 2b, then it should cause a similar impairment in Experiment 3, and subjects should search equally for the object behind the two walls. In contrast, if verbal shadowing specifically impaired the ability to conjoin geometric and nongeometric information to specify the position of the object, then it should not impair performance in Experiment 3: Subjects should confine their search to the wall of appropriate coloring.

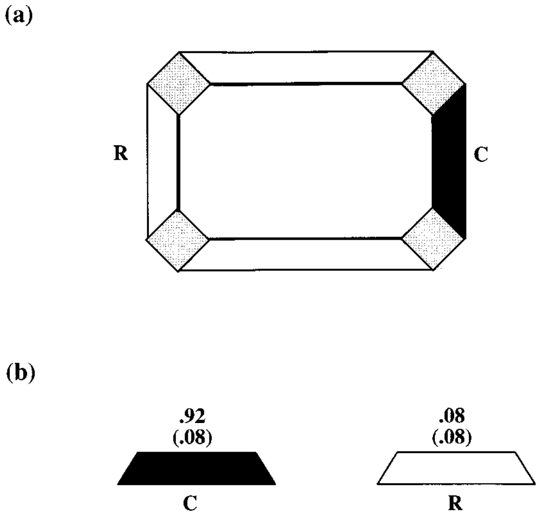


**FIG. 6.** Search rates at the correct location (C) and the geometrically equivalent opposite location (R) in Experiment 3.

## *Method*

*Subjects.* Participants were 5 females and 7 males between the ages of 17 and 25 years (mean age 19.8 years), recruited as in Experiment 1. No subjects were omitted from the sample.

*Apparatus.* The rectangular chamber from Experiment 2 was used so as to permit removal of the two short false walls and their attached corner pillars. Each removable short wall was attached to the inside of the chamber's permanent short walls with Velcro. They could be taken through the door of the experiment room and moved to a position against a wall in the larger experiment room, where they stood side by side (Fig. 6). A large, flat, red sticker served as the search target. The shadowing tape recording was the same as that in Experiment 2b.

*Design.* Each subject was tested on one trial, with one half of subjects having the object hidden behind the short blue wall and the other half having it hidden behind the short white wall. An attempt was made to test subjects on a second trial as well, with continuous shadowing during and between the two trials, but the data from the second trial were either unusable (5 Ss) or questionable, because the length of the procedure strained subjects' shadowing ability. Only the first trial data were analyzed.

*Procedure and analyses.* Subjects were taught to shadow and then were led into the experiment room as in Experiment 2b. Once inside the room and shadowing, they saw an experimenter point out the two short walls as before and then hide the large red sticker directly behind one of the false-wall panels, affixed to its top. While subjects were rotating themselves after the object had been hidden, the two experimenters opened the chamber door, pulled each of the short wall panels out from the room in turn, and moved them to their new position outside the experiment room so that they were side by side along a large white wall just outside. The experimenters then returned to the room and led the subject, who was still shadowing with eyes closed, out to the two panels. Once midway between the two walls and in a location where the hidden object could not be seen, subjects were asked: ''Where's the sticker?'' Subjects gave their responses, which were coded online by the experimenters as correct if the subject pointed to the correctly colored wall panel and as incorrect if he or she pointed to the other colored panel. Analyses were the same as those for the first trial data of Experiments 1 and 2, based on the single measure of landmark-appropriate responding (search at C, chance = .50).

### *Results*

The results are presented in Fig. 6. Subjects located the hidden object with high accuracy, choosing the correctly colored wall reliably more than the other wall (binomial $p < .005$). Landmark-appropriate search was higher in Experiment 3 than in the verbal shadowing conditions of Experiments 1 and 2b (both $\chi^2$ $p$s $< .005$).

### *Discussion*

Disoriented, shadowing subjects correctly located the hidden object behind the wall of the appropriate color, indicating that they noticed and remembered the relevant nongeometric information. Together with the findings of Experiment 1 and 2b, this finding suggests that shadowing adults are able to detect both geometric and nongeometric properties of the environment, but that they cannot conjoin information from those two domains to specify the location of an object.

The question behind our last experiment concerns the generality of the effect of language on flexible spatial performance: Does language allow people to combine geometric and nongeometric information only in situations in which they are disoriented or does it allow for such combinations in any situation? If language provides a general-purpose medium for combining information from diverse domains, then human adults may perform more flexibly than children or other mammals on any task in which geometric and nongeometric information must be conjoined, and their flexibility should be impaired when they must engage in simultaneous verbal shadowing.

One developmental finding by Hermer-Vazquez (1997) provides preliminary support for this possibility. In 6- to 7-year-old children, the spontaneous production of expressions involving ‘‘left’’ and ‘‘right’’ correlated not only with success in the blue wall disorientation experiment but also with success in a conjunctive memory task involving no disorientation. This correlation suggests that the development of spatial language is associated with a general ability to encode the geometric relation of a hidden object to a displaced, nongeometric landmark. Experiment 4 was undertaken to investigate this possibility further by assessing the effects of verbal shadowing on oriented adults’ ability to locate a hidden object by conjoining geometric and nongeometric information.

## EXPERIMENT 4

Experiment 4 closely followed the method of Experiment 3. Subjects in one condition were trained on the verbal shadowing procedure of Experiments 2b and 3 and were led into the room used in those experiments, where they viewed an object being hidden in a corner of the room. While they were rotating with their eyes closed, the two short walls and adjoining corner boxes were moved out of the room against a large wall, as in Experiment 3. Subjects then were led from the chamber while still shadowing and were asked to point to the toy. A separate group of subjects underwent the same procedure except that they did not undergo shadowing at any time.

Like Experiment 3, the present experiment did not involve reorientation, because subjects were tested in a larger, geometrically distinctive environment and because the landmarks were moved to that environment, rendering their former geocentric positions irrelevant to finding the object. In contrast to Experiment 3, however, subjects could not locate the hidden object by forming a direct association between the object and a nongeometric cue. Rather, subjects needed to conjoin geometric and nongeometric information so as to represent the object as occupying a corner in a particular spatial relationship to a wall of a particular color. If verbal shadowing impairs the encoding of nongeometric information only in reorientation tasks, then both shadowing and nonshadowing subjects should successfully find the object, as in Experiment 3. If verbal shadowing impairs the conjoining of geometric and nongeometric information in any situation, in contrast, then nonshadowing subjects should successfully find the object but shadowing subjects should not.

### *Method*

The method was the same as that in Experiment 3, except as follows.

*Subjects.* The experimental group consisted of 10 females and 6 males between the ages of 18 and 42 years (mean age 21.4 years). The control group consisted of 3 females and 9 males between the ages of 18 and 24 years (mean age 20.1 years). Two additional subjects were omitted from the experimental condition because of failure to understand the task or give interpretable search data (they pointed toward locations in the original experiment room rather than at the corners of the movable walls outside that room).

*Design.* Each subject in both the experimental and the control condition received one search trial in which the object was hidden in a corner to one side of one movable wall. Both the color of the wall where the object was hidden (blue or white) and the side on which it was hidden (left or right) were orthogonally counterbalanced across the subjects in each condition. When subjects left the room and faced the two movable walls, half the subjects in each counterbalancing condition viewed the white wall on the left and half viewed the blue wall on the left.

*Procedure and analyses.* The procedure for the experimental condition was the same as that in Experiment 3, except that the object was the plastic frog, hidden in a corner box, as in Experiment 2. The procedure for the control group was the same except that a white noise mask replaced the shadowing tape and no shadowing was performed. Each subject was tested on one search trial, and search patterns were analyzed by binomial and $\chi^2$ tests.

### *Results*

Figure 7 presents the findings from this experiment. Subjects tested without shadowing searched primarily at the correct corner. In contrast, subjects tested with shadowing searched with high and equal frequency at the correct

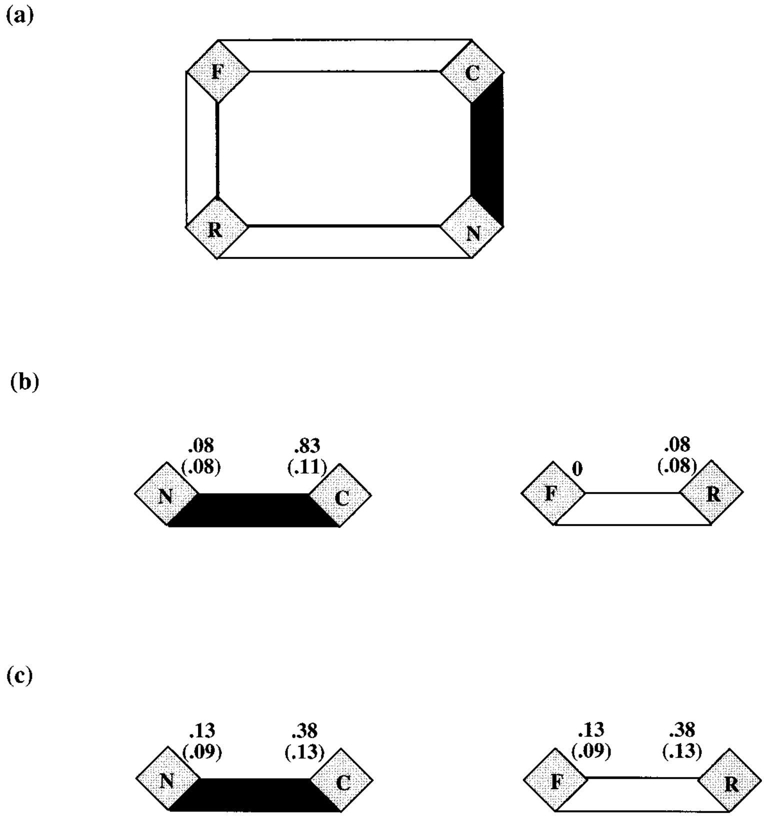


**FIG. 7.** Search rates at the correct location (C), the geometrically equivalent opposite location (R), and the adjacent corners (N and F) in Experiment 4; (b) no shadowing; (c) shadowing.

location and the geometrically equivalent location along the wall of the incorrect color. That is, if the toy had been hidden in a corner on the left side of the blue wall, the shadowing subjects tended to choose a corner on the left side of a short wall outside the chamber but chose the left side of the blue and white walls equally. Subjects focused their search on geometrically appropriate corners both in the no-shadowing condition (binomial $p < .005$) and in the shadowing condition ($p < .05$). Subjects also tended to search landmark-appropriate corners in the no-shadowing condition ($p < .005$) but not in the shadowing condition ($p > .3$). Searching at the correct corner also was high in the no-shadowing condition ($p < .001$) but not in the shadowing condition ($p > .3$).

Comparing across the two conditions, subjects showed similar rates of geometrically appropriate search whether or not they were shadowing

($\chi^2$ $p > .1$). In contrast, they showed reduced landmark-appropriate search and correct search when shadowing (both $p$s $< .005$). Search patterns in the shadowing and no-shadowing conditions of Experiment 4 did not differ from those in the corresponding conditions of Experiments 1 and 2b by any measure (all $p$s $> .3$). Landmark-appropriate search during shadowing was lower when the landmark was indirect (Experiment 4) than when it directly marked the location of the hidden object (Experiment 3) ($p < .005$).

*Discussion*

The findings of this experiment were very similar to those of Experiments 1 and 2b. All subjects tended to choose a corner that had been geometrically correct in the experiment room, whether or not they were shadowing. Whereas subjects who did not shadow restricted their search to the correct corner, those in the shadowing condition searched equally at the correct corner and at the corresponding corner of the incorrectly colored wall. Together with Experiment 3, these findings provide evidence that verbally shadowing subjects can detect and remember nongeometric information but fail to conjoin geometric with nongeometric information to guide search for an object. Together with Experiments 1 and 2b, these findings provide evidence for a failure to conjoin information regardless of whether the information is to be used to reorient the self or to locate a movable object.

These results accord with the developmental findings of Hermer-Vazquez (1997). They suggest that language provides a domain-general medium for conjoining geometric and nongeometric information specifying the positions of objects and that this representation is used for diverse purposes. The effects of language are not limited to situations involving reorientation.

In view of the findings of Experiment 3, it may appear curious that the shadowing subjects in Experiment 4 were not able to adopt any alternative strategy for solving the search task. Even without language, for example, a subject might be able to locate a hidden object by following a response rule such as ‘‘look for blue (as in Experiment 3) and then turn left.’’ As a second example, a subject might be able to locate the object by forming and maintaining a visual image of the corner where it was hidden and then searching for the best match of that image to the four visible corners during the test. Animals such as rats can learn both response rules and search images, and we suspect that humans can learn them as well, with sufficient training or time to reflect on the task. In ordinary circumstances, however, humans and other animals locate objects by representing their positions within a larger space (see McNaughton et al., 1995, for a local-space view and Gallistel, 1990, for a geocentric view). Unlike response rules or visual images, these more comprehensive spatial representations can guide search for an object under a wide range of circumstances, whatever the action to be performed and however other objects in the visible environment are moved, as long as the navigator remains at least partially oriented (Knierim, Kudrimoti, &

McNaughton, 1998). By disorienting subjects completely, our experiments therefore place them in a state for which their biology is apparently ill-prepared. What is perhaps most surprising is not that human adults do not spontaneously provide for disorientation by learning response rules or forming and maintaining visual images, but that they do spontaneously overcome the effects of disorientation through the use of language.

## GENERAL DISCUSSION

The present experiments used a dual-task method to investigate developing humans' uniquely flexible spatial performance. Focusing on situations in which human adults reorient themselves and locate movable objects more successfully than preverbal children or adult rats, we found that introduction of a verbal shadowing task abolished the unique features of adults' performance and led them to perform in ways strikingly like those of young children and other mammals. This finding supports two suggestions. First, the spatial memory system by which children and other mammals reorient themselves is present and functional in human adults. Its distinctive character is revealed by an interference task that subtracts away the effects of other, more flexible, memory systems. Second, language plays a role in the generation of the flexible spatial performance that is unique to humans among extant species.

Both suggestions depend on the assumption that a secondary task (here, verbal shadowing) impairs performance on a primary task (here, reorientation and object search) because the two tasks share a specific component (here, productive language). Contrary to that assumption, it is possible that dual-task interference stems from more general limits on cognitive resources such as attention and memory. Although we do not regard this issue as fully resolved, two features of the present findings suggest that shared components of language production account for the impairment observed in these experiments. First, verbal shadowing interfered with conjunctive spatial memory but nonverbal shadowing did not, even though the nonverbal shadowing task appeared to be at least as demanding as the verbal shadowing task and showed equal or greater interference with a third, attention-demanding activity (Experiment 2a).

Second, verbal shadowing impaired subjects' abilities to reorient and to locate a movable object by conjoining geometric and nongeometric information, but it had little effect on subjects' abilities to reorient and locate movable objects by geometric or nongeometric information alone. If verbal shadowing impaired performance by placing general demands on attention or memory, then the size of its effect on the ability to detect and remember the conjunction of geometric and nongeometric information might be predictable from the size of its effects on the ability to detect and remember either source of information alone. This prediction might be tested by using the difference between search at the correct corner in the shadowing and no-shadowing conditions of Experiments 1, 2b, and 4 as a measure of the impairment of sensitivity to the conjunction of information, using the difference between search at a geometrically appropriate corner in the blue wall shadowing and the white no-shadowing conditions of Experiment 1 as a measure of the impairment of sensitivity to geometric information, and using any difference between search at the correctly colored wall in the shadowing condition of Experiment 3 and in a similar task run with no shadowing as a measure of the impairment of sensitivity to nongeometric information. Addressing each component first, there is a minimal impairment of use of geometric information by shadowing indicated by this logic (a reduction in rate of use of this kind of information by 2% between the two conditions). Although we did not run a no-shadowing condition of Experiment 3, even if nonshadowing subjects searched the correctly colored wall 100% of the time, the findings would indicate only an 8% decrease in the use of nongeometric information caused by shadowing. The union of these two measures[2] would predict a 10% decrease in the use of both types of information together, if shadowing caused no specific interference with the process of conjoining information. In contrast to this prediction, much larger effects of shadowing were observed in Experiments 1, 2b, and 4. These effects provide evidence that verbal shadowing specifically impaired subjects' ability to conjoin geometric and nongeometric information about the object's location.

One possible account for the effect of language on flexible performance proposes that humans have a collection of cognitive systems for representing the environment, including, for example, information represented in the ''what'' and ''where'' visual systems (Ungerleider & Mishkin, 1982) and in the cognitive mapping system of the hippocampus (O'Keefe & Nadel, 1978). Each system may be largely homologous to those in other animals and largely continuous in its functioning over development. Moreover, each system may be relatively autonomous and resistant to interference: a desirable characteristic for an animal that must maintain its sense of orientation and remember where it has been as it runs through the forest, its attention riveted to predator or prey. Finally, each system may be relatively encapsulated in its functioning. According to a strong encapsulation thesis (Fodor, 1983; Gallistel, 1990), each system would receive its inputs from, and send its outputs to, a limited set of other systems to which it has specific connections. According to more moderate versions of this thesis, each system would receive inputs from, and send outputs to, a wide set of other systems but would communicate more directly, readily, and consistently with some systems than with others. On either version of the encapsulation thesis, however,

[2] The two measures of impairment must be added, because failure to search at C could result from the effect of shadowing on geometric or nongeometric information use alone or from its effect on their combination.

the cognitive systems that humans share with other animals would not be uniformly connected to one another. Information that is represented by distinct systems therefore could be combined readily in ways privileged by the cognitive architecture, but not in arbitrary ways.

In addition to these systems, adults may have a further system of representation that is uniquely human and that emerges over the course of human development. This system may connect to many other systems of representation, regardless of their domain-specific content. Its operation may be governed by rules and principles allowing the arbitrary combination of information from distinct, domain-specific sources. This uniquely human system therefore may serve as a medium in which information captured by different encapsulated systems can be combined rapidly and with ease. The language faculty appears to have all the right properties to serve as this uniquely human combinatorial system of representation.

It has been argued that language cannot extend the range of nonverbal cognitive abilities, because language itself is learned, and its learning depends on the nonverbal cognitive abilities in question (Fodor, 1975). By this argument, a child could not learn to represent an object as located *left of a blue wall* by virtue of learning the corresponding linguistic expression, because learning the expression itself requires that the child map that expression to a preexisting nonverbal representation. The proposal sketched above suggests a reply to this argument. Young children (and other mammals) have nonverbal systems for representing geometric properties of the environment, such as sense relations: for example, the children in Hermer's experiments distinguished corners with a short wall on the *left* from those with a short wall on the *right*, as did the rats in Cheng's studies. Children and other mammals also have nonverbal systems for representing nongeometric properties of the environment, such as brightness or color. As children learn language, therefore, they may learn the meanings of terms like ''left'' and ''blue'' by relating the use of these terms to the appropriate geometric and nongeometric representations. Once the terms are learned, the combinatorial properties of the language faculty allow the terms to be concatenated to form expressions such as ''left of the blue thing.'' Such expressions can serve to represent relationships that the child's nonverbal systems cannot capture, because of the encapsulation of those systems.

These suggestions lead to a number of predictions that further experiments could test. First, people with language impairments may show reduced flexibility on spatial memory experiments, performing more like children and other animals. Second, children with language delay may show a delayed transition from the inflexible performance of rats to the flexible performance of human adults. Third, people living in language communities lacking terms such as ''left'' and ''right'' may show qualitatively different patterns of performance on spatial memory experiments (cf. Levinson, 1996a).

Fourth and most important, flexible performance may emerge over human development not only in situations involving spatial memory but in any situations requiring arbitrary combinations of information from diverse sources. Language may be implicated wherever such transitions occur, and so verbal interference may abolish humans' distinctively flexible performance. The use of dual-task methods therefore might serve to unmask a variety of cognitive systems that humans share with other species, and it may help to decompose the processes that underlie uniquely human cognitive performance.

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