Maturation of Spatial Navigation Strategies: Convergent Findings from Computerized Spatial Environments and Self-Report

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Using 2 computerized spatial navigation tasks, we examined the development of cue and place learning in children ages 3 to 10 years, comparing their data to adults. We also examined relations between place learning in computerized and real space. Results showed children use the 2-dimensional space as if it were real space. Results also demonstrated that children ages 3 to 10 years cue learn (locating a visible target) but do not show evidence of mature place learning (locating an invisible target) until around age 10 years. Self-report data indicated an age-related increase in use of relations among distal cues during place learning. Children ages 3 to 4 years did not report using distal cues; most 9- to 10-year-old children reported using multiple distal cues to guide their search during place learning. Results suggest that, as maturation proceeds, children make increasing use of relations among multiple distal cues to guide a search for places in space.

In this study, we examined the developmental time course of two externally referenced spatial navigation strategies: cue learning and place learning. Cue learning refers to coding a location in space relative to coincident landmarks or proximal

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cues. Under this condition, successful navigation to a location simply requires learning to move to a localized cue (i.e., operation of a motor taxis). Place learning refers to coding a location in space relative to multiple distal landmarks. Under this condition, successful navigation to a location requires learning computations involving the trained and/or remembered location of that place relative to relations among distal cues.

Previous research suggests that cue learning emerges before place learning in humans and other mammals (for reviews, see Brandeis, Brandys, & Yehuda, 1989; Newcombe & Huttenlocher, 2000). In addition, several human studies suggest that basic components of place learning begin to emerge around 2 years of age (DeLoache & Brown, 1983; Mangan, Franklin, Tignor, Bolling, & Nadel, 1994; Newcombe, Huttenlocher, Drummey, & Wiley, 1998) but that place learning may not reach maturity until sometime after 9 years of age (Acredolo, 1976; Lehnung, Leplow, Friege, Herzog, & Ferstl, 1998; Overman, Pate, Moore, & Peuster, 1996). These patterns are of interest because they point toward two unique developmental time courses in an individual’s ability to effectively navigate to places in space.

The question, then, is what critical elements do individuals develop over this time frame (between approximately 2–9 years) to reach mature place-learning competence? Studies that focus on the emergence of place learning have used a variety of methods. Some studies use tasks that involve hiding an object under one of several identical containers in full view of the child. After disorientation or distraction, children must then use multiple distal objects in the surrounding room to determine the location of the object. Results from these studies demonstrate that under these experimental conditions, children under 24 to 26 months of age typically fail to use the distal cues, and hence do not find the hidden object (DeLoache & Brown, 1983; Mangan et al., 1994).

Newcombe et al. (1998), however, reported that children as young as 22 months of age can make use of distal cues to help refine a search for an object. This experiment used a task that involves hiding a toy somewhere within a 5 ft (1.524 m) long rectangular shaped sandbox located in a small room. After watching the toy be hidden, the child moved to the opposite side of the box and then had to find the toy. Children in one group had visual access to landmarks outside of the sandbox; children in a second group had a circular all-white curtain obscuring all external landmarks. Children 22 months and older searched more precisely when external landmarks were available, whereas children under 22 months were not as precise in locating the toy and therefore did not appear to use the external cues to refine their search behavior. These results imply that children as young as 22 months can successfully utilize an external frame of reference (Newcombe et al., 1998). The question of whether this ability is comparable to mature place learning remains open because, as noted by the experimenters, the rectangular sandbox is a salient cue that has been shown to help children as young as 16 months locate a hidden object through coding of distance (from the edge of the sandbox itself) rather than rela-
tions among distal cues (Huttenlocher, Newcombe, & Sandberg, 1994). Hence, it may be that the external cues were not used to locate the hiding place in the sandbox but were instead used to provide coarse directional information within the frame of the rectangular sandbox. If this were true, then the results of these studies point toward an emergence of a key component in place learning in these young children (i.e., distal cue use) rather than adult-level competence.

Other researchers have used a task modeled after the Morris Water Maze (MWM; Morris, 1981), a well-established task often used to examine place learning in rodents (for reviews, see Brandeis et al., 1989; Burgess, Jeffrey, & O’Keefe, 1999; Nadel, 1991, 1994; Redish, 1999). The MWM consists of a large circular pool of opaque water placed in the center of an experimental room. The walls of the experimental room contain various items visible from the surface of the pool. Under some experimental conditions, a platform is placed just above the surface of the water rendering it visible from the surface of the water. Under other experimental conditions, the same platform is placed just beneath the surface of the water rendering it invisible from the surface of the water. Studies conducted using various experimental manipulations of this task have shown various species of rodents learn and remember spatial configurations of distal stimuli (i.e., the outer room walls) to locate the platform successfully (Morris, 1983; Morris, Garrud, Rawlins, & O’Keefe, 1982).

Since 1981, use of the MWM has provided a powerful method for the examination of processes underlying cue learning and place learning. The recent development of dry-land versions of the MWM task has been useful in the study of place learning in humans. Studies conducted using this task show that place learning is not fully matured until much later than the aforementioned studies with children would suggest. For example, Lehnung et al. (1998) and Overman et al. (1996) reported that children 6 years and under were bound to using an unsuccessful cue-based strategy to navigate, whereas children 9 years of age and older were as proficient as adults in place learning. Children 7 years of age fell into a transitional stage, with some exhibiting evidence of place learning. The results of these studies suggest place learning emerges some time before 7 years of age and continues to develop through at least 9 or 10 years of age.

In this study, we examined the development of place learning between the ages of 3 and 10 years using a computer-based task: an analog of the MWM named the computer generated arena\(^1\) (CG Arena; Jacobs, Laurance, & Thomas, 1997). The task, which runs on a personal computer (PC), offers portability, standardization of testing, and automated acquisition of data without incurring the methodological costs of uncontrolled naturalistic navigation tasks or the financial costs of constructing real-world analogs of tasks like the MWM. In addition, use of the CG

\(^{1}\) The software for the CG room and CG Arena may be downloaded from http://w3.arizona.edu/~arg/data.html.
Arena helps rule out confounds such as losses in gross motor coordination or swimming efficiency. Several recent studies using similar tasks have been reported (Gillner & Mallot, 1998; May, Peruch, & Savoyant, 1995; Nadel et al., 1998; Ruddle, Payne, & Jones, 1997). Studies using such tasks have reported that both children and adults can make accurate judgments about metrics in real space after active learning in a virtual environment and that there is often good transfer of spatial information from virtual to real environments (Brooks et al., 1999; Foreman et al., 2000; McComas, Pivik, & LaFlamme, 1998; Peruch, Vercher, & Gauthier, 1995; Richardson, Montello, & Hegarty, 1999; Wilson, Foreman, & Tlauka, 1997).

Our laboratory, the Anxiety Research Group (ARG) at the University of Arizona, has shown that data obtained from college-age adults and older adults performing in the CG Arena closely resemble data obtained from rodents performing in the MWM task (Jacobs et al., 1997; Jacobs, Thomas, Laurance, & Nadel, 1998; Laurance et al., 2002; Thomas, Hsu, Laurance, Nadel, & Jacobs, 2001). In addition, ARG has found that cue learning and place learning in the CG Arena correlates highly both with performance and self-reported competence in real space (Laurance et al., 2002; Skelton, Bukach, Laurance, Thomas, & Jacobs, 2000). The CG Arena therefore appears to be a convenient and ecologically valid method of examining aspects of spatial navigation in humans.

This study furthers research in this area by exploring age-related behavioral differences in spatial navigation utilizing both behavioral and self-report data. The study occurred in two phases.

The first phase of this study asked whether the computerized spatial task is valid for use with children. We used custom software to model a CG, all-white, rectangular room devoid of any nongeometric cues. A square target appeared on the floor of each corner of the room. On Trial 1, the child saw three blue and one green target. On Trial 2, the child saw an identical display except that all four targets were blue. The child was asked to navigate to the previously green target. The child could determine the location of the correct target only with respect to the different wall lengths (i.e., the target was in the corner with a longer wall to the left and a shorter wall to the right). Because the room was rectangular, there were always two geometrically identical corners. It is well established that children as young as 18 months can orient themselves according to the geometric shape of real-world environments in that they search the two geometrically appropriate corners equally and more often than the two geometrically inappropriate ones (e.g., Hermer, 1997; Hermer & Spelke, 1994, 1996; Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, in press).

If the children treat this CG space as if it were real three-dimensional space, then all of the children should relocate the formerly green target on Trial 2. If children do not treat the CG space in the same way they treat real space, then our results should not replicate the research findings in the real-space literature. This
phase has the additional benefit of allowing the children to become comfortable and familiar with the computer, joystick, and CG procedures.

The second phase of the study asked at what ages do children tested in the CG Arena (a) show competent cue learning as evidenced by accurate navigation to a proximally cued place (a visible target) and (b) show competent place learning as evidenced by accurate navigation to and successful relocation of a distally cued place (an invisible target). Based on the results of studies using complex, real-world spatial navigation tasks reported in both animal and human literature, (e.g. Lehung et al., 1998; Overman et al., 1996.) we predicted that (a) all children ages 3 to 10 years and young adults will show evidence of competent cue learning, (b) young children (i.e., 3- to 4-year-olds) will not show evidence of competent place learning, and (c) the oldest children (9- to 10-year-olds) and adults will show evidence of competent place learning. Moreover, as previous studies have shown, we should observe (d) a steady improvement in place-learning competence from the youngest to the oldest of our participants.

We also wanted to go beyond previous studies to begin an exploration of why developmental differences in place learning occur. To accomplish this, the second phase also incorporated a questionnaire designed to gather information about how the children used distal cues when place learning. O’Keefe and Nadel (1978) suggested that successful navigation occurs when an individual forms and utilizes a spatial map of the environment consisting of multiple distal cues and the relations among them. We therefore predicted that (a) unlike the youngest children, the older children and adults will report using multiple distal cues and relations among them to guide a search for the invisible target, and (b) as the reported use of distal cues and relations increase, so too will the efficiency of place learning.

**METHOD**

**Participants**

Children ages 3 to 10 years were recruited in the Tucson, Arizona area from a local private school and from a list of families who previously participated in experiments at the University of Arizona. Young adults ages 18 to 21 years were recruited from University of Arizona psychology undergraduate classes. A total of 184 children and young adults participated in this study. This study was comprised of two phases completed in a single 30-min session (approximately 10 min for Phase 1 and 20 min for Phase 2). All participants completed Phase 1; however, 22 children did not complete Phase 2. The data obtained from these children were not used for the Phase 2 analysis. Table 1 provides a summary description of demographic variables by age group for both phases. Children were grouped according to their year of age.
We made clear both to the parent and the child that if the child expressed a desire to discontinue participation in the experiment, data collection would be terminated immediately. This produced a high rate of dropouts in children 3 to 5 years of age during the second phase of the experiment, apparently due to frustration on the part of the child. Many of the children who did not find the invisible target expressed a loss of interest in continuing the experimental task.

Phase 1

**CG room.** A PC and custom-designed software (ARG, 1999) generated a display on a conventional flat screen PC monitor. The monitor displayed a first-person view of a 60 × 40 × 8 unit\(^2\) rectangular room from the perspective of one standing on the floor of the room. The computer screen showed a perspective as if the participant’s eye level were 5 units from the floor. The monitor did not display a representation of the participant. Figure 1 provides an aerial illustration of the CG room.

The ceiling was light gray and the floor dark gray. The walls were white and featureless. For the sake of convenience, the four walls of the CG room were arbitrarily designated North, East, South, and West. Participants were moved into the middle of the CG room facing the center of one wall (e.g., in the middle of the room facing the North wall). The sequence of these start orientations was pseudo-randomly determined so that successive trials did not begin facing the

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2All measurements in the CG room and arena are expressed in units. If we, for the sake of convenience, take the length of a stride in the CG room (move quantum of 0.54 units) to be the equivalent of 1 m, then in this experiment the room dimensions were approximately 111 × 74 × 15 m, and each target measured 18.5 × 18.5 m.
same direction. In addition, each participant received each of the four start orientations twice across his or her eight exposures to the CG room.

Four 10 × 10 unit square targets were located on the floor of the CG room, one in each of the four corners. Participants were asked to navigate to one of these four possible targets. Participants moved through the CG space using a joystick. Pushing the joystick forward or backward moved the participant in that direction 1.0 to 1.5 units/sec. Pushing the joystick left or right turned the participant in the corresponding direction 10 to 11 deg/sec. Holding the joystick in one position produced repeated corresponding movements.

Procedure

Instructions. Each participant received standardized verbal instructions about the CG room, how to move within the CG space, and the object of the task (see Appendix A). The experimenter (either Holly Laurance or Amy Learmonth) described experimental conditions and remained in the room throughout the procedure to answer questions about the task. Either Dr. Learmonth or Ms. Laurance also provided verbal encouragement and praise throughout the task. Each
participant received four trials. Each trial had two phases: a familiarization phase and a test phase.

**Familiarization phase.** In this phase, the target located in the Northeast (NE) corner was green; the three remaining targets were blue. The participant began in the middle of the CG room facing a wall. The participants were told to remember the location of the green target so they could find it in the test phase. They received this instruction during each familiarization phase. Participants were encouraged to, and allowed to, explore the environment and were given an unlimited amount of time to do so.

**Test phase.** After the familiarization phase, the participant began the test phase. Again, the participant began in the middle of the CG room facing a wall, in pseudo-randomly chosen start orientations. In this phase, all of the targets were blue. The participant was asked to navigate to the target that was green in the familiarization phase. If the participant navigated to and stood on one of the correct targets, it immediately turned green.

Because there were no cues on the room’s walls, the only way a participant could choose a correct target is according to the shape of the room. That is, if one were to stand on the correct target (NE) and face the corner, there is a longer wall on the left side and a shorter wall on the right side. In addition, there is no way to distinguish the NE and southwest (SW) corners because they are geometrically equivalent; hence, both of these targets are correct.

**Phase 2**

**CG Arena.** A PC and custom-designed software (ARG, 1999) generated a display on a conventional flat screen PC monitor. The monitor displayed a multi-colored view of a circular arena within one of two square rooms (a practice room 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 waiting room and experimental room each consisted of a $110 \times 110 \times 30$ unit room, each housing a circular arena. The circular arena consisted of a red brick textured wall 50 units in radius and 3.5 units high enclosed in the central portion of the room floor. The computer screen showed a perspective as if the participant’s eye level was 2 units high. The ceiling of both rooms was light gray, and the floor was dark gray.

The four walls of the practice room were featureless blue, green, red, and yellow, respectively. Exposure to the practice room distinguished experimental trials from one another and permitted the participant to practice moving in the CG space. The four walls of the experimental room were arbitrarily designated North, East, South, and West. The arena in the experimental room was divided into four imagi-
nary quadrants named NE, Southeast (SE), SW, and Northwest (NW). Lines demarcating each quadrant were not displayed on the monitor. In the experimental room, the participants searched for a visible or invisible target. Figure 2 provides an aerial illustration of the walls, floor, and distal icons contained in the experimental room. As illustrated, each wall contained three salient icons.

A 10 × 10 unit square target was located on the floor of the experimental room. When the experimental protocol called for the target to be part of the display, it appeared plain blue. When the protocol called for the target to be invisible, it was indistinguishable from the arena floor. When the participants moved across the space occupied by an invisible target, however, the target became blue and was accompanied by a continuous CG tone. Once participants moved onto the target, they became trapped on the target for up to 30 sec, after which the trial ended.

Procedure

Instruction phase. Each participant received standardized verbal instructions about the structure of the arena, how to move within the CG space, and the
object of the task. The experimenter described all the experimental conditions except probe trial manipulations. See Appendix B for the exact instructions given to each participant. An experimenter remained available throughout the procedure to answer questions about the task. The experimenter provided verbal encouragement and praise throughout the task.

**Cue-learning trials.** Each participant then completed two cue-learning trials in the experimental room. The participant began in the center of the practice room and was allowed to explore the room for several minutes. When the participant was ready to begin the trial, the experimenter pressed the space bar, and the participant was moved (“teleported”) to a pseudo-random start position\(^{3}\) in the experimental room. The participant’s task was to locate and stand on a visible blue target. The location of the visible target changed on each trial (Trial 1 in the center of the arena, Trial 2 in the SE quadrant). Each trial lasted no more than 120 sec. Performance on these trials demonstrated whether or not participants could move directly to a target marked by the presence of a conspicuous proximate visual cue (Anooshian, 1988). These trials also demonstrated whether or not participants understood the instructions, recognized the computer display as a spatial array, and could use the joystick to move effectively within CG space.

**Place-learning trials.** Immediately following the cue-learning trials, each participant received a series of six place-learning trials in the experimental room. Again, the participant began in the center of the practice room. After either Ms. Laurance or Dr. Learmonth pressed the space bar, the participant was moved to a pseudo-random start position in the experimental room. Once in the experimental room, the participants searched for an invisible target located in the NW quadrant on the arena floor. On the first two trials, if the participant did not find the target within 120 sec, Ms. Laurance or Dr. Learmonth guided the participant to the target. On the remaining trials, if the participant did not find the target within 120 sec, the trial ended. Results from these trials measure place learning in the presence of distal visual cues that are conspicuous and that facilitate navigation to a particular area in space (O’Keefe & Nadel, 1978).

**Arena questionnaire.** Immediately following the place-learning trials, each participant was asked (a) “Did you know where the carpet was hiding?” and (b)

\(^{3}\)There were four different start locations labeled (for the sake of convenience) North, East, South, and West. The North start location was near the middle of the North wall, the East start location near the middle of the East wall, and so on. Participants entered into the experimental room facing and within 2 units of the arena wall. The sequence of these start locations was pseudo-randomly determined so that successive trials never began the participant in the same location. Each participant received an identical sequence of start locations.
“How did you know where the carpet was hiding? How did you find the carpet?” If the child had difficulty answering the second question, the experimenter prompted him or her by asking, for example, “Was there anything that helped you find the carpet that was hiding?”

**Probe trial.** Immediately following the questionnaire, each participant received one 60-sec probe trial. The probe trial was identical to the place-learning trials except, unknown to the participant, the target was removed from the arena. Results from this trial provide a second measure of place learning by permitting us to record persistence of search (dwell time) in circumscribed areas of the experimental room (Morris, 1981).

**Final trial.** The last trial, the 10th, was identical to a cue-learning trial. The final, visible-target trial (located in the center of the arena) was intended to give the child some success at the end of the task so she or he would not leave the study feeling frustrated or ineffectual.

**Computer questionnaire.** Information from each participant was gathered regarding exposure to computers and computer gaming experience.

**Data collection.** The dependent variables gathered from the computer task included (a) whether participants successfully or unsuccessfully located in Phase 1, (b) the time required to find the target (latency) at Phase 2, (c) the path taken in the arena (search path), and (d) the time spent in each of the arena quadrants (quadrant time). Other measures included (e) responses to questionnaires. The Type I error rate was set at 0.05 for all statistical decisions.

**RESULTS**

Phase 1: CG Room

There were two correct target responses in the CG room: the target that was green in the familiarization phase and the target located in the rotationally equivalent (directly opposite) corner. Because these two corners were geometrically identical, both target choices were coded as correct and combined in the analyses; the two incorrect targets were coded as incorrect and combined in the analysis.

Analyses were conducted to evaluate whether there were differences in the mean number of correct or incorrect responses made by participants among the age groups. Separate one-way analyses of variances (ANOVA) detected no significant group differences for either geometrically correct responses, $F(8, 182) < 1$ or incorrect responses, $F(8, 182) < 1$. Wilcoxon tests were then conducted to evaluate whether participants within each age group showed greater selection for the geomet-
rically correct or incorrect targets. The results in each age group indicated a significant difference in favor of geometrically correct target responses: 3-year-olds ($M = 2.57, SD = 0.87), Z = –2.56; 4-year-olds ($M = 2.65, SD = 1.06), Z = –1.82; 5-year-olds ($M = 2.64, SD = 1.25), Z = –2.37; 6-year-olds ($M = 2.65, SD = 1.03), Z = –1.43; 7-year-olds ($M = 2.63, SD = 1.01), Z = –2.36; 8-year-olds ($M = 2.70, SD = 0.98), Z = –2.64; 9-year-olds ($M = 2.68, SD = 1.00), Z = –2.51; 10-year-olds ($M = 2.72, SD = 0.89), Z = –2.67; and adults ($M = 2.89, SD = 0.94), Z = –2.98.

Phase 2: CG Arena

Figure 3 illustrates the mean time the participants in each group required to find the target across all trials in the CG Arena.

Cue-learning trials. All participants found the visible target quickly and consistently on the two cue-learning trials (see left panel of Figure 3, cue-learning [CL] trials) and on the final cue-learning trial (see far right panel of Figure 3, CL3). It appears that 3- to 4-year-olds required more time to locate the visible target on the first two cue-learning trials than did the participants in the other groups. By the final cue-learning trial, however, there appear to be no group differences in time required to locate the visible target.

A split-plot repeated measures ANOVA conducted on the mean time required by the participants in each group to find the visible target on the three cue-learning

![FIGURE 3](#)  
Mean latency and standard error to find the target in seconds across CG Arena trials. CL refers to the cue-learning trials; PL refers to the place-learning trials.
trials confirmed these impressions. The analysis detected a significant group effect, $F(8, 153) = 10.55, p < 0.001$; a significant trial effect, $F(2, 306) = 81.73, p < 0.001$; and a significant Trial × Group interaction, $F(16, 306) = 3.51, p < 0.001$. Separate analyses on the visible trials detected a significant group effect on the first visible trial, $F(8, 153) = 7.23, p < 0.001$ and second visible trial, $F(8, 153) = 11.39, p < 0.001$, but not on the third, $F(6, 117) = 1.74, p = 0.17$. Post hoc pairwise comparisons with a Bonferroni correction to control Type I error rates found that the performance of 3- and 4-year-olds significantly differed from the performance of 5- to 10-year-olds and adults. No other pairwise comparisons reached statistical significance.

Place-learning trials. There appears (see middle panel of Figure 3, place-learning [PL] trials) to be a stepwise developmental trend in the consistency with which children of various ages learned the location of the invisible target across place-learning trials. The 3- to 4-year-olds did not consistently relocate the invisible target, whereas the 9- to 10-year-olds relocated the invisible target quickly and consistently. The performance of the children at intermediate ages fell in between these age groups with a steady improvement in consistency from 5- to 10-year-olds. The adults appeared to learn the location of the invisible target quickly and relocated the target consistently across the place-learning trials.

A split-plot repeated measures ANOVA confirmed these impressions. The analysis detected a significant group effect, $F(8, 153) = 42.01, p < 0.001$; a significant trials effect, $F(5, 765) = 14.70, p < 0.001$; and a significant Group × Trials interaction, $F(40, 765) = 1.99, p < 0.001$. See Figure 4 for representative search paths for all age groups.

Post hoc pairwise comparisons with a Bonferroni correction were then conducted to evaluate the group differences on latency during place-learning trials. No differences were detected in the performance of the 3- to 4-year-olds, but these two age groups were significantly different from all the other age groups. There was a stepwise progression of significance across age groups ending with the adults whose performance did not differ significantly from 9- or 10-year-olds but differed significantly from all other age groups. See Table 2 for a breakdown in this analysis.

During the first two invisible acquisition trials, 11 of the eleven 3-year-olds, 16 of eighteen 4-year-olds, 14 of seventeen 5-year-olds, 7 of nineteen 6-year-olds, 9 of nineteen 7-year-olds, 8 of nineteen 8-year-olds, 3 of nineteen 9-year-olds, 0 of nineteen 10-year-olds, and 0 of nineteen adults required help to locate the invisible target (see Figure 5).

Analyses were conducted to determine whether there were differences in acquisition between those individuals who required help to locate the target and those individuals who did not receive help. Several age groups were excluded from this analysis because too few individuals within the age group either required help or did not require help to locate the target (3- to 5-year-olds, 9- to 10-year-olds, and
FIGURE 4  Representative search paths across the six place-learning trials for each age group.

TABLE 2
Significant Differences in Place-learning Across Age Groups

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Note. *Indicates that there is a significant difference (.05) between the two age groups on place-learning performance.
adults). Separate split-plot repeated measures ANOVAs for the remaining age groups detected no significant differences: 6-year-olds, $F(1, 17) < 1$; 7-year-olds, $F(1, 17) < 1$; or 8-year-olds, $F(1, 17) < 1$.

**Probe trial.** Figure 6 illustrates the time each group spent searching the four quadrants during the probe trial. It appears 3- to 5-year-olds did not persistently or preferentially search any of the four quadrants. In contrast, it appears that 6- to 10-year-olds and adults searched the target quadrant (NW) preferentially and more persistently than the other three quadrants.

Separate within-subjects repeated measures ANOVAs conducted on the mean quadrant search times (dwell times) confirmed these impressions. The analysis detected no significant quadrant effects among the 3-year-olds, $F(3, 27) = 1.33$; 4-year-olds, $F(3, 51) < 1$; or 5-year-olds, $F(3, 54) < 1$, but it detected a significant quadrant effect among the 6-year-olds, $F(3, 54) = 4.00$; 7-year-olds, $F(3, 54) = 5.77$; 8-year-olds, $F(3, 57) = 6.44$; 9-year-olds, $F(3, 54) = 122.21$; 10-year-olds, $F(3, 54) = 110.01$; and adults, $F(3, 48) = 124.19$. Orthogonal post hoc contrasts were then conducted on each age group. Analyses for 6- to 10-year-olds and adults detected no differences in mean time spent searching the SE, SW, and NE quadrants but a significant difference between these taken together and the time spent searching the NW quadrant. Analyses for 3- to 5-year-olds detected no significant differences.
Two independent raters examined participants’ responses to questions on this questionnaire; interrater agreement was perfect ($\kappa = 1.0$). Figure 7 illustrates the percentages of participants at each age reporting knowing or not knowing the location of the target.

As depicted, 36% of 3-year-olds, 56% of 4-year-olds, 35% of 5-year-olds, 68% of 6-year-olds, 84% of 7-year-olds, 74% of 8-year-olds, 100% of 9-year-olds, 100% of 10-year-olds, and 100% of the adults reported that they knew the location of the invisible target.

Table 3 illustrates the number of participants at each age reporting use of one or more distal cues. No 3-year-olds and 4 (22%) of the 4-year-olds reported using one distal cue to guide their search. Nine (53%) of the 5-year-olds reported using a distal cue to guide their search for the invisible target, but only one of those reported using multiple cues. A greater number of 6-year-olds reported using distal cues to navigate, 15 of 19 children (79%), with 9 (60%) of those reporting the use of multiple distal cues. Nevertheless, six 6-year-olds reported using only one cue. The 7- to 8-year-olds reported even a greater number of multiple distal cues use than the younger children. All but 3 of these children reported distal cue use, and 24 (69%) reported using multiple distal cues. Almost all (97%) 9- and 10-year-olds reported using distal cues to guide their search, and 33 of these 38 (87%) children reported
TABLE 3  Reported Distal Cue Use

<table>
<thead>
<tr>
<th>Age</th>
<th>N</th>
<th>One Cue</th>
<th>Multiple Cues</th>
<th>% Reporting Distal Cue Use</th>
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<tbody>
<tr>
<td>3</td>
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<tr>
<td>Adults</td>
<td>19</td>
<td>2</td>
<td>17</td>
<td>100</td>
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</table>

FIGURE 7  The number of individuals (expressed in percentages) in each group who either reported knowing or reported not knowing the location of the invisible target.
using multiple cues. All of adults reported using distal cues to relocate the invisible target. In addition, 24 of the fifty-seven 9- and 10-year-olds and the adults reported using three or more distal cues.

It appears that the number of participants who reported using one or more distal cues significantly increased with age. Analyses confirmed these impressions. Results from a Kruskal–Wallis test found significant differences between the groups on self-reported cue usage, $\chi^2(8, N = 158) = 89.73, p < 0.001$. Additional orthogonal post hoc contrasts showed a significant, systematic increase in the number of distal cues reported across age groups. See Table 4 for a breakdown of this analysis.

**Place learning and cue use.** To determine if place-learning performance and self-reported cue usage are related, the slope of each participant’s place-learning performance (latency on invisible-target trials) was calculated. Next, a linear regression analysis was conducted relating the slope and the number of reported distal cues used to navigate. This analysis found a significant positive relation between the slope of the place-learning curve and the reported number of distal cues used to find the invisible target, $F(1, 157) = 23.47, p < .001$.

**Computer questionnaire.** Information gathered to determine computer experience indicated that all participants reported some exposure to computers and some computer gaming experience. Obviously, the older children and adults reported more experience (in years) with computers and computer games than the younger children. Nevertheless, all children reported playing two or more three-dimensional games using a monitor and hand controls. A chi-square analysis detected no significant differences between the groups on use of monitors and hand controllers, $\chi^2(8, N = 158) = 3.98, p < 0.001$.

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Note. *Indicates that there is a significant difference (.05) between the two age groups on self-reported distal cue usage.
**Sex differences.** To determine if the sexes differed in acquisition performance on place-learning trials, we conducted a series of split-plot repeated measures ANOVAs comparing the mean time required to find the invisible target across the acquisition trials obtained from the male and female participants in each group. The analyses detected no significant sex group effects for the following age groups: 4-year-olds, $F(1, 16) = 1.43$; 6-year-olds, $F(1, 17) < 1$; 7-year-olds, $F(1, 17) < 1$; 8-year-olds, $F(1, 17) < 1$; 9-year-olds, $F(1, 17) < 1$; 10-year-olds, $F(1, 17) < 1$; and adults, $F(1, 17) < 1$. Analyses could not be conducted for 3- and 5-year-olds because there were either too few female or male participants within the age group.

**DISCUSSION**

**CG Behavioral Performance**

The results from Phase 1 demonstrate that children between ages 3 and 10 years can use the geometric shape of a space to effectively locate places within a CG environment. These findings extend those previously reported using a task based in real three-dimensional space (e.g., Hermer & Spelke, 1994; Learmonth et al., in press). In so doing, the children demonstrated that they understood the three-dimensional nature of the desktop display and treated the display as if it were a three-dimensional space.

The results from Phase 2 demonstrate that children between ages 3 and 10 years cue learn. There was an age-related difference for the first two, but not for the final visible-target trial. Although the 3- and 4-year-olds required 10 to 20 sec more than the other children to navigate to the target on the first two trials, all of the children successfully found the visible target on each of these three trials. Hence, as reported in several previous spatial navigation studies using animals or humans, even the youngest children can effectively navigate using proximal cues (e.g., see Acredolo, 1978; Rudy, Stadler-Morris, & Albert, 1987).

The results from Phase 2 also suggest a continuous development of place-learning competence. The 3- to 4-year-olds appeared to show no place learning and were unsuccessful at relocating the invisible target. That is, even if the child found the target once, he or she did not necessarily find the target on the subsequent trial. Children around 5 to 6 years of age began to show some competence in place learning. They were more able to relocate the invisible target, and 6-year-olds showed a significant change compared to younger children in their persistence in and location of their search for the target. Children 7- to 8-years-old showed an even greater improvement than younger children in their competence to relocate the invisible target; however, it is not until 9 to 10 years of age that children appeared to show mature place-learning competence comparable to that of an adult. There is a signif-
significant change in the efficiency and speed with which these oldest children consistently located and relocated the invisible target.

In sum, these results replicate those of previous studies by demonstrating (a) children between ages 3 and 10 years consistently cue learn, but (b) children do not show evidence of mature place learning until around the age of 9 to 10 years (e.g., Acredolo, 1976; Lehnung et al., 1998; Overman et al., 1996). The results of this study also extend previous work by demonstrating comparable phenomena occur in CG space.

Strategy and Distal Cue Use

Results from the self-reported spatial navigation strategies questionnaire demonstrated that as children age, the frequency of self-reported use of distal cue(s) to find the invisible target increased. This trend has heretofore only been predicted theoretically (e.g., Newcombe & Huttenlocher, 2000).

Although many 3- and 4-year-olds reported knowing the location of the invisible target, none of them successfully located or relocated that target. In addition, only four of these children reported using a distal cue to guide their search. It appears that exclusive use of a proximal-cue strategy permitted 3- to 4-year-olds to successfully locate the visible target, but when this landmark disappeared they were unable to locate or relocate the invisible target. Rather, it appears these children, without any other means to navigate, wandered aimlessly (see Figure 4). Even when or if the child discovered the invisible target, she or he did not necessarily return to that place on the subsequent trials.

In contrast, most of the 5- to 6-year-olds reported using at least one distal cue, and a few reported using multiple distal cues (mainly the 6-year-olds). When these children did use a cue, however, many seemed to use the cue to guide a ballistic search. Generally, they moved from the start location directly toward the distal cue without taking into account distance or angle. What this means is that if the target was directly between the child and the distal cue she or he was orienting toward, then the child would be likely to run across the target. These children also seemed to use a second strategy. Once in the vicinity of their chosen cue(s), most of the children simply moved back and forth in front of that cue (or cues) until they located the target (see Figure 4). Thus, it seems that many 5- and 6-year-olds used distal cues but used them as if the distal cue was a proximal cue. Distance, angle information, and relations among multiple cues did not yet seem to be a part of their navigational strategy.

The 7- to 8-year-olds located and relocated the invisible target more efficiently than the younger children. Over 60% of these children reported using multiple distal cues to guide their navigation during the place-learning trials. It therefore seems likely that they are more successful than the younger children in navigating to the target based on these learned relations among multiple distal
cues (see Figure 4). However, place-learning performance in these children is not as successful as older children or adults. This could possibly be attributed to the other 40% of children in this age range that report using one or no distal cues to guide their search.

Children ages 9 to 10 years and the adults in this study showed efficient and successful place-learning performance. Almost all of these individuals reported using distal cues to guide their navigation; some of them reported using four or more distal cues (see Figure 4). Incorporation of multiple distal cue information appeared to allow the 9- to 10-year-olds and adults to locate a place in space quickly and easily from any start location.

This pattern of results suggests that humans, as they mature, make increasing use of the relations among multiple distal cues to guide a search for places in space. The same developmental pattern (discussed previously) was found in successful place-learning performance in these children. Analyses found that the emergence of successful place learning was indeed significantly related to the children’s self-reports of using appropriate and multiple distal cues, and in fact, successful use of multiple distal cues to relocate a place in space is a hallmark of place learning.

It therefore appears that asking participants to describe the strategies they used to relocate the target provided valuable information allowing valid inferences to be made about the navigational strategy they attempted to implement. This then allowed the comparisons to be made between self-report and actual behavior in the CG space, resulting in converging evidence of a continuous developmental trend in place-learning competence.

A note on self-report measures. It has been argued that there are many limitations inherent in the use of self-report measures given that their very nature is subjective assessment of internal cognitive processes. Therefore, an individual’s assessment may not reflect reality, especially in cases of verbal self-assessments (for an in-depth discussion of this limitation, see Nisbett & Wilson, 1977). It can be argued that self-report measures would be even more unreliable when taken from children. However, the value of self-report data cannot be dismissed out of hand. Rather, researchers can protect against drawbacks to self-report data through the use of convergent measures, as was done in this study. As can be seen, determining how well the measure correlates (converges) with another method of data collection can yield valuable and informative results.

Sex Differences

This study found no sex differences in the navigational abilities of humans on any measure. Although many of the rodent studies using the MWM task reported more efficient place learning by males (see, e.g., Galea, Kavaliers, &
Ossenkopp, 1996; Galea, Kavaliers, Ossenkopp, Innes, & Hagreaves, 1994; Williams & Meck, 1991), there are several studies that did not detect sex differences in navigational abilities and others that report better place learning performance in female rats (e.g., Perrot-Sinal, Kostenuik, Ossenkopp, & Kavaliers, 1996). In addition, studies conducted with prepubescent young animals and humans demonstrate inconsistent sex differences in spatial cognition (e.g., Galea, Ossenkopp, & Kavaliers, 1994; Overman et al., 1996; Sawrey, Keith, & Backes, 1994).

In recent years, a handful of research groups have developed computerized versions of the MWM task to examine human place learning, and a few have examined the issue of sex differences (e.g., Astur, Ortiz, & Sutherland, 1998; Sandstrom, Kaufman, & Huettel, 1998). One laboratory made the claim that sex differences in spatial navigation are large and reliable (Astur et al., 1998); another found that sex differences are dependent on the types of cues (e.g., geometrical vs. landmark) that are provided in the virtual environment (Sandstrom et al., 1998). The latter study replicates the finding that female and male humans, as in other species, use different strategies in solving spatial tasks (e.g., Roof & Stein, 1999). Specifically, it has been argued that males preferentially use Euclidian navigation strategies relying on distance and direction information, whereas females preferentially use topographic navigation strategies relying on landmark information (e.g., Choi & Silverman, 1997; Dabbs, Chang, Strong, & Milun, 1998; Williams, Barnett, & Meck, 1990).

Analyses of data gathered from the CG Arena across several years and several thousand participants do not reveal sex differences in cue- or place-learning competence (see Thomas, Laurance, Luczak, & Jacobs, 1999). We are currently undertaking experiments to determine why some laboratories consistently find sex differences in CG environments, whereas others do not (Laurance et al., 2003). Nevertheless, the environment used in this experiment was constructed and validated so that enough information is provided for the various successful types of spatial wayfinding strategies that can be employed (e.g., Euclidean or landmark). In this way, the issue of possible sex differences in strategy usage can be circumvented for the moment because it was not the goal of this study.

Possible Relations to Brain Systems

One advantage of the methods used in this study is that performance in the CG Arena is comparable to performance in the MWM, a task used extensively to investigate behavioral, cognitive, and neural components of spatial navigation in nonhuman animals. Although this study was not designed to explore contributions of these components to the development of spatial competence, two points concerning neuroanatomy are of interest.

First, animal and human studies consistently demonstrate the importance of the hippocampus in place learning and the caudate nucleus in cue learning
(Maguire et al., 1998; Maguire, Burgess, Donnett, Frith, & O'Keefe, 1997; Packard & McGaugh, 1992; Redish, 1999). Second, it appears that in humans, the hippocampus matures later (up to several years later) than the caudate nucleus, which seems fully functional by 3 months (Chugani & Phelps, 1986; Chugani, Phelps, & Mazziotta, 1987). If place learning and cue learning are related to the hippocampus and caudate nucleus, respectively, then one would expect to see an age-related difference in spatial navigation similar to those observed in this study. Indeed, studies conducted with both animals and humans have demonstrated that cue learning emerges much earlier than place learning (e.g., Acredolo, 1976, 1978; Brandeis et al., 1989; Lehnung et al., 1998; Newcombe & Huttenlocher, 2000; Overman et al., 1996).

The idea that there is differential development between the hippocampus and the caudate nucleus may help researchers understand the age-related findings in these two externally referenced spatial navigation strategies.

Computerized Spatial Environments

This study demonstrates that the use of computer simulated space, such as the CG spaces used in this study, can detect developmental changes in spatial competence in children between the ages of 3 and 10 years.

Use of computerized environments to study spatial competence potentially provides an efficient and portable research tool useful for a variety of populations. However, computerized spatial environments may require skills or be dependent on a variety of factors that differentially impact performance in computerized environments and that have nothing to do with place learning. For instance, successful performance in the CG task does require the use of a joystick and understanding the three-dimensional nature of the task, which might have been difficult for some of the youngest participants. These requirements may have led to the high dropout rate in the youngest group. However, the 3-year-olds who did complete the experiment did not appear to be hindered by a lack of experience with the equipment, and all children demonstrated facility with the procedure after minimal practice. In addition, all of the children even at age 3 years reported at least some exposure to a computer as well as three-dimensional video games. Moreover, there were no performance differences between age groups on the last visible-target trial, clear evidence that all the children were equally competent navigating through the CG environment.

Although computer and gaming experience does not seem to impact the pattern of data in this study, it remains possible that in other populations previous familiarity with computers and three-dimensional environments might enable more efficient performance in this medium. With the increasing use of computerized spatial tasks, more research in this area is warranted.
CONCLUSION

The results reported in this study join the growing body of evidence demonstrating the differential onset of cue- and place-learning competence in children. A computerized spatial task provided detailed data concerning children’s navigational behavior, which correspond to findings in analogous three-dimensional tasks. In addition, a procedure allowing the individual to report how she or he located a place in space provided clues about the nature of children’s navigational strategies. The children in this study showed an age-related increase in the use of the relations among distal cues to guide their search for a place in space. Behavioral performance measures and self-reported information provide evidence converging on the idea that there are several related, continuous, and age-related developmental processes leading to the successful implementation of externally referenced spatial navigation.

ACKNOWLEDGMENTS

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**MATURATION OF SPATIAL NAVIGATION STRATEGIES**

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**APPENDIX A**

I have a computer game for you to play. In this game you are going to search for a green square. You will first see a room with a square in each corner. One of the squares will be green and the others will be blue. When you think you know where the green square is, press the space bar. You will go to the same room, but this time all the squares will be blue. See if you can find the square that was green and go stand on it.

First let me show you how to use this joystick. What side do you want the joystick to be on?

Have you used a joystick before? It’s easy … (DEMONSTRATE WITH HEAD OR ENTIRE BODY EACH MOVE WITH JOYSTICK):

To go forward, push the joystick forward.
To go backward, pull the joystick backward.
To turn to the right, push the joystick to the right.
To turn to the left, push the joystick to the left.

When you feel like you really know how to use the joystick, tell me you are ready, and I will send you into the room where you are going to play the game.

(ONCE THE CHILD HAS CHOSEN A TARGET)

Did you find it? Good job! You can press the space bar to start again in the room with the green square.

(WHILE THE CHILD IS IN THE WAITING ROOM) If you know where the green square is, you can press the space bar and go into the room where all the squares are blue and try to find the one that was green again.

(THROUGHOUT THE EXPERIMENT: If the child seems hesitant or uncertain, repeat the relevant part of the instructions and offer encouragement.)

APPENDIX B

Let me tell you about another computer game you are going to play. To do well, you have to find a blue carpet that is hiding in a room. The goal of this game is to find this carpet as quickly as you can.

Each time before trying to find the carpet, you will start in the practice room. There is no carpet in this room. All you have to do here is practice moving and looking around. When you feel like you really know how to use the joystick, tell me you are ready, and I will send you into the room where you are going to play the game.

For the first two trials, you will see the carpet. Just go directly to it.

(REMIND THEM FOR TRIAL 1 AND 2 THAT THE CARPET IS VISIBLE)

(WHILE STILL IN THE PRACTICE ROOM BEFORE TRIAL 3 BEGINS): Now, the carpet will hide from you until you step on it. When you step on it, it will (magically) appear. Once you find the carpet, make sure you look all around the room, since the carpet will always be in the same place. When you are done looking, tell me and then I will send you to the practice room. Each time you are ready to leave the practice room, tell me and I will put you back into the room where you are playing the game.

Try to find the carpet as quickly as you can.

The most important thing to remember is that the carpet will always be hiding in the same place. When you first find it, stand on it, and take a GOOD look around the room.

(THROUGHOUT THE EXPERIMENT: If the child seems hesitant or uncertain, repeat the relevant part of the instructions and offer encouragement.)