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The Emergence of Cognitive Maps for Spatial Navigation in 7- to 10-Year-Old Children

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Although much is known about adults' ability to orient by means of cognitive maps (mental representations of the environment), it is less clear when this important ability emerges in development. In the present study, 97 seven- to 10-year-olds and 26 adults played a video game designed to investigate the ability to orient using cognitive maps. The game required participants to reach target locations as quickly as possible, necessitating the identification and use of novel shortcuts. Seven- and 8-year-olds were less effective than older children and adults in using shortcuts. These findings provide clear evidence of a distinct developmental change around 9 years of age when children begin to proficiently orient and navigate using cognitive maps.

The ability to orient and navigate successfully throughout familiar and unfamiliar surroundings is a fundamental skill for our daily activities (Postma, van Oers, Back, & Plukaard, 2012). This important skill may involve the use of different information available in the surroundings such as salient environmental landmarks, or rely on body turns and distances to be travelled in order to reach a given destination (Iaria, Petrides, Dagher, Pike, & Bohbot, 2003). Among the different cognitive strategies that individuals may adopt for navigation and orientation, the most efficient and flexible approach relies on the ability to form a cognitive map (Arnold et al., 2013). A cognitive map refers to a mental representation of the surroundings in which individuals represent the spatial relations between environmental landmarks; therefore, once formed, a cognitive map allows individuals to reach any target place from all possible locations within the environment, even shortcutting and traveling routes never explored before (Epstein, Patai, Julian, & Spiers, 2017). Although much is known about the cognitive and neurological mechanisms underlying adults' ability to orient by means of cognitive maps, it is less clear when this important ability emerges in development. In this experiment, we addressed this developmental gap by examining 7- to 10-year-olds' abilities to form and use cognitive maps to navigate a virtual environment.

The Landmark-Route-Survey model proposed by Siegel and White (1975) is a compelling cognitive paradigm to understand how navigational behaviours develop in children. This model posits that children (as well as adults) create mental representations of the environment in a stereotyped and serial order. First, children identify and store information about the *landmarks* contained in the environment. Secondly, children's movements are registered with respect to these landmarks, providing the basis for memorizing *routes* to target locations not immediately visible (Purser et al., 2012). It is not until the final "stage" in which the route-based knowledge of the environment is integrated into something resembling a *survey*-like representation of the environment, that is, a cognitive map (Tolman, 1948). A cognitive map of an environment affords unique behaviours that would not be expected from the mental representations of the environment stored at the *landmark* and *route*

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stages. For instance, identifying novel shortcuts in an environment is presumably only possible with a survey-like representation (Epstein et al., 2017; Newcombe, 2018), which includes information on the spatial relations between landmarks in the environment, information that is not necessarily present at the *landmark* and *route* stages. Indeed, for navigational purposes, cognitive maps are the more effective and flexible mental representation (Arnold et al., 2013).

Unsurprisingly, younger children appear to be less proficient than older children at forming mental representations of the environment. Cousins, Siegel, and Maxwell (1983) examined the wayfinding performance and environment configural knowledge of 7-, 10-, and 13-year-olds on their school campuses. Although all age groups effectively performed at ceiling when asked to follow the best route from one room to another, 7-year-olds performed notably worse than 10- and 13-year-olds when asked to point to unseen locations within the campus. Similarly, Overman, Pate, Moore, and Peuster (1996) demonstrated that children younger than 7 years were not as skilled as older children at solving tasks using spatial relations present in the environment. Lehnung et al. (1998) noted that 10-year-olds appeared to make use of cognitive-map-style strategies at greater rates and generally made fewer errors than 7- and 5-year-olds in a spatial orientation task. Additional, albeit indirect, support for this sensitive time period comes from a study of children who had suffered a traumatic brain injury (Lehnung, Leplow, Ekroll, Benz, et al., 2003). That is, children who acquired a traumatic brain injury before 10 years of age displayed greater long-term impairments in the ability to orient by means of cognitive maps. Taken together, this body of evidence suggests that children's spatial cognition abilities develop rapidly between 7 and 10 years (Nazareth, Weisberg, Margulis, & Newcombe, 2018). Indeed, Lehenung and colleagues have proposed that the relational place strategies critical for cognitive mapping do not appear to be developed before 7 or 8 years of age, and are fully functional by age 10 (Herman, Shiraki, & Miller, 1985; Lehnung, Leplow, Ekroll, Benz, et al., 2003; Lehnung et al., 1998; Overman et al., 1996).

It is worth noting that the vast majority of the aforementioned studies investigating the emergence of cognitive mapping in children make use of metrics such as pointing to unseen objects, or trying to locate a non-visible location in tasks analogous to the Morris Water Maze task popular in the rodent literature. These measurements often make assumptions about the formation of one's cognitive map, rather than directly testing it. For instance, asking participants to point to unseen objects provides *some* sense of the accuracy of the cognitive map of the environment, but analyzing pointing errors in this way is most appropriate if the cognitive map takes a similar form as a paper map or satellite imagery, as envisioned by Tolman (1948). On the other hand, Siegel and White characterized their survey representation of the environment as decidedly non-map-like, and intentionally avoided the term "cognitive map" due to it's connotation that one's mental representation of the environment shares similarities with a physical map of the same space (Siegel & White, 1975). While there is no clear consensus on the form of the cognitive map in humans (Filimon, 2015), there appears to be notably fewer studies in the literature examining cognitive map development in children utilizing the non-map-like cognitive map paradigm of Siegel and White (1975).

With this in mind, we set out to assess the emergence of survey-like mental representations of the environment in children while navigating within a novel virtual environment. We asked a group of 7- to 10-year old children and a group of young adults to play a computer game appositely designed in-house to assess the ability of children to navigate by means of cognitive maps. Importantly, this task required the integration and inference of spatial information and not simply the presence of *any* non-egocentric spatial behaviour. The game was set in a large-scale virtual museum in which participants were explicitly asked to learn the locations of different exhibits, and were explicitly asked to learn the locations of each exhibit in order to navigate between them as quickly as possible. Consistent with the previous literature, we hypothesized that 7- and 8-year-old children will not display navigational behaviours indicative of the presence of a cognitive map at the same rates as young adults, while 9- and 10-year-old children will exhibit greater rates of these behaviours as compared to younger children, with rates approaching those or equal to young adults (Lehnung, Leplow, Ekroll, Benz, et al., 2003).

Method

Participants

We tested 97 children (M = 8.96, SD = 1.27, range = 7.01–10.96 years of age; constituted by 24 seven-year-olds (11 males), 23 eight-year-olds (13 males), 28 nine-year-olds (14 males), and 22 ten-year-olds (10 males) recruited through a database of families within the community who voluntarily indicated an interest in participating in research studies. Children were placed into age groups by floor rounding (e.g., children aged ≥ 7 years, and < 8 years, were considered "7-year-olds"). The primary inclusion criteria for this study were: (a) children between the ages of 7 and 10 years; (b) no history of developmental problems (assessed through parent report); and (c) no evidence of cognitive deficits as assessed by a neuropsychological evaluation (i.e., the Vocabulary, Block Design, Digit Span, and Cancellation subtests of the Wechsler Intelligence Scale for Children Fourth Edition, Wechsler, 2003), alongside the Children's Color Trail Test (Llorente, Williams, Satz, & D'Elia, 2003); (d) sufficient understanding of English to ensure adequate comprehension of questionnaires and task instructions. Parents and children completed additional demographic, developmental history, and other questionnaires that were not included in the analyses of the present study.

The sample consisted of children predominantly self-identified as Caucasian and broadly from middle-class families. English was typically the primary spoken language, except for six children who spoke non-English languages at home. Additionally, we included a group of 26 young adults (13 Males; $M = 20.82$, $SD = 2.15$, range = 17.12–25.25 years of age) recruited from the undergraduate university population as part of a larger study; these participants reported no history of neurological or neurodevelopmental disorders, brain injuries, cognitive complaints affecting daily life activities, or history of drug or alcohol abuse.

Procedure

Participants performed our in-house spatial orientation task. This task consisted of a game that takes place in a virtual museum, and appositely designed to evaluate the ability to form and make use of cognitive maps. The virtual environment included different environmental clutter, such as abstract paintings, statues, and windows, to ensure the visual scenes from different hallways were distinct. The game consisted of three phases: (a) a practice phase, (b) a guided tour phase, and (c) a testing phase. Participants used an Xbox 360 controller to navigate through the virtual museum and perform the task, which was displayed on a 24-inch LCD monitor with 1,920 × 1,080 pixel resolution. Figure 1a depicts a bird's-eye view of the virtual museum in which the three phases take place.

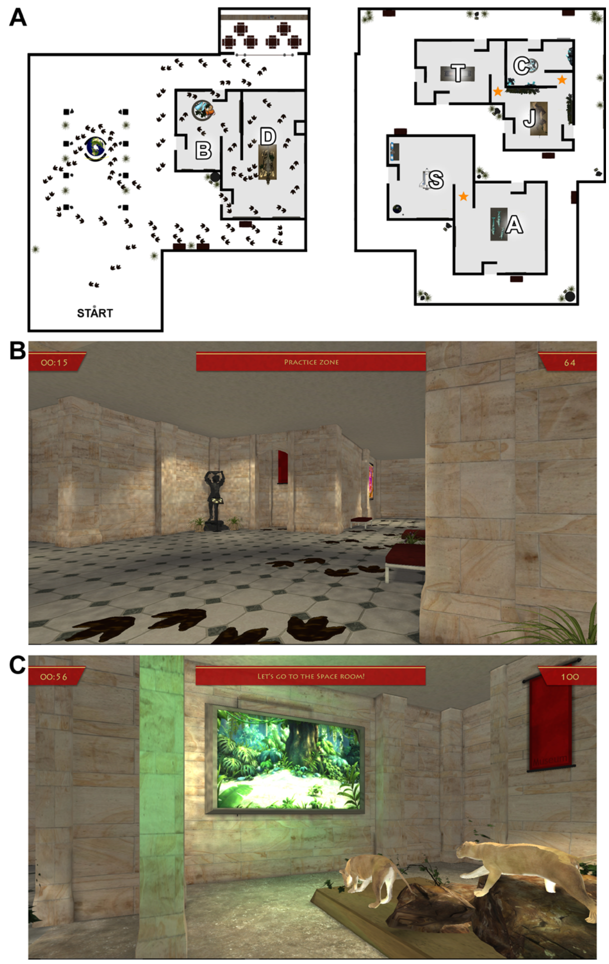

Figure 1. (a) Depicts a schematic view of the virtual museum environments. The left environment was used for the practice phase and included one atrium and two themed rooms. The environment in the right portion of the museum consisted of five themed rooms and was used during the tour and testing phase. (b) A view of the practice phase of the game in which participants were required to follow a pathway of dinosaur footprints and collect footsteps within a given predetermined time limit of 90 s. (c) An example of a trial during the testing phase. In this specific trial, the start location is the jungle room and the target location is the space room. An accumulated total reward-points score is displayed in the top right corner of the screen throughout the testing phase. A timer in the top left corner automatically reset at the beginning of each trial.

Before the task began, participants listened to an audio-recorded introduction to the game. The narrator explained that the goal of the game was to learn the locations of different rooms in the museum in order to deliver a series of letters from one room to another as quickly as possible and by following the shortest pathway; children were also told that points were awarded according to the time they required to deliver a letter from a room to another one (less time spent, more points awarded), and that rooms were connected with each other and shortcuts were available in order to reach a given target location as quickly as possible.

To ensure adequate use of the controller, participants were first asked to complete the practice phase, which required them to move through a section of the virtual museum as quickly and precisely as possible by following a predetermined pathway of dinosaur footprints (Figure 1b). As participants stepped over each of the dinosaur footprints, the footprints disappeared along with a brief auditory feedback. A counter placed at the top left corner of the screen served as an additional cue, indicating the number of remaining footsteps to be collected. This practice phase was considered completed only after participants navigated the pathway by sequentially clearing all footprints within 90 s (as determined by the results of a pilot study), ensuring a moderate level of competence in using the interface. Although not recorded, most participants required two or three attempts to reach criterion.

After the practice phase, participants began in a new section of the museum (see Figure 1a) and the guided tour phase began. This portion of the museum was comprised of five uniquely themed rooms (i.e., a crystal, jungle, space, aquarium, and train room) and connecting corridors. Each room had multiple exits, which connected it to one or more other themed rooms. During the guided tour phase, participants were guided clockwise along the perimeter of the environment. To ensure equal initial exposure time among participants, the tour was passively guided, with all rooms were revealed in a specific order and for the same amount of time across all participants. During the tour, participants listened to interesting facts about each themed room to help direct and maintain their attention; throughout the guided tour, participants were specifically informed that each room had more than one exit, and that these exits were marked by a bright red banner. The guided tour ended in the same location where it began, outside of the train room, and participants were instructed that the testing phase was about to begin.

The testing phase consisted of 20 trials. In each trial, participants started from a given room and were required to reach a different target room. The pairs of starting and target rooms were unique throughout the testing phase (each path was performed only once) and the same trial order was administered to all participants. In each trial of the testing phase, participants were instructed to pick up a visible envelope that revealed a target location (one of the other four rooms) to be reached. The instructions were presented simultaneously via an audio prompt and on-screen text; the text was displayed at the top of the screen for the entire duration of the trial as a remainder of the target room. Participants were asked to travel to the indicated target room quickly and via the shortest pathway possible to receive the most points, and were informed that the point rewards would be based on their trial completion time (and not necessarily distance), and participants were allowed as much time as they required to complete a trial. Upon entering the target room, the trial was complete and participants were immediately given feedback (e.g., hearing an audio clip of "hooray!") and awarded points (the assignment of points was determined based on the shortest time required to complete the trial; slower participants receiving fewer points, ranging from 100 to 10 points). See Figure 1c for a snapshot of a participant performing a trial of the testing phase.

Measures and Data Analyses

Participants' performance at the Spatial Orientation task was scored in terms of time and distance efficiency, as well as pathways followed while reaching target locations (as evidence of the strategy used to orient and navigate within the environment). Time to completion, distance travelled, and the participant's location were recorded by the computer every 10 ms for each trial.

Due to differences in pathway lengths between target and starting locations, standardized scores for each trial were calculated; the time and distance required to complete the task were converted into an efficiency score based on performance compared to the ideal performance (e.g., shortest possible time and distance for each trial). The shortest time or distance possible for each trial was identified by the best performance (i.e., quickest time or distance to complete the trial) among all participants included in the present study, as well as an expanded group of adults ($n = 103$, 51 males, $M = 20.8$ years, $SD = 2.5$ years) who performed the same task for a different study (Murias, Kwok, Castillejo, Liu, & Iaria, 2016). To calculate a time efficiency score, we divided the shortest recorded trial time by the participant's trial completion time. An ideal performance yielded an efficiency score of 1, with poorer performances resulting in efficiency scores approaching 0. For example, if a participant completed a trial in 40 s and the ideal time for that trial is 20 s, they would have received a time efficiency score of 0.5. For each participant, we calculated the average time and distance efficiency scores.

In addition to efficiency scores, which indicate proficiency at solving the task, we also qualitatively evaluated each participant's travelled pathway at each trial to assess their use of a cognitive map for navigation. For each trial a primary coder, blind to the participant's age group, identified if the participant got lost (i.e., "lost"), initially went in the correct direction toward the target room (i.e., "first correct"), followed the same pathway as experienced through the guided tour (i.e., "learned route"), or used a shortcut to reach the target room (i.e., "attempted shortcut"). These boolean scores are not mutually exclusive, as participants could have, for instance, set off in the correct direction initially, made use of the learned route as well as attempted to make use of shortcuts, and appeared to be lost.

The participant's performance was scored *lost* if they met one of the following criteria: they retraced their path, entered the same room more than once, missed the target room when walking by, or walked around the perimeter of the environment more than once (see Figure 2a for an example of this scoring). A participant, however, could have looked into a room and stopped at an entrance and not been marked as "lost"; also, if a participant retraced the route by immediately correcting a wrong turn, they were not marked as "lost." If, however, they made a wrong turn and continued in that direction for more than a few steps the trial would be marked as "lost."

Participants' performance was scored *first correct* on a trial based on their initial path choice; this could be reflected by either setting off in the most efficient direction towards the target room or going directly to an efficient exit at the beginning of the trial. As some exits were exclusive to shortcut paths, exits towards the learned path leading to the target room could have also been considered correct. If an exit did not lead directly towards the target room, the initial direction chosen after exiting the starting room was scored. This metric was intended to capture purposeful, goal-directed navigation, regardless of whether participants subsequently got lost, that is, initially knowing where something is but not knowing the best way to get there or getting lost along the way. Examples of correct and incorrect initial choices are shown in Figures 2b and 2c, respectively.

Participants' performance was scored as *learned route* if they reached the target room by utilizing the same pathway travelled during the guided tour (the learned route was along the perimeter hallway). An example of using only the learned route to reach the target room is shown in Figure 2d.

Finally, participants' performance was scored *attempted shortcut* if they entered the bisecting hallway or used the doorways connecting rooms to reach their target room (e.g., Figure 2e). Shortcuts and learned routes could both be used in a given trial, such as in Figure 2b. Using shortcuts did not necessarily indicate that a participant had not gotten lost or had used the most efficient path to their destination, as shown in Figure 2a; therefore, we additionally computed an "effective shortcutting" score (referring to a performance in which a shortcut was utilized, and the participant did not get lost – evidence of the effective use of a cognitive map as opposed to simply wandering or systematic searching). This classification is critical for a qualitative description of participants' navigational behaviour, providing additional insights into the participants' performance at the task beyond that measured by the efficiency score. To establish interrater reliability, a second rater independently coded the performance of 25 participants pseudorandomly selected in order to ensure full coverage of the age groups (20% of the total sample). The average agreement between the raters was high (M = 94.5%, SD = 2.42%, range = 90%–98.75%).

For each participant, we computed the average score across all trials for each performance metric; for the qualitative metrics, the average score across trials represents the rate at which a participant was observed exhibiting the given behaviour. For instance, a "lost" score of 0.8 indicated that a participant got lost on 80% of their trials. Statistical analyses were performed via IBM SPSS Statistics Version 22, Armonk, NY, USA. The performance of participants on the Spatial Orientation Task was then compared using a series of one-way analyses of variance (ANOVAs; with age group as the between-groups factor), with Bonferroni-corrected follow-up tests performed when appropriate. For these follow-up tests, at an n of 22 and $\alpha = .005$ we would expect powers of at least 0.13, 0.37, 0.69, 0.91, at ds of 0.5, 0.75, 1.0, 1.25, respectively, indicating our analyses would not be sufficiently powerful for ds < 1.

Results

The participants' age group, sample size, and group performances are detailed in Table 1 and group differences depicted in Figure 3 and Table 2, and the relations between performance metrics, corrected

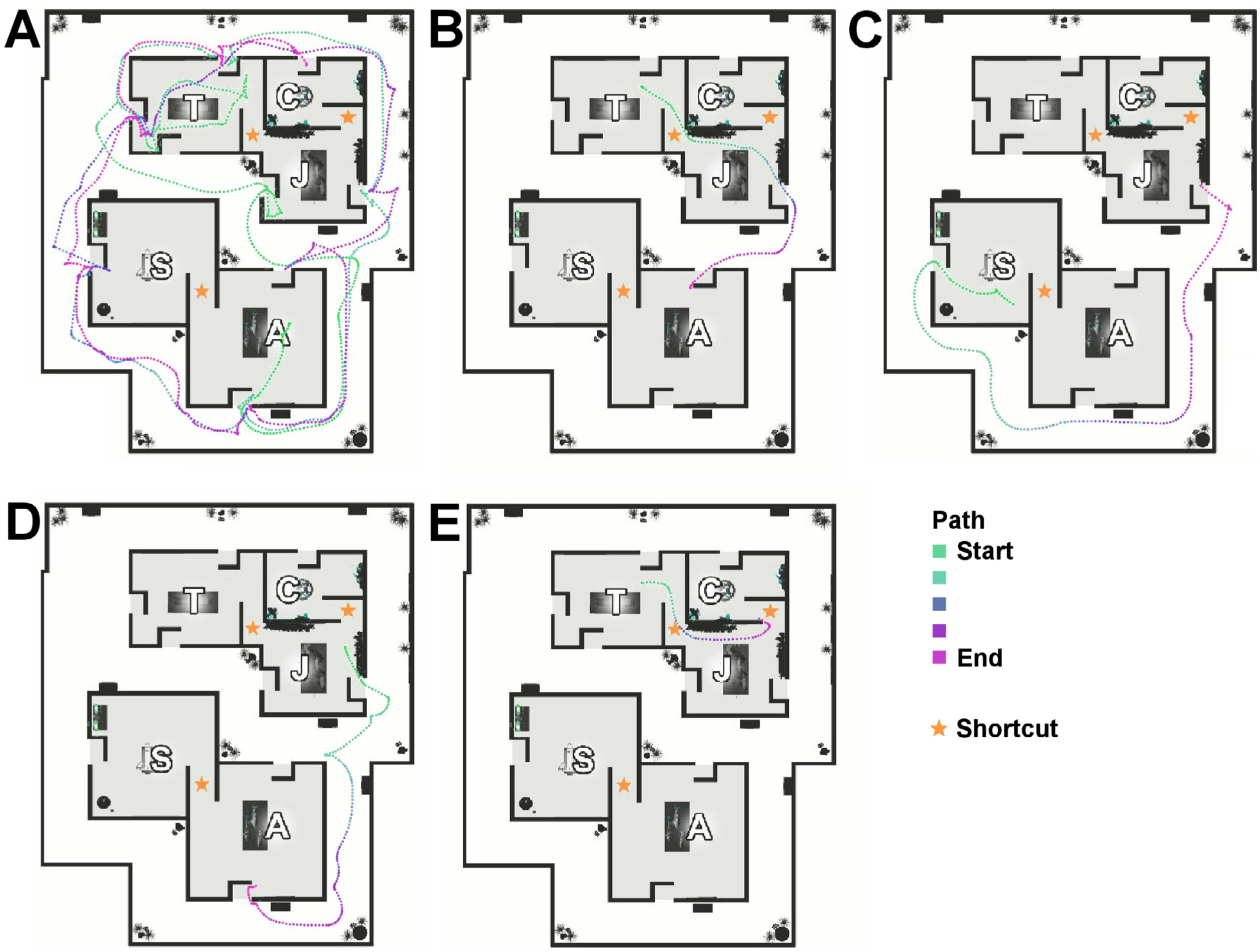

Figure 2. The figure displays examples of performances and their respective scores. (a) An example of a trial where the participant was scored "lost," as they walked through some areas multiple times and walked past the target room without entering. This trial was also scored as not "first correct," "learned route" and "attempted shortcut." (b) A trial scored as "first correct," not "lost," "attempted shortcut" and "learned route." (c) A trial in which the participant was scored not "first correct" in the exit or direction chosen. This trial was also scored not "lost," and "learned route." (d) In this trial, the participant's performance was scored "learned route" since they used the learned route exclusively. This was also scored as and "first correct" as they initially moved in the correct direction toward the target room. (e) In this example, the participant's performance was scored as "effective shortcut" since they reached the target room by shortcutting and avoiding the learned route entirely. This trial was also scored as not "lost" and "first correct."

for age, are reported in Table 3. One-way ANOVAs revealed significant differences across age groups on the rates at which participants got lost, $F(4, 118) = 11.492$, $p < .001$, $\eta^2 = .280$, struck off in the correct direction initially, ($F(4, 118) = 16.551$, $p < .001$, $\eta^2 = .360$, made use of the learned route, $F(4, 118) = 9.187$, $p < .001$, $\eta^2 = .237$, as well as their time, $F(4, 118) = 23.396$, $p < .001$, $\eta^2 = .442$, and distance, $F(4, 118) = 41.274$, $p < .001$, $\eta^2 = .583$, efficiency. Interestingly, there were no differences across age groups in the rates of attempted shortcutting, $F(4, 118) = 2.084$, $p = .087$, $\eta^2 = .066$, but significant differences in the rates of effective shortcutting, $F(4, 118) = 11.144$, $p < .001$, $\eta^2 = .274$.

Bonferroni-corrected ($\alpha = .005$) follow-up tests, detailed in Table 2, indicated that adults got lost significantly less often than 7-, 8-, and 9-year-olds, but not 10-year-olds, and 10-year-olds got lost significantly less often than 7-year-olds. Adults were also more likely to take the first correct exit as compared to 7-, 8-, 9-, and 10-year-olds, with no other significant differences between groups. Seven-year-olds were more likely to rely on the learned route than both 10-year-olds and adults. Additionally, 8- and 9-year-olds relied more heavily on the learned route than adults. The adults' average time and distance efficiency were significantly greater than 7-, 8-, 9- and 10-year-olds, and 10-year-olds average

Table 1
Rates of Spatial Orientation Task Behaviours Observed at Each Tested Age Group

		Lost		First exit correct		Learned route		Time efficiency		Distance efficiency		Attempted shortcuts		Effective shortcuts	
	n	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
7 y/o	24	.36	.15	.54	.13	.43	.18	.36	.07	.23	.05	.72	.24	.39	.14
8 y/o	23	.30	.14	.53	.10	.35	.16	.36	.06	.26	.07	.70	.17	.41	.15
9 y/o	28	.26	.14	.54	.12	.34	.15	.40	.07	.27	.05	.84	.13	.58	.14
10 y/o	22	.19	.12	.54	.15	.25	.12	.43	.09	.33	.07	.74	.18	.56	.17
Adults	26	.12	.12	.78	.15	.20	.09	.56	.14	.49	.13	.76	.19	.64	.22

Note. "Lost" refers to participants wandering in search of the target room. "First exit correct" refers to participants striking off in the correct direction at the beginning of a trial. "Learned route" indicates use of the route performed in the guided tour phase of the task. Time and distance efficiency indicate how close a participants performance was to the best performance. Attempted shortcuts refers to any use of corridors or exits not along the "Learned route," whereas effective shortcuts only refer to attempted shortcutting in which the participant did not appear to be "lost." y/o = year-olds.

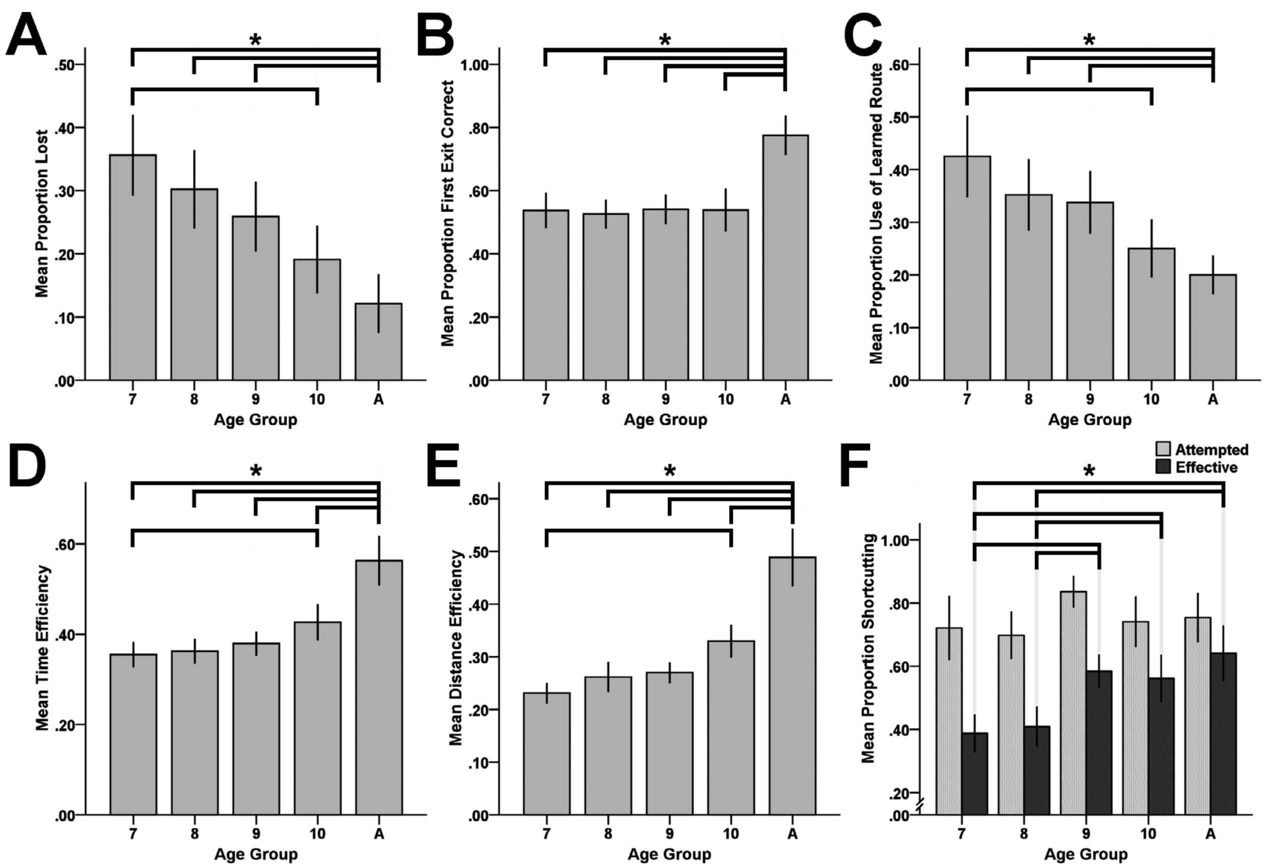

Figure 3. Performance on the Spatial Orientation Task across different age groups. Errors bars represent uncorrected 95% CIs. Group differences significant at $p \leq .005$ are denoted with * and horizontal bars.

efficiencies were greater than those of the 7-year-olds. Interestingly, the rates of effective shortcutting revealed two distinct groups, with 7- and 8-year-olds performing worse than 9-year-olds, 10-year-olds, and adults, with no other significant differences between groups.

Discussion

In this study, we first exposed children and young adults to a large-scale environment through a guided tour, and then asked them to reach target locations as quickly as possible, necessitating effective shortcutting and making use of a cognitive

Table 2

Performance on the Spatial Orientation Task Compared Between Different age Groups

	7-year-olds				8-year-olds				9-year-olds				10-year-olds			
	t	*df*	*p*	*d*	*t*	*df*	*p*	*d*	*t*	*df*	*p*	*d*	*t*	*df*	*p*	*d*
Lost																
8 y/o	1.256	45	.215	0.374												
9 y/o	2.384	50	.021	0.674	1.080	49	.286	0.309								
10 y/o	**4.067**	**44**	**< .001**	**1.226**	2.824	43	.007	0.861	1.796	48	.079					
Adults	**6.196**	**48**	**< .001**	**1.789**	**4.914**	**47**	**< .001**	**1.434**	**3.897**	**52**	**< .001**	**1.081**	2.051	46	.046	0.605
First exit correct																
8 y/o	0.329	45	.744	0.098												
9 y/o	-0.103	50	.919	−0.029	−0.472	49	.738	−0.135								
10 y/o	−0.027	44	.978	−0.008	−0.324	43	.747	−0.099	0.063	48	.950	0.018				
Adults	**−5.864**	**48**	**< .001**	**−1.693**	**−6.713**	**44.264**	**< .001**	**−2.018**	**−6.226**	**47.262**	**< .001**	**−1.811**	**−5.348**	**46**	**< .001**	**−1.577**
Use of learned route																
8 y/o	1.461	45	.706	0.436												
9 y/o	1.878	50	.066	0.531	0.337	49	.739	0.096								
10 y/o	**3.758**	**44**	**.001**	**1.133**	2.412	43	.020	0.736	2.174	48	.035	0.628				
Adults	**5.428**	**33.247**	**< .001**	**1.883**	**4.074**	**34.502**	**< .001**	**1.387**	**4.036**	**44.670**	**< .001**	**1.208**	1.600	46	.116	0.472
Time efficiency																
8 y/o	−0.380	45	.706	−0.114												
9 y/o	−1.293	50	.202	−0.366	−0.912	49	.366	−0.261								
10 y/o	**−3.069**	**44**	**.004**	**−0.925**	**−2.412**	**43**	**.002**	**−0.736**	−2.107	48	.040	−0.608				
Adults	**−6.948**	**37.157**	**< .001**	**−2.280**	**−6.733**	**36.635**	**< .001**	**−2.225**	**−6.205**	**36.318**	**< .001**	**−2.059**	**−4.142**	**43.806**	**< .001**	**−1.252**
Distance efficiency																
8 y/o	-1.842	45	.072	−0.549												
9 y/o	−2.844	50	.006	−0.804	−0.501	49	.619	−0.143								
10 y/o	**−5.673**	**44**	**< .001**	**−1.710**	**−3.346**	**43**	**.002**	**−1.021**	**−3.486**	**48**	**.001**	**−1.006**				
Adults	**−9.191**	**31.386**	**< .001**	**−3.281**	**−7.626**	**37.412**	**< .001**	**−2.494**	**−7.789**	**31.660**	**< .001**	**−2.769**	**−5.257**	**38.767**	**< .001**	**−1.689**
Attempted shortcutting																
8 y/o	0.373	45	.711	0.111												
9 y/o	−2.082	34.097	.045	−0.713	−3.239	40.118	.003	−1.023								
10 y/o	−0.316	44	.753	−0.095	−0.815	43	.419	−0.249	2.152	48	.036	0.621				
Adults	−0.534	48	.596	−0.154	−1.058	47	.292	−0.309	1.829	52	.073	0.507	−0.237	46	.814	−0.070
Effective shortcutting																
8 y/o	−0.497	45	.621	−0.148												
9 y/o	**−5.014**	**50**	**< .001**	**−1.418**	**−4.362**	**49**	**< .001**	**−1.246**								
10 y/o	**−3.750**	**44**	**.001**	**−1.131**	**−3.211**	**43**	**.003**	**−0.979**	0.517	48	.607	0.149				
Adults	**−4.879**	**43.637**	**< .001**	**−1.477**	**−4.396**	**44.253**	**< .001**	**−1.322**	−1.128	41.779	.266	−0.349	−1.381	46	.174	−0.407

Note. Group differences significant at $p \leq .005$ are emboldened. Positive *t* and *d* statistics indicate that the group identified in the column header displayed a greater proportion of the given measure as compared to the group identified in the row heading. y/o = year-olds.

Table 3
Partial Correlations Between Performance Metrics of the Spatial Orientation Task, Controlling for Effects of Age Group

		Lost	First exit correct	Use of learned route	Time efficiency	Distance efficiency	Attempted shortcutting
First exit correct	*r*	−.082					
	p	.371					
Use of learned route	*r*	**.918**	.116				
	p	**< .001**	.203				
Time efficiency	*r*	**−.406**	**.622**	−.165			
	p	**< .001**	**< .001**	.069			
Distance efficiency	*r*	**−.474**	**.526**	**−.290**	**.888**		
	p	**< .001**	**< .001**	**.001**	**< .001**		
Attempted shortcutting	*r*	**.380**	**.397**	**.625**	**.271**	.124	
	p	**< .001**	**< .001**	**< .001**	**.003**	.173	
Effective shortcutting	*r*	**−.323**	**.464**	−.025	**.569**	**.460**	**.740**
	p	**< .001**	**< .001**	.783	**< .001**	**< .001**	**< .001**

Note. $n = 123$. Emboldened relations are significant at $p < .05$.

map to collect as many points as possible. The explicit request to navigate and orient by shortcutting gave us the opportunity to measure the ability of participants to orient and navigate by means of cognitive maps. Our results yielded a number of insights into the development of the ability to form cognitive maps.

First, examination of the navigational strategies that participants used while reaching their target destinations indicated that 7- to 9-year-olds were more likely to rely on following the previously learned route compared to 10-year-olds and young adults. This finding is consistent with previous research by Bullens, Iglói, Berthoz, Postma, and Rondi-Reig (2010), who demonstrated that younger children spontaneously utilize egocentric, route-based strategies with greater frequency than older children. Second, examination of participants' tendency to engage in shortcutting revealed no differences across all groups in the rate of attempted shortcutting, suggesting that all participants understood the task and tried to perform it as effectively as possible. Next, and most relevant to the purpose of this study, we found that 7- and 8-year-old children were less effective than older children and young adults in effectively using shortcuts to navigate. Together, these findings provide clear evidence of a distinct developmental change at approximately 9 years of age, when children begin to proficiently orient and navigate in large-scale surroundings by means of cognitive maps.

The findings that children around 9 years of age were comparable to adults in their use of cognitive maps contrasts with the results of many of the other performance measures we used, such as path time and distance efficiency. Across these other measures, adults generally outperformed children of all ages; they were more likely to set off in a correct direction at the beginning of a trial, and generally produced quicker and shorter paths. It is likely that the greater distance and time efficiencies are partially due to a more map-like and refined understanding of the direction or path required to reach goals in the environment, as indicated by the adult's greater frequency of setting off along the correct direction initially, as well as perhaps a greater capability to maintain their sense of direction and wayfinding, evidenced by their lower rates of getting lost. The improved time and distance metrics exhibited by adults, however, may also be influenced by greater proficiency or previous experience with the controls or virtual environments.

Taken together, these results suggest that children first develop some form of cognitive map around 9 years of age. With further development, this mental representation becomes more map-like, or children get better at deriving and computing map-like metrics from their mental representations of the environment as they age. In support of this proposal, Nazareth et al. (2018) demonstrated that it was not until 12 years of age that children's pointing accuracy and map-building accuracy were comparable to that of adults. Furthermore, other measures which rely on rough configural, as opposed to precise metric information about the environment are often observable in children as young as ten (Bullens et al., 2010). This evidence supports Lehnung and colleagues' view that these faculties are developed by 10 years of age (Lehnung, Leplow, Ekroll, Benz, et al., 2003), and are generally preceded by the development route-based strategies (Bullens et al., 2010; Lingwood, Blades, Farran, Courbois, & Matthews, 2018), as predicted by the landmark-route-survey model proposed by Siegel and White (1975). This progression from visual, path-based wayfinding at age 7 and younger, to making and utilizing proto- cognitive maps at approximately age 9, to nuanced and more metric cognitive maps in adulthood may be due to age-related changes in the extended neural network supporting these abilities. While total brain volumes are still in flux, gray matter volume peaks at approximately 9–11 years of age (Dosenbach et al., 2010; Lenroot & Giedd, 2006), and regions such as the hippocampus and posterior cingulate (Blankenship, Redcay, Dougherty, & Riggins, 2017; Power, Fair, Schlaggar, & Petersen, 2010) are exhibiting age-related changes in functional connectivity across this developmental timespan. It is possible that the changes in wayfinding performance are either afforded by or providing the impetus for some of the network-level changes in brain connectivity.

While the findings presented in this study shed some light on the developmental timeline of specific spatial orientation skills, there are limitations that must be acknowledged. First, we have assessed the ability to orient by means of cognitive maps in a large-scale virtual environment using a cross-sectional design; further investigations would need to confirm that the same findings could be replicated in ecological surroundings and ensure the effects we detected are representative of the typical individual developmental trajectory between 7 and 10. While virtual environments are more malleable, faster and easier to create and administer, the vast majority lack the complete vestibular, proprioceptive, and kinesthetic sensory experience that is present in real-world navigation (Lehnung, Leplow, Ekroll, Herzog, et al., 2003; Richardson, Powers, & Bousquet, 2011; Taube, Valerio, & Yoder, 2013). It is possible that the particular age threshold (i.e., 9 years of age) identified in our study is related to the particular complexity, size, and demands of the virtual environment we employed, as well as the experiences of our particular sample, including the effects of video game experience (Herman et al., 1985; Murias et al., 2016; Richardson et al., 2011). Second, the experimental protocol adopted in our study cannot dissociate between the ability to form cognitive maps and the ability to make use of them for the purpose of orientation. Thus, although our findings are consistent with previous studies and specifically identify the age of 9 years as a significant milestone for orienting and navigating efficiently by means of cognitive maps, further studies are needed to disentangle the timeline by which the capacity to form and the capacity to separately and subsequently use cognitive maps develops in children (Burles, Slone, & Iaria, 2017; Howe & Brainerd, 1989; Iaria, Chen, Guariglia, Ptito, & Petrides, 2007). Finally, in our study, participants were passively guided through a set route for an initial tour of the environment; Although difficult to control for, an active exploration directed by the participants themselves may affect the manner in which they develop and use their mental representation of the environment. Indeed, previous research has found that factors such as self-directed as opposed to passive exploration can alter the accuracy of sketch maps of an environment (Chrastil & Warren, 2012).

In summary, we presented evidence that the ability to effectively orient and navigate by means of cognitive maps in large- scale surroundings develops by the age of 9 years. We specifically identified that utilizing shortcutting as a measure that taps into one's configural knowledge of the environment, avoiding making the assumption of the map-like nature of this knowledge (in pointing tasks, for instance), may provide a more sensitive tool to detect the more qualitative emergence of this cognitive capacity.

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