II. Topographical Relations as One Dimension of Stimulus Control

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Three experiments using human participants examined a major prediction derived from cognitive mapping theory of place learning: In the absence of proximal cues, place performance depends on relations among distal cues. Experiments 1 and 2 showed that, after learning to find an invisible target in computer-generated (C-G) space, removing the full set of distal stimuli disrupted place performance but removing subsets of distal stimuli did not. These results demonstrate that the full array of distal cues are critical to stimulus control of place performance in this C-G space whereas individual stimuli are not. Experiment 3 showed that, after learning to find an invisible target in the same C-G space, changes in topographical relations among the distal stimuli disrupted place performance. As predicted by cognitive mapping theory, the results suggest that participants use relations among distal cues to guide place performance in C-G space. In addition, the results support the assertion that place learning in C-G space is comparable to both rat and human place learning in mundane space. © 1998 Academic Press

The present experiments examined the role of distal stimuli in guiding human place performance in computer-generated space. To do so, we used a task in which humans observe a computer display of a circular arena, consisting of a featureless purple wall enclosing a gray floor, housed within a large experimental room. The walls of the experimental room, programmed to appear at some distance from the arena wall, contain complex stimuli...
representing various objects. The participants use a joystick to search for an invisible target on the floor of the arena. After several acquisition trials, humans typically move through the computer-generated space directly to the invisible target and successfully end each learning trial (Jacobs, Laurance, & Thomas, 1997).

Jacobs et al. (1997) interpreted these data within the context of cognitive mapping theory (see, e.g., Nadel, 1991; O'Keefe & Nadel, 1978). By this account, an organism may successfully navigate an environment by using a previously formed spatial map of that environment. Spatial maps of an environment, consisting of information about specific objects and relations among them, are formed when an organism enters and observes an environment. By definition, such a map allows an organism to apprehend that every object stands in some spatial relation to every other object in that environment. Spatial relations among these objects specify places in the environment and thus may exert stimulus control over place performance. Hence, an organism may locate itself in a familiar environment without reference to specific environmental stimuli, so long as there is a sufficiently large set of stimuli available to generate the relations needed to permit accurate spatial localization and navigation (see also Gallistel, 1990).

Such a model of place learning and performance predicts that relations among stimuli representing distal objects control place performance. The major purpose of the present series of experiments was to examine this prediction within the Computer-Generated Arena (C-G Arena) described by Jacobs et al. (1997).

Conventionally, stimulus control is inferred when changes in a specific feature of a stimulus complex correlates with changes in a specific feature of a behavioral sequence (Terrace, 1966; Rilling, 1977). Following this convention, Experiments 1 and 2 examined the effects of removing individual distal stimuli on place performance in the C-G Arena. If the removal of the stimuli from one or more distal walls correlates with a change in place performance, then we have evidence of stimulus control by localized distal stimuli. If we observe little or no change during these trials, then we have evidence that these stimuli exert little or no essential stimulus control. Experiment 3 examined the effect of changing topographical relations among the distal stimuli on place performance in the C-G Arena. If a change in spatial relations among arrays of distal stimuli correlates with changes in place performance, then we have evidence of stimulus control by topographical relations among distal stimuli. If we observe little or no change during these trials, then we have evidence that relations among these stimuli exert little or no essential stimulus control in this situation.

Cognitive mapping theory predicts that (a) removing any subset of distal stimuli will leave well-learned place performance unaffected, but (b) changing topographical relations among distal stimuli will disrupt well-learned place performance. Thus, the experiments specifically ask whether humans
associate the place of the invisible target with some specific distal stimulus or whether they use information about spatial relations among arrays of distal stimuli to guide place performance in the C-G Arena.

EXPERIMENT 1

Experiment 1 examined the effect of removing sets of distal stimuli on place performance in the C-G Arena. Participants learned to find an invisible target and then received test trials during which all distal stimuli from one of the four walls of the experimental room were removed. Distal stimuli from a different wall were removed on each test trial. If the distal stimuli located on any wall of the experimental room exert stimulus control over place performance in the C-G Arena, then removing these stimuli will disrupt place performance. If these distal stimuli exert little or no stimulus control over well-learned place performance in the C-G Arena, then removing these stimuli will have little or no effect on place performance.

Method

Participants

Twenty undergraduates, 9 males and 11 females, between 18 and 23 years of age, served as participants.

Apparatus

A personal computer and custom-designed software generated a display on a computer monitor. The monitor displayed a multicolored view of a circular arena patterned after that described by Morris (1981). The arena was contained within one of two square rooms, a waiting and an experimental room, from the perspective of one standing on the floor of the room. The monitor did not display a representation of the participant.

The C-G waiting room. The waiting room consisted of a computer-generated display of a 1500 × 1500 × 475-unit room housing an arena. Four walls colored blue, green, red, and yellow, respectively, demarcated the C-G waiting room. The ceiling of the room was a light gray and the floor a dark gray. The walls, ceiling, and floor of the C-G waiting room lacked texture.

A featureless purple wall, 460 units in radius and 30 units high, enclosed the central portion of the waiting room floor, thus defining the waiting arena. The computer screen displayed a view as if the eyes of the participant were 15 units from the waiting room floor. When one stood against and faced the purple arena wall, the wall filled the computer screen. When one stood against the arena wall but turned away from it, the screen displayed a large portion of the arena, a portion of the surrounding waiting room, and a part of its ceiling. Exposure to the waiting room distinguished the experimental trials from one another and, if needed, permitted the participant to practice moving in the computer-generated space.

The C-G experimental room. The experimental room consisted of a com-
puter-generated display of a 1500 × 1500 × 475-unit room housing an arena. The ceiling of the room was a light gray and the floor a dark gray. The walls of the room were arbitrarily designated the North, East, South, and West walls. The North wall was gray and displayed a door flanked by two windows; the East wall displayed six and one half black arches; the South wall was gray and displayed three centered windows; the West wall was textured gray and displayed a single centered window.

As in the C-G waiting room, a featureless purple wall, 460 units in radius and 30 units high, enclosed the central portion of the floor of the experimental room, thus defining the arena. The computer screen displayed a view as if the eyes of the participant were 15 units from the experimental room floor. As in the waiting room, when one stood against and faced the purple arena wall, the wall filled the computer screen. When one stood against but turned away from the arena wall, the screen displayed a large portion of the arena, the surrounding room, and part of the ceiling.

Target. A 142 × 142-unit square target was located on the floor of the C-G experimental room. The visible target was a featureless blue and, when facing it, could be seen from any location in the arena. The color of the invisible target was identical to the surrounding arena floor. The target was level with the arena floor.

Joystick and keyboard. Participants used a joystick to move in the C-G Arena. Moving the joystick forward moved the participant’s view forward 10.0 units. Holding the stick forward moved the participant’s view forward about 20–30 units/s; moving the joystick backward moved the participant’s view backward at the same rate; moving the joystick to the left or to the right turned the participant’s view of the arena in place 3.0° to the left or right. Holding the joystick to the left or right turned the participant’s view about 30–40°/s.

Participants moved (“teleported”) from the waiting room to the experimental room by striking the space bar on the computer keyboard. They moved from the experimental room to the waiting room by striking the space bar while standing on the target.

Quadrants. The arena was divided into four imaginary quadrants. Moving clockwise, the first was named Northwest (NW), the second was named Northeast (NE), the third was named Southeast (SE) and the fourth was named Southwest (SW). Lines delineating the quadrants were not a part of the computer-generated display. The invisible target was located in the SE quadrant. Figure 1 provides an illustration of each of the four quadrants and the visible target, as viewed from the opposite quadrants.

1 If we, for the sake of convenience, take the length of a stride (10 units) to be the equivalent of 1 meter, then both the experimental and waiting rooms were 150 × 150 × 47.5m, the walls of the arenas in each room were 3 m high and the radius of each was 46 m. The target in the experimental room was 14.2 × 14.2 m. Finally, participants moved at 2–3 m/s.

2 A color illustration may be seen at http://w3.arizona.edu/~arg/clip1.jpg.
FIG. 1. Four representations of the computer-generated arena as seen by the participants. The upper left panel illustrates the participants’ view of the NW Quadrant as seen from the opposite (SE) quadrant. A portion of the left end of the North wall and the right end of the West wall are visible. The target is not visible from this angle. The upper right panel illustrates the participants’ view of the NE Quadrant as seen from the opposite (SW) quadrant. A portion of the right end of the North wall, the left end of the East wall, and the target (at the far left) are visible from this angle. The lower left panel illustrates the participants’ view of the SE Quadrant as seen from the opposite (NW) quadrant. A portion of the left end of the South wall, the right end of the East wall, and the target (on the right side of the arena floor) are visible from this angle. Finally, the lower right panel illustrates the participants’ view of the SW Quadrant as seen from the opposite (NE) quadrant. A portion of the right end of the South wall and the left end of the West wall are visible. The target is not visible from this angle (see Jacobs et al., 1997, for a top-view representation of the configuration of this arena).

Procedure

Instruction Phase. Each participant entered the laboratory and read and signed a consent form. Each participant then received written instructions outlining the rules governing (a) what they would see on the computer screen, (b) how to teleport from the arena in the waiting room to the arena in the experimental room, (c) how to teleport from the arena in the experimental room to the arena in the waiting room, (d) the order in which these rooms
would be presented, (e) how to move in the arenas, and (f) the goal to be reached in each arena (see Jacobs et al., 1997, for an example). An experimenter remained seated behind the participants throughout the experiment to answer questions about the instructions or the task.

**Practice Phase.** The instructions were followed immediately by two practice trials. Each trial began with the participant facing the yellow wall in the center of the C-G waiting room. The participant teleported from the arena in the waiting room to the arena in the C-G experimental room by pressing the space bar. Each participant entered the experimental arena at a randomly determined start position facing and within 2 units of the arena wall. The task was then to turn around, search for, find, and stand on a *visible* blue target located on the arena floor. Pressing the space bar while on the target ended the practice trial and teleported the participant back to the arena in the waiting room. If the participant did not find the target within 2 minutes, then the practice trial terminated and the participant automatically teleported to the middle of the arena in the waiting room.

The next practice trial began when the participant teleported from the waiting room to the arena in the experimental room by pressing the space bar. The location of the target was changed for each of the two practice trials.

**Acquisition Phase.** The Practice Phase was followed immediately by eight acquisition trials. Each trial began in the center of the C-G waiting room with the participant facing the yellow wall. The participant teleported from the arena in the waiting room to the arena in the experimental room by pressing the space bar. They entered at a randomly determined start position facing and within 2 units of and facing the arena wall. The task was then to turn around, search for, find, and stand on an *invisible* target on the arena floor. The invisible target was centered in the NW quadrant, approximately 234 units from the closest part of the arena wall, on each of the acquisition trials.

When the participant found and stood on the invisible target, it became visible, but became invisible if the participant moved off it. The target, when visible, was identical to the target presented during the practice trials.

For the first three of the acquisition trials, the experimenter helped the participant locate the target if the participant had not found it within 3 minutes. For the remaining trials, if the participant did not find the target within 3 minutes, the trial terminated and the participant automatically teleported from the experimental to the waiting room.

**Test Phase.** Four cycles of trials immediately followed the Acquisition Phase. Each cycle of the test phase consisted of two trials. The first, a test trial, was followed immediately by a trial identical in all respects to those that occurred during the Acquisition Phase. During the test trial, the distal stimuli located on one randomly chosen wall of the experimental room were eliminated, leaving the wall blank. The invisible target remained in the same place relative to the walls.
If the participant did not find the target on either trial in the test phase within 3 minutes, the trial terminated and the participant automatically teleported from the experimental to the waiting room.

Probe Phase. The Test Phase was followed immediately by a single 2-minute probe trial. The probe trial was identical to the acquisition trials with these exceptions: (a) The target, unknown to the participant, was not in the arena, and (b) after 2 minutes, the trial terminated and the participant automatically teleported to the waiting room.

Final Phase. Each participant received a final (20th) trial immediately following the Probe Phase. The final trial began in the waiting room. The participant teleported from the waiting room to the arena in the experimental room by pressing the space bar and entered the arena at a random start position within 2 units and facing the arena wall. The task was then to turn around, search for, find, and stand on a visible blue target located in the center of the arena floor. Pressing the space bar while on the target ended the final trial and this portion of the experiment. 3

The participants completed the experimental procedures within 30–60 minutes of entering the laboratory. The Type I error rate (\(\alpha\)) was set at 0.05 for all statistical decisions.

Results

All participants located the target during the Practice Phase and the Final Trial. During the Acquisition Phase, however, 11 of the 20 participants received help locating the target on one or more of the first three acquisition trials.

Figure 2 illustrates the mean time required to find the invisible target obtained from the 20 participants during the Acquisition Phase of the experiment. As can be seen, orderly learning occurred. A repeated-measures ANOVA detected significant differences across the trials (\(F[7, 133] = 6.74\)). Orthogonal post hoc comparisons showed no significant differences in the time required to find the invisible target among Acquisition trials 4, 5, 6, 7, and 8. The mean of these six Acquisition trials taken together did not differ significantly from the mean of trial 3 (\(F[1, 19] = 4.09\)). The mean of these six Acquisition trials (3–8) taken together differed significantly from the mean obtained on Acquisition trial 2 (\(F[1, 19] = 10.32\)), and the mean of these seven Acquisition trials (2–8) differed significantly from the mean obtained on Acquisition trial 1 (\(F[1, 19] = 14.79\)). This pattern implies the following order of the means:

\[
\text{Acquisition trial 1} > \text{2} > \text{3} = \text{4} = \text{5} = \text{6} = \text{7} = \text{8}.
\]

3 We included the Practice and Final Phases on the suggestion of Ron Skelton. The Practice Phase helped eliminate nonoptimal search strategies during the acquisition trials and the Final Phase served to leave each participant with a successful final trial.
FIG. 2. Mean time and SE (±1) in seconds to find the target over the acquisition trials of Experiment 1.

This pattern of data suggests that performance was asymptotic across Acquisition trials 3–8. Based on this and other analyses, we used the data from Acquisition trials 5–8 as a baseline representing asymptotic place performance in the present and all subsequent experiments.

Figure 3 illustrates the mean time required to find the invisible target on an asymptotic baseline (the mean of Acquisition trials 5–8) and the trials when distal stimuli were removed from the North, East, South, or West wall of the computer-generated room containing the C-G Arena. As can be seen, no obvious differences appear among these means. A split-plot ANOVA confirmed this impression. The analysis detected no significant differences among the mean times required to find the invisible target on acquisition trials 5–8, and the trials during which the distal stimuli on either the North, East, South, or West walls were absent.

Discussion

The results of Experiment 1 show that, once acquired, no set of stimuli on a single distal wall exerted detectable stimulus control over human place performance in the C-G Arena. The results are compatible with this prediction derived from cognitive mapping theory: The removal of any single subset of distal stimuli will have no effect on any measure of place performance.

Although removing the stimuli on a single distal wall did not disrupt stim-
FIG. 3. Mean Time and SE (±1) in seconds to find the target for the baseline (the mean of Acquisition trials 5–8 is illustrated) and the trials on which the distal cues from the North, East, South, or West wall were removed.

ulcus control of place performance in the C-G Arena, it is possible that removal of a larger number of distal stimuli would demonstrate stimulus control over place performance in this situation. As described in the traditional stimulus control literature (Terrace, 1966), removing increasingly large arrays of distal stimuli should increasingly disrupt place performance. In contrast, cognitive mapping theory predicts that removing increasingly large arrays of distal stimuli should leave place performance intact. All models, of course, predict that removing the full set of distal stimuli will profoundly disrupt place performance.

EXPERIMENT 2

Fenton, Arolfo, Nerad, and Bures (1994) reported that rats may learn to locate an escape platform hidden in a Morris water maze using as few as two distal cues. In addition, after learning the place of a hidden target in the presence of four distal cues, the removal of any two of these cues did not impair performance. Experiment 2 extended the Fenton et al. (1994) design by allowing human participants to learn the location of an invisible target in the C-G Arena. Following acquisition, participants received three test trials during which all stimuli on randomly chosen sets of one, two, or three of the distal walls were absent. On a fourth test trial, the stimuli on the four distal walls of the experimental room were absent. These test trials were presented in random order.

An “increasing array” hypothesis of stimulus control in this situation predicts increasing disruption of place performance as a function of the number of stimuli eliminated. A cognitive mapping hypothesis predicts no disruption
in place performance when the stimuli on one, two, or three of the distal walls of the experimental room are absent. It also predicts that place performance will be disrupted when the stimuli on all four walls of the experimental room are removed.

Method

Participants

Twenty-four undergraduates, 9 males and 15 females, between 18 and 27 years of age, served as participants. They were recruited as described in Experiment 1.

Apparatus

The apparatus described for Experiment 1 was used. The invisible target was located in the SE quadrant of the C-G arena.

Procedure

Instruction Phase. Each participant read and signed a consent form immediately upon entering the laboratory. Each then received the instructions described in Experiment 1.

Practice Phase. The instructions were followed immediately by two Practice trials as described in the Methods section of Experiment 1. If the participant did not find the target within 2 minutes, the trial terminated and the participant automatically teleported from the experimental to the waiting room.

Acquisition Phase. The Practice Phase was followed immediately by eight Acquisition trials administered under the conditions described in Experiment 1. For the first three acquisition trials, the experimenter helped the participant locate the target if the participant had not found it within 3 minutes. For the remaining trials, if the participant did not find the target within 3 minutes, the trial terminated and the participant automatically teleported from the experimental to the waiting room.

Test Phase. Four cycles of trials immediately followed the Acquisition Phase. Each cycle consisted of a test trial immediately followed immediately by a trial identical in all respects to those that occurred during the Acquisition Phase. During each test trial, all stimuli located on one, two, three, or four randomly chosen distal walls were eliminated. The invisible target remained in the same place relative to the remaining distal stimuli. The trials on which stimuli from one, two, three, or four distal walls were eliminated was randomly determined for each participant. The set of distal stimuli to be eliminated on any given trial (those on the North, East, South, or West walls) was also randomly determined.

If the participant did not find the target within 3 minutes, the trial termi-
nated and the participant automatically teleported from the experimental to the waiting room.

*Probe Phase.* The Test Phase was immediately followed by a single 2-minute Probe trial during which, as described in Experiment 1, the full set of distal stimuli were present. The target was not in the arena during this trial.

*Final Phase.* The Probe Phase was immediately followed by a single 2-minute trial identical to the trials presented in the Practice Phase as described in Experiment 1.

**Results**

All participants located the target during the Practice Phase and the Final Trial. During the Acquisition Phase, 6 of the 24 participants received help locating the target on one of the first 3 acquisition trials.

Figure 4 illustrates the mean time required to find the invisible target obtained from the participants during the Acquisition Phase of the experiment. Orderly learning occurred. As in Experiment 1, we used acquisition trials 5–8 as a baseline against which to compare the effects of removing one or more sets of distal stimuli on place performance in the C-G Arena.

Figure 5 illustrates the mean time required to find the invisible target during the performance baseline (the mean of Acquisition trials 5–8) and the 4 test trials. As can be seen, the mean time required to find the invisible target does not appear to change from baseline when one, two, or three sets...
of distal stimuli were removed from the walls. Removing all distal stimuli disrupted place performance.

A repeated-measures ANOVA conducted on the baseline and four test trials confirmed this impression. The analysis detected significant differences among the mean time required to find the invisible target on baseline and the trials during which the distal stimuli on one, two, three, or four walls were absent \( (F[7, 161] = 2.24) \). Orthogonal post hoc contrasts detected no differences among the mean search times on the baseline or the trials on which the distal stimuli on one, two, or three walls were absent. The analysis detected a significant difference among the means from these conditions taken together and compared against the mean search time obtained when distal stimuli from all four walls were eliminated \( (F[1, 23] = 9.92) \).

This set of statistical decisions implies the following order of means:

Mean of Acquisition trials 5–8 = One = Two = Three < Four

Figure 6 illustrates representative search paths for 4 of the participants on the last baseline trial (Trial 8) and each of the 4 test trials (Eliminate 1 Wall, Eliminate 2 Walls, Eliminate 3 Walls, Eliminate 4 Walls). The participants appear to take a reasonably direct path to the invisible target on the baseline (Trial 8) and each of the test trials except Eliminate 4 Walls on which all distal cues were removed.
Discussion

Eliminating the stimuli from one, two, or three distal walls did not disrupt place performance in the C-G Arena. In contrast, eliminating the stimuli from all four distal walls significantly disrupted place performance in this space. Nonetheless, the participants found the invisible target when all stimuli on the distal walls were absent. Inspection of the individual search paths on these trials suggests that when the stimuli on the distal walls were absent, many participants searched in a rough circle, the periphery of which was about equidistant from the arena wall, to locate the invisible target. This search pattern suggests the participants estimated the distance between the arena wall and the target and used that estimate to guide a relatively efficient circular search path. Thus, in the absence of distal stimuli, the participants appeared to use available stimuli to control a search for the invisible target.

As predicted by cognitive mapping theory, no single array—even very large arrays—of distal stimuli exerted detectable influence on place performance. It appears that even when the notion of a single distal stimulus is broadly defined, no single set of distal stimuli control place performance in the C-G Arena.

EXPERIMENT 3

The data patterns reported in both Experiments 1 and 2 are consistent with a prediction obtained from cognitive mapping theory (e.g., O’Keefe and Nadel, 1978). Removing all distal stimuli disrupted place performance, but removing subsets of those stimuli left place performance unaffected. Thus, although relations among distal stimuli exerted stimulus control over place performance in the C-G Arena, individual sets of these stimuli did not.

A cognitive mapping account of place learning asserts that relations among stimuli representing distal objects, rather than stimuli representing the objects themselves, control place performance in the arena. Suzuki, Augerinos, and Black (1980) used rats in an eight-arm radial maze to examine this assertion. These authors reported that transposing spatial relations among distal stimuli immediately disrupted spatial performance in an eight-arm radial maze. Following Suzuki et al. (1980), the present experiment examined the effect of transposing spatial relations among distal stimuli on place performance in the C-G Arena.

**FIG. 6.** Representative search paths for 4 of the participants on the last baseline (Trial 8) and each of the 4 test trials (Eliminate 1 Wall, Eliminate 2 Walls, Eliminate 3 Walls, Eliminate 4 Walls).
Method

Participants

Twelve undergraduates, 7 males and 5 females, between the ages of 18 and 24 years, served as participants.

Apparatus

The apparatus described in the method section of Experiment 1 was used. The invisible target was located in the SE quadrant of the arena.

Procedure

Instruction Phase. Each participant read and signed an informed consent form and received instructions as described in Experiment 1.

Practice Phase. The Instruction Phase was followed immediately by two Practice trials as described in Experiment 1. If the participant did not find the target within 2 minutes, the trial terminated and the participant teleported from the experimental to the waiting room.

Acquisition Phase. The Practice trials were followed immediately by eight acquisition trials administered under the conditions described in Experiment 1. For the first three acquisition trials, the experimenter helped the participant locate the target if the participant did not find it within 3 minutes. For the remaining trials, if the participant did not find the target within 3 minutes, the trial terminated and the participant was teleported from the experimental to the waiting room.

Test Phase. Three cycles of trials immediately followed the Acquisition Phase. Each cycle consisted of a test trial followed immediately by a trial identical in all respects to those that occurred during the Acquisition Phase. Moving clockwise, the normal arrangement of the walls was North, East, South, and West. During one test trial (Swap A), walls in the experimental room were arbitrarily rearranged, moving clockwise, as North, West, South, and East. During the second (Swap B), the walls were arbitrarily rearranged, moving clockwise, as North, West, East, and South. During the third (Swap C), the walls were arbitrarily rearranged, moving clockwise, as North, East, West, and South. The order of presentation (Swap A, B, or C) was determined randomly for each participant. If the participant did not find the target within 3 minutes, the test trial terminated and the participant automatically teleported from the experimental to the waiting room.

Due to the design of the right end of the East and the left end of the West walls, Swap C yielded an arrangement among distal stimuli similar to the normal view with one distal cue removed. Given that the removal of one distal cue does not affect performance in this computer-generated space (see Experiments 1 and 2), the results obtained from this test trial (Swap C) were excluded from the analysis.
FIG. 7. Mean time and SE (±1) in seconds to find the target on the acquisition trials of Experiment 3.

_Probe Phase._ The Test Phase was immediately followed by a single 2-minute probe trial as described in Experiment 1. The target was not in the arena during this trial.

_Final Phase._ The Probe Phase was immediately followed by a single 2-minute trial identical to the trials presented in the Practice Phase as described in Experiment 1.

Results

All participants located the target during the Practice Phase and the Final Trial. During the Acquisition Phase, however, 6 of the 12 participants received help locating the target on one of the first three acquisition trials.

Figure 7 illustrates the acquisition curve obtained from the 12 participants during the Acquisition Phase of the experiment. Orderly acquisition occurred. As in the previous experiments, we used trials 5–8 as a baseline against which to compare the effects of transposition of distal stimuli on place performance in the C-G Arena.

Figure 8 illustrates the mean time required to find the invisible target on acquisition trials 5–8 taken together (Baseline) and the 2 transposition test trials (Swap A and Swap B). As can be seen, the mean time required to find the invisible target increased dramatically on the transposition trials. A repeated-measures ANOVA detected significant differences among the mean time required to find the target on the baseline and the 2 transposition trials ($F[5, 55] = 6.60$). Orthogonal post hoc comparisons of these means detected no differences among the baseline trials (trials 5–8) or between the transposition trials (Swap A and Swap B). A significant difference was detected when
FIG. 8. Mean time and SE (±1) in seconds to find the target for the baseline (the mean of acquisition trials 5–8 is illustrated) and the trials on which the distal cues were transposed. These baseline trials were taken together and compared against the two transposition trials taken together ($F[1, 11] = 18.35$). This set of decisions implies the following order of means:

Mean of Acquisition trials 5–8 < Swap A = Swap B

Figure 9 illustrates representative search paths for four of the participants on the last baseline trial (Trial 8) and the two transposition trials (Swap A and Swap B). The participants appear to take a reasonably direct path to the invisible target on the baseline trial (Trial 8) and indirect or incomplete paths to the invisible target on each of the transposition trials.

Discussion

As predicted by cognitive mapping theory (e.g., Nadel, 1991; O’Keefe & Nadel, 1978; see also Poucet, 1993), disrupting topographical relations among distal stimuli disrupted place performance in the C-G Arena. Thus, it appears that relations among distal stimuli, rather than the distal stimuli themselves, exert stimulus control over place performance in this situation.

GENERAL DISCUSSION

The present experiments show that relations among distal stimuli, rather than the stimuli themselves, exert stimulus control over human place performance in the C-G Arena (Jacobs et al., 1997). Experiments 1 and 2 demonstrated that humans do not require any given set of distal stimuli, but do require at least one set, to relocate a place in this space. Experiment 3 demon-
strated that changes in topographical relations among sets of distal stimuli disrupt the ease with which humans relocate a place in this space. Taken together, the data are consistent with the suggestion that humans form a cognitive map of the computer-generated space housing the C-G Arena, learn the location of a place within that map, remember that location, and then
use relations among computer-generated distal stimuli to recall that location and find it in the computer-generated space (e.g., Nadel, 1991; O’Keefe & Nadel, 1978).

It is important to note the test of stimulus control we have accepted (Tere- race, 1966) permits another interpretation of the data. It is possible that the results of Experiment 3 occurred as a result of interfering responses produced by a novel stimulus configuration. Such an interpretation, however, does not explain the data obtained in Experiments 1 and 2. A ‘‘novel response’’ interpretation of the former data requires post hoc speculation about what constitutes a stimulus configuration, and of differential effects of stimulus removal versus stimulus transposition. Cognitive mapping theory, on the other hand, predicts the full pattern of data.

No matter what the mechanism (see also Riley, 1984), the present study demonstrated that humans use relations among stimuli rather than discrete stimuli to guide their search for an invisible target in the C-G Arena. The fact that removing large sets of distal stimuli did not affect place performance in the C-G Arena, but changing topographical relations among them did disrupt place performance in the C-G Arena, is consistent with data obtained when place performance in rats is examined in a tangible three-dimensional eight-arm radial maze (Suzuki et al., 1980) or Morris water maze (Fenton et al., 1994). The present data join a growing body of data suggesting that spatial learning in a two-dimensional environment maps rather well on to spatial performance in a mundane three-dimensional environment (e.g., Cole & Honig, 1994; Honig & Stewart, 1988; Jacobs et al., 1997; Laurance, 1997; Nadel et al., 1998; Skelton, Bukach, Laurance, Thomas, & Jacobs, submitted; see also Ouellette, 1989).

The present results are the first to demonstrate that place performance in computer-generated space meets several of the criteria of spatial mapping as specified by O’Keefe and Nadel (1978). These results are also the first to show that patterns of human place performance in computer-generated space compare remarkably well to those of rats in three-dimensional space. These data join a growing body of demonstrations suggesting that exploration of computer-generated spatial environments produce behavioral patterns and thus, by inference, cognitive representations (maps) remarkably similar to those produced following exploration of mundane space (e.g., Arthur, Hancock, & Chrysler, 1997; May, Péruch, & Savoyant, 1995; Péruch, Vercher, & Gauthier, 1995; Richardson, Montello, & Hegarty, 1998; Ruddle, Payne, & Jones, 1997; Sandstrom, Kaufman, & Huettel, in press; Thomas, Nadel, & Jacobs, 1998).

In addition, the present results suggest that although humans may use proprioceptive, vestibular, proximal, and sets of stimuli when place learning in mundane space, such stimuli are not necessary for a cognitive map to be formed. It appears that a relatively rich set of distal stimuli provide the stimulus support necessary for the formation of such a map (see Fenton et al., 1994). How stimuli from these various sources enter a map may depend
upon the salience of the stimuli as well as the organism’s sensory capacities (Restle, 1957). The relevance of these stimuli to the organism’s task (e.g., Mackintosh, 1975) may also help determine what stimuli enter the map, either through attentional or other mechanisms. Experiments designed to examine such issues are in progress in our laboratory.

Finally, it is important to ask if this approach to the study of stimulus control contributes to our theoretical understanding of behavior in the three-dimensional world. The stimulus dimension we have identified as critical to performance in computer-generated space is clearly abstracted from the three-dimensional world and has been programmed in this space. The fact that the present results correspond well with the animal results (e.g., Fenton et al., 1994; Suzuki et al., 1980) suggests we got it right. The present results also suggest that the stimulus control demonstrated here and, by inference, in mundane space, is not inherently spatial, but instead is abstracted from dynamic patterns of stimuli that serve as cues for places in space. As noted by Honig (1992, p. 319), “... some aspects of the [stimulus] array are invariant, and this maintains the perceived constancy of space as the person ... moves about” (Gibson, 1950, 1966). Hence, it appears that perceived relations among environmental stimuli provide information about places in space and, as such, lend a certain stability to otherwise uncertain environments. Identifying and systematically probing these patterns may enrich our understanding of the ways in which an organism explores, comprehends, and exploits the environment.

REFERENCES


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