Journal of Experimental Child Psychology 170 (2018) 86–106

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Charting the development of cognitive mapping

Alina Nazareth [a,*], Steven M. Weisberg [b], Katherine Margulis [c], Nora S. Newcombe [a]

[a] *Temple University, Philadelphia, PA 19122, USA*
[b] *University of Pennsylvania, Philadelphia, PA 19104, USA*
[c] *Vanderbilt University, Nashville, TN 37235, USA*

ARTICLE INFO

Article history:
Received 7 August 2017
Revised 12 January 2018

Keywords:
Virtual environment
Spatial cognition
Development
Navigation
Cognitive map
Perspective-taking

ABSTRACT

Developmental research beginning in the 1970s has suggested that children's ability to form cognitive maps reaches adult levels during early adolescence. However, this research has used a variety of testing procedures, often in real-world environments, which have been difficult to share widely across labs and to use to probe components of mapping, individual differences in success, and possible mechanisms of development and reasons for individual variation. In this study, we charted the development of cognitive mapping using a virtual navigation paradigm, Silcton, that allows for testing samples of substantial size in a uniform way and in which adults show marked individual differences in the formation of accurate route representations and/or in route integration. The current study tested children aged between 8 and 16 years. In terms of components of normative development, children's performance reached adult levels of proficiency at around age 12, but route representation progressed significantly more quickly than route integration. In terms of individual differences, by age 12 children could be grouped into the same three categories evident in adults: imprecise navigators (who form only imprecise ideas of routes), non-integrators (who represent routes more accurately but are imprecise in relating two routes), and integrators (who relate the two routes and, thus, form cognitive maps). Thus, individual differences likely originate during childhood. In terms of correlates, perspective-taking skills predicted navigation performance better than mental rotation skills, in accord with the view that perspective

* Corresponding author.
E-mail address: alina.nazareth@temple.edu (A. Nazareth).

https://doi.org/10.1016/j.jecp.2018.01.009

taking operates on extrinsic spatial representations, whereas mental rotation taps intrinsic spatial representations.

Introduction

Spatial navigation or wayfinding is necessary for everyday life. Successful navigation requires various cognitive skills, including encoding spatial relations from multiple sensory cues, maintaining these relations in memory, and transforming representations to orient and navigate in large-scale environments entered from various vantage points (Wolbers & Hegarty, 2010). For many investigators, the knowledge created using these skills constitutes a cognitive map, defined as an internal representation of large-scale environments that is integrated across separately encountered areas and that retains sufficient metric information to allow the generation of novel shortcuts and detours (O'Keefe & Nadel, 1978; Tolman, 1948). The cognitive map metaphor was extended to development in Siegel and White's (1975) proposal of a sequence from landmark to route to survey learning in both ontogeny and microgenesis and has inspired much research on spatial development.

Although some navigationally relevant skills emerge during infancy and the preschool period, important age-related change in navigational skills and representations of natural environments continue between 6 and 12 years of age (e.g., Acredolo, Pick, & Olsen, 1975; Allen, Kirasic, Siegel, & Herman, 1979; Heth, Cornell, & Alberts, 1997; Laurance, Learmonth, Nadel, & Jacobs, 2003; Overman, Pate, Moore, & Peuster, 1996). More recent research in natural environments has supported the conclusion that changes over middle childhood lead to mature spatial representations by the dawn of adolescence (Liben, Myers, Christensen, & Bower, 2013), and similar patterns emerge in research with smaller scale studies of memory for spatial location (Hund & Plumert, 2005), research on children's facility in integrating various sources of spatial information (Nardini, Burgess, Breckenridge, & Atkinson, 2006), studies of working memory for locations in navigable spaces (Belmonti, Cioni, & Berthoz, 2015), and spatial perspective taking (PT) in a route walking task (Vander Heyden, Huizinga, Raijmakers, & Jolles, 2017).

However, this body of developmental research explicitly or implicitly assumes that the mature end point of age-related change is the ability to construct survey representations or cognitive maps. This assumption is controversial. Some investigators have argued that cognitive maps are not necessary to explain spatial memory and wayfinding. For instance, navigation might be largely based on coding of movement, supplemented by constraints from a geometric module (Wang & Spelke, 2000, 2002, 2003), spatial memory might simply contain associative links (McNamara, 1986), or locally metric maps might be only roughly related to each other (Chrastil & Warren, 2014; Jacobs & Schenk, 2003; Kuipers, 2000). A recent approach to the debate concerning cognitive maps focuses on individual differences, proposing that people can sometimes form cognitive maps but that the abilities, strategies, and motivation required to do so are not always available or used (Weisberg & Newcombe, 2016). This formulation builds on findings of large and robust individual differences in navigation (Fields & Shelton, 2006; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Ishikawa & Montello, 2006; Weisberg & Newcombe, 2016).

Individual differences research requires large samples studied under controlled and comparable conditions. Gathering such data sets has been enabled by the development of virtual environments (VEs) to simulate real-world wayfinding tasks, to avoid logistical challenges in real-world environments, and to enable standardized methods across research groups (Maguire, Burgess, & O'Keefe, 1999; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). Weisberg and colleagues (Weisberg & Newcombe, 2016; Weisberg et al., 2014) used a VE navigation task modeled on the route integration paradigm used in the natural world by Ishikawa and Montello (2006) and by Schinazi, Nardi, Newcombe, Shipley, and Epstein (2013). Participants demonstrated a substantial range of performance, suggesting that some adults form highly accurate representations of space, whereas others do not.

There are several possible reasons for these individual differences. One area of interest has involved correlations with spatial skills such as mental rotation (MR) and PT. Adults' performance on the virtual navigation paradigm Silcton is correlated with both measures (Weisberg & Newcombe, 2016). However, the two measures may tap very different spatial domains (Newcombe & Shipley, 2015). MR tasks involve the intrinsic structure of objects, whereas PT involves the extrinsic relations among objects. Measures of MR and PT, although correlated, have been found to be distinct constructs (Huttenlocher & Presson, 1973; Kozhevnikov & Hegarty, 2001; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006). These behavioral findings have been supported by functional magnetic resonance imaging (fMRI) data showing that the two tasks engage different neural substrates (Lambrey, Doeller, Berthoz, & Burgess, 2012). In fact, PT skills, but not MR skills, have been implicated in navigation proficiency (Hegarty & Waller, 2004; Lambrey et al., 2012).

In terms of the study of spatial development, an individual differences approach suggests the importance of going beyond the delineation of a normative sequence of typical development to the assessment of the development of individual differences. The standardized method needed for such research also allows a focused analysis of the components and correlates of spatial representation. Thus, using the same VE tool (Silcton) as used by Weisberg and colleagues (Weisberg & Newcombe, 2016; Weisberg et al., 2014), the current research had three main aims. First, we aimed to delineate normative developmental trajectories for two component navigation skills in children between 8 and 16 years of age. We hypothesized that within-route pointing performance would improve faster with age than between-route pointing performance. Second, we aimed to evaluate when individual differences emerge as children begin to reach adult levels of navigation proficiency. We hypothesized that there would be three types of navigators—integrators, non-integrators, and imprecise navigators—similar to adult navigator profiles and that navigator profiles would be age dependent. Third, we aimed to investigate MR and PT as mechanisms involved in navigation proficiency given that these spatial skills also develop with age, show marked individual differences, and are correlated with navigation (Weisberg & Newcombe, 2016). We hypothesized that PT skills, but not MR skills, would significantly predict performance in the VE given the distinction between extrinsic and intrinsic spatial skills proposed by Newcombe and Shipley (2015).

Method

Participants

The final sample consisted of 105 participants ranging from 8 to 16 years of age (M = 12.17 years, SD = 2.54; 54 male and 51 female; see Table 1) recruited through a database at the Temple University Infant and Child Laboratory. The spatial layout of the VE paradigm is modeled on the real-world campus on which participants were tested. However, the names and architectural features of the target buildings are different from their real-world counterparts. In addition, the investigator ensured that

Table 1
Total number of participants by age and gender.

	Male	Female	Total
8 years	8	5	13
9 years	7	5	12
10 years	4	8	12
11 years	10	6	16
12 years	5	4	9
13 years	7	8	15
14 years	4	5	9
15 years	4	6	10
16 years	5	4	9
Total	54	51	105

Note. Each 1-year age interval (i.e., beginning and ending on birthdays) was used to determine a participant's age group.

children had no prior experience with the portion of the campus on which the VE is based. Data for 8 participants were excluded from the analysis on account of computer issues, illness, or a family emergency. This age range was determined by two considerations. We began with 8-year-olds because pilot data showed that children 7 years and younger were reluctant to complete the long session, and we ended with 16 years because it is just younger than the range covered by prior college participants. Participants received a small reward (e.g., a keychain) for their participation. The current research has received the university's institutional review board approval (Protocol No. 13394, "Computer Based Spatial Abilities"). To compare younger and older children's performance with that of adults, we also included adult data collected as part of a previous study in the analyses. Adult participants were recruited by advertising on university-specific online platforms and by widely distributed flyers hung around campus. A total of 294 undergraduate students (168 female [2 did not report gender]) between 18 and 40 years of age from a large urban research university participated in one of four studies that assessed them on Virtual Silcton performance. These data were reported previously in two articles (Weisberg & Newcombe, 2016; Weisberg et al., 2014). Adults and children followed the same procedure and received the same instructions from the experimenter.

Materials

The experiment was administered on two Windows 7 64-bit computers. One of the computers had an Intel Core 2 Quad CPU at 2.66 GHz and an NVIDIA Quadro FX 1800 graphics card; the second computer had an Intel Core i5 CPU at 3.50 GHz and an NVIDIA GeForce GT 610 video card. Participants were randomly assigned to a testing computer. The VE was displayed on a 40 $\times$ 62-cm LCD monitor with a refresh rate of 60 Hz and a resolution of 1920 $\times$ 1200. The VE was modeled on a real-world college campus (Schinazi et al., 2013; Weisberg et al., 2014) using Unity 3D and Google SketchUp. The VE was designed to replicate the saliency and spatial location of buildings and nonbuilding objects, such as trees and trash cans, without replicating the exact architecture of the real-world structures (Schinazi et al., 2013).

VE navigation paradigm: Virtual Silcton

Virtual Silcton is a desktop-based VE navigation paradigm. It comprises two main routes in different areas of the same VE and two connecting routes. Each main route consists of four unique target buildings for a total of eight target buildings (see Fig. 1). During the learning phase, participants were first instructed to learn the names and locations of all eight target buildings by virtually walking along each main route indicated by red arrows. They were told to pay attention to the front door of each building because that was the specific spot they would be asked to point to later in the experiment. Target buildings in the VE were indicated by a blue gem hovering near the names of the target buildings (see Fig. 2). The two main routes were counterbalanced between participants. Participants walked from the start of each route to the end and then back to the start; thus, each route was completed twice before moving on to the next route. They were told not to veer off the path marked by red arrows but that they could take as much time as they liked on each route. Each of the routes was surrounded by invisible walls that kept participants along the arrowed routes.

Participants used the arrow keys on a computer keyboard to move along the virtual paths and used a computer mouse to look 360° around the VE. The experimenter encouraged participants to practice using the controls and to ask clarification questions before beginning the task. The 8-year-olds did not show greater difficulty in using the arrow keys than older children, and the experiment began only after the experimenter determined that they were in control of the program.

Immediately after learning the four target buildings on each main route, participants learned how the eight target buildings were connected by walking down two connecting routes. Before starting the two connecting routes, participants were told that these paths would "connect" or "go in between" the first two paths they had just learned. The experimenter noted that these connecting routes would not include any new buildings for participants to remember and that instead their role was to help participants understand how the buildings related to one another. Similar to the main routes, the connecting routes were counterbalanced between participants (but always occurred after the main

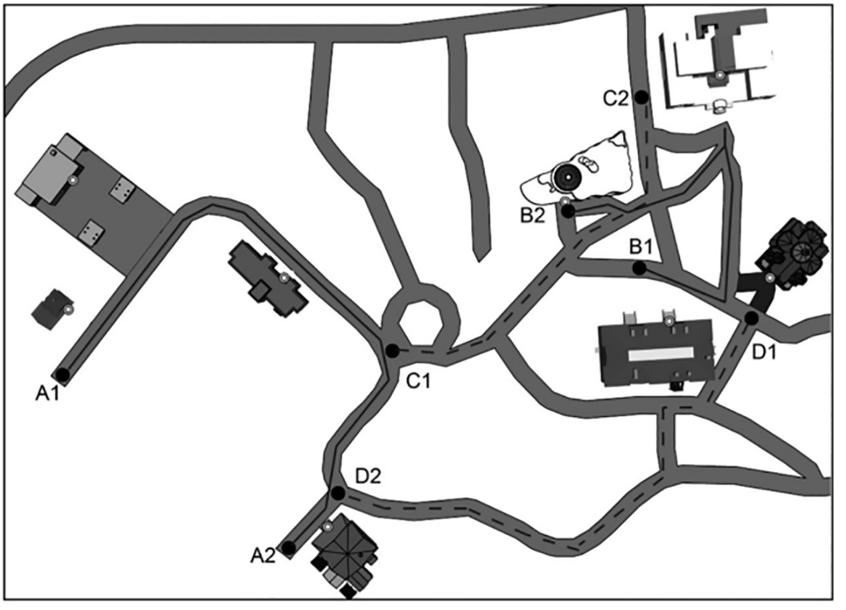

Fig. 1. An aerial view map of Virtual Silcton showing the two main routes (solid lines A and B), two connecting routes (dashed lines C and D), and the layout of buildings on each route. The letter–number combinations are used to indicate the start and end points along each of the main and connecting routes; that is, participants walked from point 1 to point 2 and then back to point 1 for each of the main and connecting routes, thereby traversing each route twice. The presentation of the main routes was counterbalanced (A first or B first), and the presentation of the connecting routes was counterbalanced (C first or D first).

Fig. 2. A route in Virtual Silcton. A blue gem was used to indicate target buildings, and red arrows were used to indicate the route in the VE. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

routes were learned). Participants were reminded to stay on the route marked by red arrows, and invisible walls along the connecting routes prevented participants from veering off course.

The learning phase was untimed, and participants could take as long as they needed on each of the routes. There was no additional learning criterion before participants moved to the testing phase. During the testing phase, participants completed two spatial tasks—a pointing task and a model-building task—that tested their ability to create accurate and integrated representations of the VE. In addition to the two spatial tasks, participants completed a cued building recognition task.

Pointing task. In the pointing task, participants were randomly located adjacent to the first target building of one of the two main routes and were prompted to point in the direction of each of the remaining seven buildings using a virtual crosshair (see Fig. 3). Using the computer mouse, participants could rotate 360° in the horizontal plane. They were specifically instructed to point the crosshair to the front door of each target building and to be careful to click only once to record their answer using the mouse. Clicking the mouse also changed the target building in the prompt at the top of the screen.

Once participants had pointed to the seven target buildings, they were relocated to the next target building and this process was repeated for each of the eight buildings in the VE. A pointing error score for each participant was calculated based on the absolute value of the participant's answer minus the correct answer. If that value exceeded 180, we corrected it by subtracting the value from 360. A within-route error score was calculated for trials in which the target building was on the same route as that of the participant. A between-route error score was calculated for trials in which the target building was on a different main route than that of the participant. For example, if a participant were placed adjacent to the first target building on Route A, three of the target buildings would be on the same route as that of the participant in the VE (i.e., along A1–A2 and excluding the target building at which the participant was positioned) and four buildings would be on the second main route (i.e., along B1–B2). In this case, pointing trials with the three target buildings on Route A would be "within-route" pointing trials and the four target buildings on Route B would be "between-route" pointing trials. Therefore, performance on the pointing task was subdivided into within-route and between-route pointing performances based on the position of the target building in relation to the participant's pointing location in the VE. All participants were placed next to each of the eight target buildings and asked to point to the remaining seven target buildings for a total of 56 pointing

Fig. 3. Pointing task. Participants could rotate a virtual crosshair 360° along the horizontal plane to point in the direction of a target building.

trials—24 within-route trials and 32 between-route trials. The 24 within-route pointing trials were further divided into "seen-within" and "unseen-within" trials based on the intervisibility of target buildings along a route. This was done because a number of target buildings were mutually visible for the within-route trials, but none was mutually visible in the between-route trials. This occurred because in within-route trials, target buildings were along the same route and may have been visible in the distance depending on bends in the route and the degree to which participants chose to rotate the virtual crosshair. In total, there were 14 seen-within and 10 unseen-within pointing trials.

Model-building task. In the model-building task, participants were told that they would construct a map of the VE using a bird's-eye view. Participants were shown an aerial view of the eight buildings and their names alongside a blank box on a computer screen. Participants needed to drag and drop the miniature models of the eight buildings into the blank box at spatial locations relative to each other in order to recreate the VE (see Fig. 4). A bidimensional regression analysis (Friedman & Kohler, 2003; Tobler, 1994) was used to calculate the R^2 for each participant. The R^2 value corrects for rotational, translational and scale differences between the participant map and the actual map and indicates the remaining proportion of variance in the participant's map accounted for by the actual map. It can be interpreted as configurational accuracy.

Building recognition task. Participants were shown images of each of the eight target buildings in the VE and were asked to name the building (similar to target image on the right without the name listed in Fig. 4). Participants could either type the name directly into the computer or dictate it to the experimenter.

Participants received 1 point for each correct response, and scores could range from a minimum of 0 to a maximum of 8 points. Building names were counted as correct if the building was uniquely identifiable from the response (e.g., "house" was incorrect because it could refer to either "Batty House" or "Harvey House," whereas "museum" and "Batty" were correct because they could refer only to "Tobler Museum" and "Batty House," respectively).

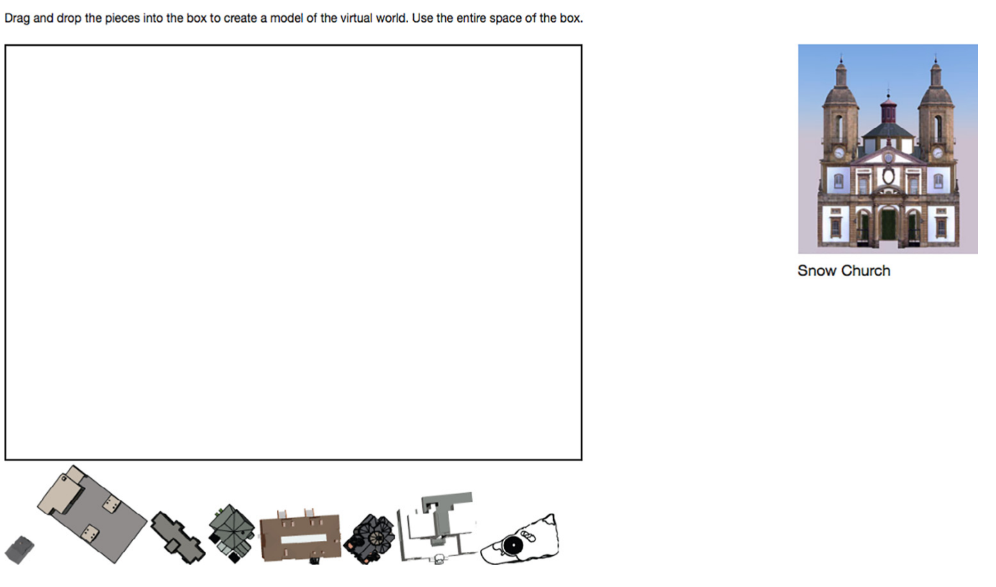

Fig. 4. Model-building task. The aerial view of the eight target buildings was presented at the bottom of the screen. Participants could place the mouse on any of the target buildings to see the front view and name of the building on the right of the screen. Participants were asked to drag and position the eight target buildings in the empty box to represent the spatial relations of the buildings in the VE.

Psychometric and self-report measures

Spatial Orientation Test. The Spatial Orientation Test (SOT; Hegarty & Waller, 2004) is a revised version of the test used by Kozhevnikov and Hegarty (2001) and tests the ability of participants to imagine different perspectives and orientations in space. In this task, participants saw an array of two-dimensional object drawings on a sheet of paper and were asked to imagine that they were standing at one object with a specific facing orientation. They were asked to draw an arrow from this spatial location and orientation to a third object in the array. There were a total of 12 items, and participants were given 5 min to complete the test. The SOT error score was the average of the absolute difference in angle between the correct response and the participant's response. If that value exceeded 180, we corrected it by subtracting the value from 360. To ensure that even the youngest children understood the task, every child was asked to explain the example or indicate understanding by pointing to the images in the example, after which the experimenter started the task.

Mental Rotation Test. The Mental Rotation Test (MRT; Vandenberg & Kuse, 1978, adapted by Peters et al., 1995) consists of 20 items, each made up of one target figure and 4 response items. Of the 4 response items, 2 are identical to the target figure but are presented at varying orientations. The remaining 2 items are mirror images of the target figure. Participants were asked to identify the 2 response items that were identical but rotated images of the target figure. Before beginning the task, participants were given three practice trials. If they got any of the practice problems incorrect, they reviewed their answers with the experimenter and found the right one before moving on to the actual task. This ensured that even the youngest children understood the task, and the experimenter did not move on to the test problems until children demonstrated an understanding of the sample problems. Participants received 2 points for each correct response and lost 2 points for each incorrect response.

Procedure

The entire study from start to finish took approximately 1 h. Participants' parents completed an informed consent form while their children completed an assent form with assistance from the experimenter if needed. Participants were then taken to the testing room and guided through the learning and testing phases of the VE task. Following the VE task, participants completed the MRT and SOT psychometric measures. Finally, participants completed the building recognition task.

Results

We begin by showing that the children—even as young as 8 years—performed above chance in the VE. We then address our three main aims. First, to delineate the developmental trajectories of within- and between-route navigation skills in children, we examined the correlations among age, completion time, and VE performance and used regression models to compare the developmental trajectories for the spatial measures derived from the VE. Second, to evaluate individual differences, we used cluster analyses and compared patterns of navigators across childhood, adolescence, and adulthood. Third, to investigate mental rotation and perspective taking as predictors of navigation proficiency, we report stepwise regressions with age, sex, and psychometric performance and examine the unique variances contributed by each skill. Table 2 presents descriptive statistics for spatial, nonspatial, and psychometric measures. Analyses of sex differences are presented at the end of the Results section. For comparison, we also present data collected from 294 adults in the same VE (Weisberg & Newcombe, 2016; see Table 3).

VE as a testing tool

The first step in the analyses aimed to determine whether participants performed above chance, including the 8-year-old children. Guessing in the pointing task would result in an average score of 90°. Optimal pointing performance would be approximately 10° to 15° from the front door of the target building to which participants were asked to point. A pointing error score for each participant was

Table 2
Descriptive statistics for psychometric and navigation tasks in children.

	Min	Max	*M*	*SD*
Within-route (error)	6.23	63.05	30.99	12.43
Seen-within (error)	4.26	61.98	26.68	15.77
Unseen-within (error)	8.06	65.55	37.02	12.79
Between-route (error)	13.59	72.76	52.72	10.91
Model-building (total)	.001	.92	.33	.23
Model-building (within)	.03	.94	.53	.23
Building Recognition	1.00	8.00	6.10	1.87
MRT	−28.00	80.00	29.10	22.20
SOT (error)	7.33	127.50	60.92	32.27

Table 3
Descriptive statistics for navigation tasks in adults.

	Min	Max	*M*	*SD*
Within-route (error)	3.86	77.27	23.66	11.87
Between-route (error)	7.91	75.07	45.70	13.65
Model-building (total)	.00	.96	.47	.26

calculated based on the absolute value of the angular difference between the participant's answers and the correct angle, averaged across all trials. Participants' average pointing error scores ranged from a maximum of 63.44° to a minimum of 10.43° across all age groups, where age group was defined by each 1-year age interval ($M = 43.40°$, $SD = 9.64$; see Table 2). Overall, a one-sample *t* test showed that participants were able to point to the locations of the buildings significantly better than chance, $t(104) = 49.52$, $p < .001$, $d = 4.83$. One-sample *t* tests were also conducted for each age group. No participant's pointing error was above the 90° threshold, indicating that all participants, even the youngest ones, were able to comprehend the pointing task and had successfully encoded enough spatial information to point with at least rough success.

Analyses were also done separately on within- and between-route pointing trials. In within-route pointing trials, the target building was on the same route as participants' current position in the VE; in between-route pointing trials, the target building was on a different main route than participants' current position in the VE. In total, there were 24 within-route trials and 32 between-route trials. A paired-sample *t* test showed significantly smaller error on the within-route pointing trials ($M = 30.99$, $SD = 12.43$) than on the between-route pointing trials ($M = 52.72$, $SD = 10.91$), $t(104) = 17.14$, $p < .001$, $d = 1.69$, consistent with adult performance (Weisberg & Newcombe, 2016). Thus, a crucial question is whether children perform above chance on between-route pointing as well as on within-route pointing. Participants' average within-route pointing error scores ranged from a maximum of 63.05° to a minimum of 6.23° ($M = 30.99°$, $SD = 12.43$, range = 56.82; see Table 2); participants' average between-route pointing error scores ranged from a maximum of 72.76° to a minimum of 13.59° ($M = 52.72°$, $SD = 10.91$, range = 59.17; see Table 2). No participant's within- or between-route pointing error was above the 90° threshold, indicating that all participants were able to successfully comprehend and perform on between-route pointing trials as well as on within-route pointing trials.

The within-route pointing trials were further divided into seen-within and unseen-within trials based on the intervisibility of target buildings along a route. A paired-sample *t* test showed significantly smaller error on the seen-within pointing trials (M = 26.68, SD = 15.77) than the unseen-within pointing trials ($M = 37.02$, $SD = 12.79$), $t(104) = 6.81$, $p < .001$, $d = 1.06$. Unseen-within pointing trials were also significantly easier than between-route pointing trials, $t(104) = 11.39$, $p < .001$, $d = 0.64$.

In addition to the pointing task, children completed a model-building task. A bidimensional regression analysis using the eight target buildings (MB–total; Friedman & Kohler, 2003; Tobler, 1994) showed R^2 (total) values ranging from .001 to .92 (M = .33, SD = .23; see Table 2), which is similar to the very wide range seen with adult participants (see Table 2). We also ran a separate bidimensional regression for each of the two main routes consisting of four target buildings each (MB–within). The R^2 (within) values ranged from .03 to .94 (M = .53, SD = .23; see Table 2), thereby exhibiting performance through the entire range of possible scores, similar to adults (see Table 3).

Age-related changes in VE performance

Table 4 presents the correlations among age, time, and performance in the VE as well as with psychometric measures and building recognition. There was a significant correlation between age and within-route ($r = -.59$, $p < .001$) and between-route ($r = -.32$, $p = .001$) pointing errors. Mean performance at each age group for the within- and between-route pointing data is shown in Fig. 5. Age was a significant predictor of within-route pointing performance, $b = -2.88$, $F(1, 103) = 53.34$, $p < .001$, with a significant linear trend ($R^2 = .35$, $p < .001$). There was no significant quadratic trend ($R^2_{change} = .02$, $p_{Fchange} = .09$). Age was a significant predictor of between-route pointing performance, $b = -1.39$, $F(1, 103) = 12.10$, $p = .001$, with a significant linear trend ($R^2 = .11$, $p = .001$). There was no significant quadratic trend ($R^2_{change} = .001$, $p_{Fchange} = .73$).

We evaluated whether there was a difference in slopes (i.e., rate of improvement in pointing performance) for within-route versus between-route pointing by regressing pointing error on participant age and calculating the interaction between age and type of pointing trials. In the regression model, the interaction term tested for the assumption of parallelism of the slopes of within- and between-route pointing trials. Results of the regression model indicated that there was no significant difference in the intercepts ($\beta_{intercept} = 3.51$, $p = .61$) but that the slopes were significantly different for the within- and between-route trials ($\beta_{slope} = 1.50$, $p = .007$). Thus, although within- and between-route errors appear to be similar at around 8 years of age, the significant difference in slopes suggests that the age-related rate of change for within-route error is significantly faster than that for between-route error.

We ran a similar analysis to compare the slopes and intercepts of seen-within and unseen-within pointing trials (see Fig. 6). There was no significant difference in the intercepts of the two regression lines ($\beta_{intercept} = -9.81$, $p = .25$), but there was a significant difference in the slopes ($\beta_{slope} = 1.65$, $p = .02$), suggesting that the age-related rate of change for seen-within error is significantly faster than that for unseen-within error.

For model building, there was a significant correlation between age and MB–total ($r = .52$, $p < .001$) and MB–within ($r = .51$, $p < .001$) in children. As Fig. 7 indicates, accuracy in the model-building task improved with age. Examination of the figures suggests that children's performance reached adult levels at around 12 years of age, consistent with prior findings (Cornell, Heth, & Alberts, 1994; Heth et al., 1997; Jansen-Osmann & Wiedenbauer, 2004).

To statistically test this observation, we created three age categories for children 8–11, 12, and 13–16 years of age and ran analyses of variance (ANOVAs) to test for significant differences between

Table 4
Correlations among age, performances on VE, and psychometric measures in children.

	1	2	3	4	5	6	7	8	9
1. MRT	1								
2. SOT (error)	−.55**	1							
3. Building Recognition	.29**	−.43**	1						
4. Model-building (total)	.22*	−.41**	.30**	1					
5. Model-building (within)	.28**	−.32**	.37**	.41**	1				
6. Within-route (error)	−.47**	.50**	−.39**	−.41**	−.45**	1			
7. Between-route (error)	−.30**	.38**	−.20*	−.44*	−.26**	.39**	1		
8. Age (years)	.41**	−.62**	.33**	.52**	.51**	−.59**	−.32**	1	
9. Completion time	−.08	.26**	−.01	−.07	.04	.15	.10	−.16	1

* $p < .05$.
** $p < .01$.

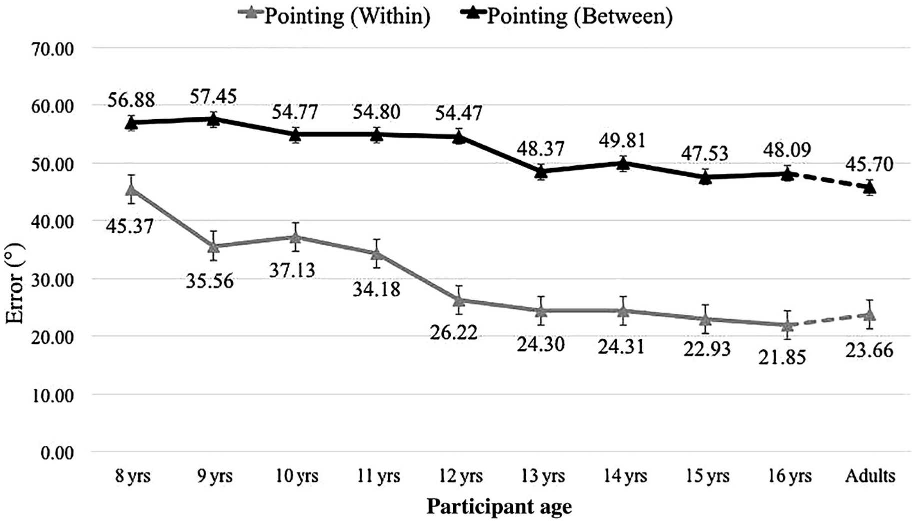

Fig. 5. Developmental trend lines for between-route and within-route pointing trials. Error bars represent ±*SEM*.

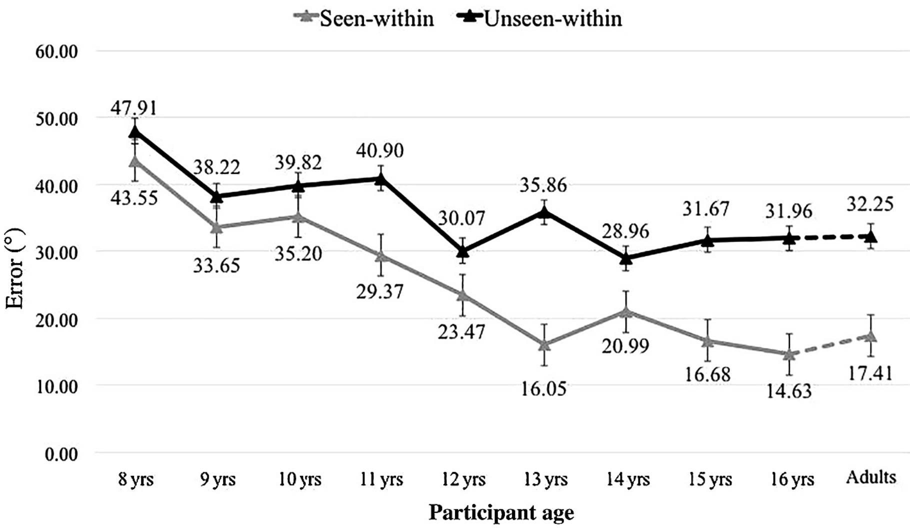

Fig. 6. Developmental trend lines for seen-within and unseen-within pointing trials. Error bars represent ±*SEM*.

younger and older children. To compare younger and older children's performance with that of adults, we also included adult data in the analyses. Fig. 8 shows a scatterplot of all child and adult participants' within- and between-route pointing errors. There were significant differences among the groups on the within-route pointing task, $F(3, 395) = 23.54$, $p < .001$, the between-route pointing task, $F(3, 395) = 10.39$, $p < .001$, and the model-building task, $F(3, 394) = 16.42$, $p < .001$. The younger children (i.e., 8–11 years) did significantly worse than the older children and adults on the within-route and model-building tasks, respectively. On the between-route pointing, 8- to 11-year-olds were not significantly different from 12-year-olds but did significantly worse than the 13- to 16-year-old and adult groups. There were no significant differences between the children aged 12 years and older and the adults. Thus, children aged 12 years and older performed at comparable levels to adults.

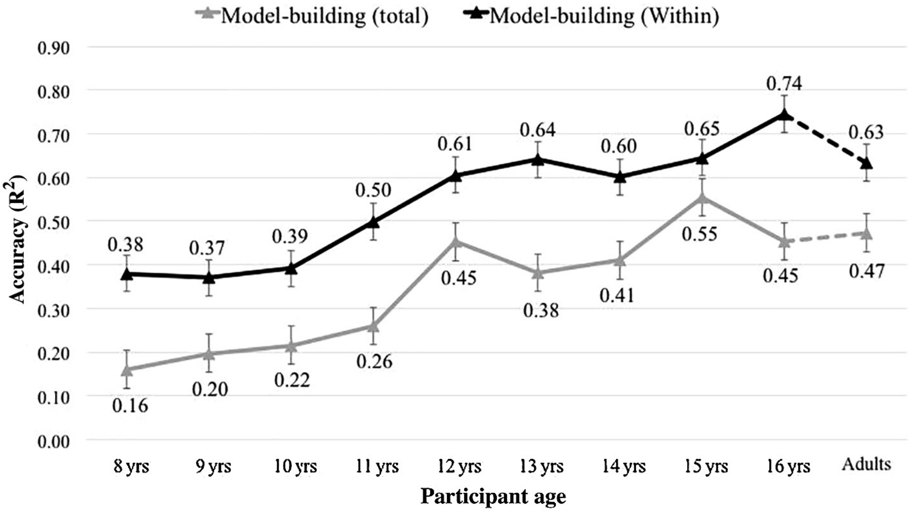

Fig. 7. Developmental trend lines for model-building performance. Error bars represent ±*SEM*.

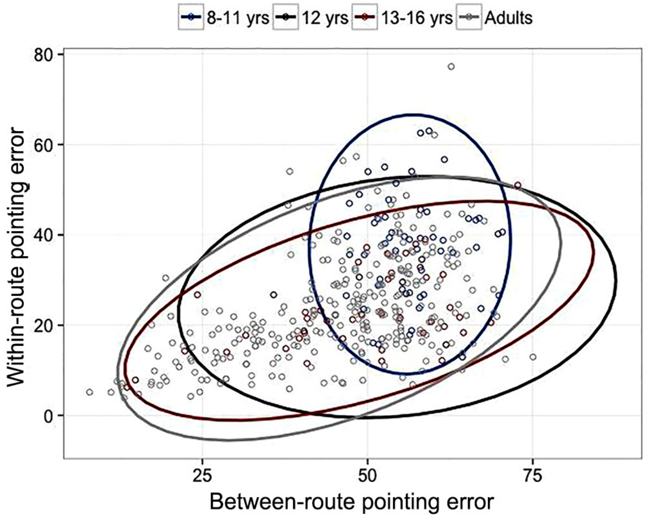

Fig. 8. Scatterplot with ellipses at the 95% CI for participants' performance on the between-route and within-route pointing trials grouped by age. Results suggest that 12 years is a transition age when children's navigation performance in the VE begins to resemble that of adults.

This finding supports the idea that 12 years is a transitional age when children begin to demonstrate adult-like proficiency in large-scale navigation tasks. Given the small number of 12-year-olds in our sample, we might not have had sufficient power to detect significant differences between 12-year-olds and the older children and adults. However, 12-year-olds significantly outperformed the younger age group, and this finding should be interpreted as a continual and gradual change toward adult-like navigation proficiency. The next section, examining individual differences, further supports the distinction between younger children and 12-year-olds in navigation performance.

Development of individual differences

We began with a cluster analysis using within- and between-route pointing errors. Building on the earlier analysis comparing different age groups on individual navigation skills, the cluster analysis allowed us to compare individual differences in patterns of navigation behavior by combining the two pointing tasks. SPSS 20 statistical software's two-step cluster analysis algorithm with log likelihood as the distance measure was run using participants' between- and within-pointing error one at a time. The two-step algorithm assigns cases (i.e., participants) into clusters that maximize the log likelihood of a case belonging to that cluster. The analysis simply clustered participants into two groups—good and bad—based on their performance on each of the two variables. We explored further by using cluster membership for each variable to classify participants as one of four types of navigators: bad between/bad within (imprecise navigators; $n = 55$), bad between/good within (non-integrators; $n = 29$), good between/good within (integrators; $n = 17$), and good between/bad within ($n = 4$). Given the small proportion of participants in the last category and to stay consistent with previous work (Weisberg et al., 2014), and because the last category is logically odd (i.e., it is unlikely that an individual is able to perform the between-route task but not the comparatively easier within-route task), we discuss our findings with regard to the first three categories only. The 4 participants in the Good Between/Bad Within category were discarded from further analyses. There were no participants younger than 12 years of age who fell into the integrator category; only participants who were age 12 or older were able to successfully integrate the two main routes needed to generate a cohesive spatial representation of the VE (see Fig. 9).

Relations of VE performance to age-related changes in mental rotation and perspective taking

There was a significant correlation between age and performance on the MRT ($r = .41$, $p < .001$) and SOT ($r = -.62$, $p < .001$) tasks. There was also a significant correlation between the MRT and performance in the VE as measured by within-route error ($r = -.47$, $p < .001$), between-route error ($r = -.30$, $p = .003$), and model building ($r = .22$, $p = .005$). Similarly, there was a significant correlation between the SOT and within-route error ($r = .50$, $p < .001$), between-route error ($r = .38$, $p < .001$), and model building ($r = -.41$, $p < .001$) (see Table 4). Thus, we may ask to what extent improvement

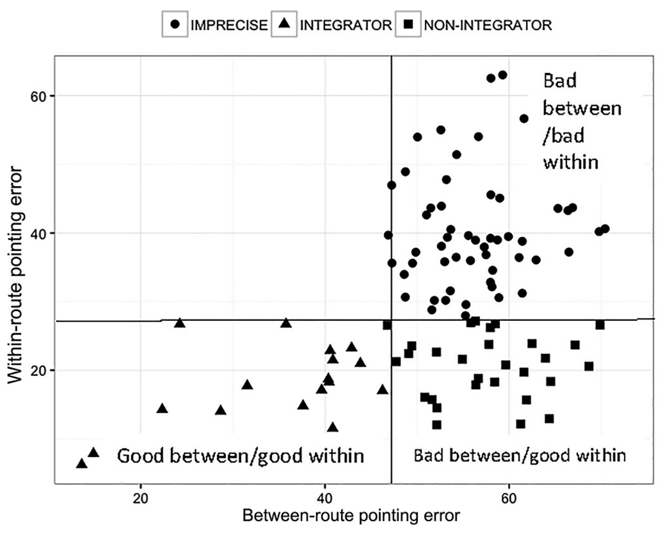

Fig. 9. Scatterplot of performance on the between-route and within-route pointing trials grouped by cluster membership—good between/good within (integrators), good between/bad within (non-integrators), and bad between/bad within (imprecise navigators). Quadrants are based on cluster membership cutoffs.

on the VE task with age can be attributed to improvement on the correlated skills of mental rotation and perspective taking, controlling for sex because of the significant sex differences in mental rotation.

To investigate this question, we ran two-step hierarchical regression models. In Model 1, we entered participant sex and psychometric tasks (MRT and SOT) as predictors of navigation performance. In Model 2, we added participant age to the regression model to calculate the percentage of unique variance explained by age-related effects after controlling for participant sex and psychometric performance. Table 5 presents the two-step hierarchical regression results for the pointing and model-building tasks. Tests to see whether the data met the assumption of collinearity indicated that multicollinearity was not a concern (tolerance >.50 and variance inflation factor [VIF] < 2.0 for all predictors in the model; also, $r < .70$). We repeated these analyses using building recognition as a predictor along with participant sex, psychometric tasks, and age; building recognition was not a significant predictor of navigation performance, and there were no significant differences in the values of R, ΔR^2, F, and ΔF from those reported in Table 5. In addition, the interaction between building recognition and age did not significantly predict VE performance. Hence, for the sake of brevity, we do not present separate regression coefficients with building recognition as a predictor.

Within-route pointing performance

During Stage 1, psychometric performance contributed significantly to the regression model and accounted for 31% of the variation in within-route performance. Both the MRT and SOT were significant predictors of within-route pointing performance. In Model 2, age-added variance accounted for an additional 16% of the variation in within-route performance, and this change in R^2 was significant. This finding suggests that although mental rotation and perspective taking are important mechanisms in navigation proficiency and are widely researched in children, other age-related cognitive and experiential changes significantly contribute to within-route pointing performance.

Between-route pointing performance

During Stage 1, psychometric performance contributed significantly to the regression model and accounted for 17% of the variation in between-route performance. Perspective-taking skills as measured by the SOT were the only significant predictor of between-route pointing performance. In Model 2, age-added unique variance did not significantly contribute to the variation in between-route performance. This finding supports the hypothesis that the within- and between-route pointing trials tap different dimensions of navigation proficiency and rely on different cognitive processes and spatial representations. The reliance on different cognitive processes in the within- and between-route pointing trials may also explain the significant difference in rates of improvement with age (discussed in the previous section).

Table 5
Stepwise regression models with psychometric performance entered at Stage 1.

Measure	Model-building		Within-route		Between-route	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Sex	−.04	−.11	.08	.16	−.02	.01
SOT	−.46**	−.21	.35**	.07	.34**	.24
MRT	−.05	−.13	−.26*	−.17	−.12	−.08
Age	–	.47**	–	−.52**	–	−.19
R^2	.19	.33	.31	.47	.17	.19
F	7.51**	11.30**	14.07**	20.54**	6.62**	5.66**
ΔR^2	–	.13	–	.16	–	.02
ΔF	–	18.45**	–	27.96**	–	2.49

Note. Regression analyses with data expressed as standardized betas are shown. Controlling for psychometric tests (i.e., SOT and MRT), age explains a significant portion of the variance and improves the fit of the model for the model-building task and within-route pointing trials; it does not significantly predict unique variance and does not significantly improve the model fit for between-route pointing trials. Adults are not included.

* $p < .05$.

** $p < .01$.

Model-building performance

During stage 1, psychometric performance contributed significantly to the regression model and accounted for 19% of the variation in model-building performance. The SOT, but not the MRT, was a significant predictor of model-building performance. In Model 2, age-related effects accounted for an additional 13% of the variation in model-building performance, and this change in R^2 was significant.

Reverse order of entry

Table 6 presents results of a second hierarchical regression in which age-related variance is accounted for in Model 1 and psychometric measures are added in Model 2 for within-route, between-route, and model-building tasks. The order in which the predictors were entered into the model did not change our findings, and this supports the conclusions derived from the first hierarchical regression model.

Comparing the MRT and SOT as predictors

To test differences in importance of component skills (i.e., mental rotation and perspective-taking skills) in predicting VE performance, we ran multiple regressions using *z* scores of the MRT and SOT to predict performance in the pointing and model-building tasks (see Table 7).

Consistent with the earlier regressions, and again controlling for sex, psychometric performance significantly predicted within-route performance, $F(2, 96) = 20.76$, $p < .001$, between-route performance, $F(2, 96) = 10.00$, $p < .001$, and model-building performance, $F(2, 95) = 11.29$, $p < .001$. Consistent with the hierarchical regression, the MRT ($p = .006$) and SOT ($p = .001$) significantly predicted within-route pointing error; the SOT ($p = .002$), but not the MRT ($p = .34$), significantly predicted between-route pointing error; and the SOT ($p < .001$), but not the MRT ($p = .74$), significantly predicted model-building performance.

To test whether the standardized beta weights were significantly different from each other, their corresponding 95% confidence intervals (CIs) were estimated using *z* scores. In the event that the

Table 6
Stepwise regression models with participant age entered at Stage 1.

Measure	Model-building		Within-route		Between-route	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Age	.54**	.47**	−.62**	−.52**	−.37**	−.19
Sex	–	−.11	–	.16	–	.01
SOT	–	−.21	–	.07	–	.24
MRT	–	−.13	–	−.17	–	−.08
R^2	.29	.33	.39	.47	.14	.19
F	39.79**	11.30**	60.76**	20.54**	15.56**	5.66**
ΔR^2	–	.03	–	.08	–	.06
ΔF	–	1.56	–	4.77**	–	2.18

Note. Regression analyses with data expressed as standardized betas are shown. Adding psychometric performance (i.e., SOT and MRT), after accounting for age-related effects, does not improve model fit for the model-building task and between-route pointing performance. Adults are not included.

* $p < .05$.

** $p < .01$.

Table 7
Standardized regression beta weights and CIs for MRT and reverse-scored SOT as predictors of VE performance.

	MRT		SOT	
	β	CI	β	CI
Within-route	−.285	[−.492, −.083]	−.338	[−.541, −.135]
Between-route	−.107	[−.330, .115]	−.346	[−.567, −.125]
Model-building	−.036	[−.257, .184]	.457	[.238, .676]

CIs overlapped by less than 50%, the beta weights would be considered statistically significantly different from each other ($p < .05$; Cumming, 2009). In the within- and between-route pointing tasks, the difference between the MRT and SOT standardized beta weights was not considered to be statistically significant ($p > .05$; i.e., CI overlapped by more than 50%). However, in the model-building task, the standardized beta weight for the SOT was significantly larger than that for the MRT ($p < .05$; i.e., CI overlapped by less than 50%). It is important to highlight that the CI for the MRT, in predicting between-route and model-building performance, crossed zero. Thus, we can conclude that perspective-taking skills are more important than mental rotation skills for the between-route pointing and model-building tasks.

Sex differences

We ran independent-samples *t* tests on children's performance on the VE tasks as well as on the psychometric SOT and MRT measures. Consistent with the mental rotation literature (Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Nazareth, Herrera, & Pruden, 2013; Voyer, Voyer, & Bryden, 1995), boys ($M = 35.45$, $SD = 24.75$) outperformed girls ($M = 21.88$, $SD = 16.67$) on the MRT, $t(88.07) = 3.21$, $p = .002$, $d = 0.64$ (degree of freedom adjusted for equality of variance not assumed). On the SOT, however, boys ($M = 58.13$, $SD = 34.79$) and girls ($M = 63.87$, $SD = 29.42$) performed equivalently, $t(103) = -0.91$, $p = .37$, $d = 0.18$. In the within-route pointing task, boys ($M = 28.45$, $SD = 12.40$) had significantly lower error than girls ($M = 33.68$, $SD = 12.01$), $t(103) = -2.19$, $p = .03$, $d = 0.43$. There were no significant sex differences between boys ($M = 52.14$, $SD = 11.92$) and girls ($M = 53.33$, $SD = 9.82$) on the between-route pointing task, $t(103) = -0.56$, $p = .58$, $d = 0.11$, or between boys ($M = .33$, $SD = .24$) and girls ($M = .32$, $SD = .22$) in the model-building task, $t(102) = 0.18$, $p = .86$, $d = 0.04$. There was no significant difference between boys ($M = 5.91$, $SD = 1.98$) and girls ($M = 6.28$, $SD = 1.75$) on the building recognition task, $t(102) = -1.01$, $p = .31$, $d = 0.20$. There were no significant interactions between participant sex and age for the within-route pointing task, $F(8, 87) = 1.28$, $p = .26$, between-route task, $F(8, 87) = 1.62$, $p = .13$, model-building task, $F(8, 86) = 1.45$, $p = .19$, and building recognition task, $F(8, 86) = 0.59$, $p = .78$. We also checked for sex differences in navigator type—integrator, non-integrator, and imprecise navigator—using a chi-square test of independence. The relation between participant sex and type of navigator was not significant, $\chi^2(2, N = 101) = 3.81$, $p = .15$.

Discussion

Using a large-scale VE, we were able to construct a description of development in a standardized testing situation over a wide range of years, gathering samples large enough to allow the analysis of individual differences. The current study adds to the picture of development available from prior research in several ways. First, we found that, like adults, children perform better at the within-route task as compared with the between-route task, which requires the integration of separately learned routes; similarly, children perform better at judging the direction of a visible target building as compared with an invisible target building. Furthermore, we found that age-related improvement on the within-route task comes earlier than improvement on the between-route task and that, for within-route pointing, performance for visible targets improves first and is then followed by targets that are not visible. Although we used a cross-sectional design rather than a longitudinal design, this pattern suggests the possibility that firming up route representations aids the construction of between-route relations. Such a sequence is similar to the proposal from Siegel and White (1975) that route information allows for the further construction of survey representations. However, the data do not suggest a strict sequence because within-route performance continues to improve in parallel with between-route performance.

Second, we documented the onset of individual differences. Before 12 years of age, children were typically either imprecise navigators or non-integrators. That is, they showed substantial error in integrating separately learned routes. After 12 years, better integration was seen in a substantial proportion of the sample, but there was also still a good proportion of the sample who struggled with integration of routes as adolescents. The later appearance of integrators is a different way of saying that reduction in between-route errors comes later than reduction in within-route errors; similarly, it suggests that routes are easier than survey representations and that refining them may facilitate interrelating them. Between-route representations require more use of transitive inference and would benefit from anchoring the representation in a larger reference frame such as surrounding mountains.

Third, we showed that mental rotation and (especially) perspective taking accounted for a good part of age-related developmental improvement, but not all of it. Spatial inference in the VE requires the manipulation of the viewer–environment relation similar to that in MR and PT tasks (see review by Newcombe & Huttenlocher, 2006). However, PT skills were found to be more important than MR skills in predicting performance on between-route pointing and model-building tasks, that is, tasks presumably dependent on the integration of separately learned routes or survey knowledge. This pattern is consistent with a distinction between extrinsic and intrinsic spatial skills (Newcombe & Shipley, 2015) as well as with previous behavioral research contrasting PT and MR (Huttenlocher & Presson, 1973, 1979; Kozhevnikov & Hegarty, 2001; Newcombe & Huttenlocher, 2006) in predicting navigation performance (Kozhevnikov et al., 2006; Liben et al., 2013; Schinazi et al., 2013; Sutton, Keller, & Vollebregt, 2015; Sutton, Keller, & Vollebregt, 2016) and with fMRI data showing that PT engages navigationally relevant neural substrates, whereas MR engages areas associated with the transformation of encodings of the structure of individual objects (Lambrey et al., 2012). Thus, PT appears to be a key component in navigation development. Developmental studies suggest that PT skills are sometimes demonstrated by children as young as 3 years in a particular version of the PT task (Newcombe & Huttenlocher, 1992) but also show considerable improvement through 8 years in the classic version of the task, with 8-year-olds not yet at adult levels of proficiency and showing large variability (Frick, Möhring, & Newcombe, 2014). Thus, PT develops gradually following a developmental trajectory parallel to that of navigation skills seen in the current study. A limitation of the SOT, which was used as a measure of perspective taking in the current study, is that the two-dimensional array of objects can also be viewed as the image of a single object, thereby requiring manipulation of the intrinsic structure of the object. This weakens the extrinsic–intrinsic differentiation between the MRT and PT. Further investigation of PT using two- and three-dimensional paradigms at the behavioral and neural levels will provide important insight into the development of specific mental representations and efforts to improve navigation proficiency during childhood (Lingwood, Blades, Farran, Courbois, & Matthews, 2015).

Fourth, our results indicate additional significant age-related unique variance predicting navigation performance even after accounting for mental rotation and perspective-taking skills. There are several candidates for accounting for the remaining age-related variance that can be grouped as explanations at the cognitive, neural, and experiential levels. On the cognitive level, one possible factor is development of verbal and spatial working memory (Alloway, Pickering, & Gathercole, 2006; Belmonti et al., 2015; Cowan, 2014; Cowan, Saults, & Morey, 2006). In adults, both kinds of working memory correlate with navigationally relevant representations (Weisberg & Newcombe, 2016). Verbal working memory may support learning building names. Spatial working memory may facilitate holding multiple spatial locations in memory, together with turn information, and constructing a representation of the shape of the route and, hence, of the relations of the buildings to each other.

Another cognitive variable may be the ability to integrate various sources of information, including purely allocentric cues and information from visual flow, all of which seem to undergo extended development through middle and late childhood (Dekker et al., 2015; Gilmore, Thomas, & Fesi, 2016; Nardini et al., 2006; Negen, Heywood-Everett, Roome, & Nardini, 2016). For example, the ability to identify and use potential landmarks also appears to develop during the elementary school years (Allen et al., 1979; Siegel & White, 1975), which may be particularly important when integrating different routes. Similarly, another relevant spatial skill—spatial inference—appears as early as 6 years of age but becomes more refined over the school years (Heth, Cornell, & Flood, 2002) and may be reflective of concurrent improvements in spatial encoding and strategy use (Newcombe & Huttenlocher, 2006).

On the neural level, hippocampal maturation may be driving behavioral change and vice versa. The hippocampus—implicated in spatial navigation—shows ongoing volumetric changes throughout childhood and into adolescence (Blankenship, Redcay, Dougherty, & Riggins, 2017; Uematsu et al., 2012; Wierenga, Langen, Oranje, & Durston, 2014). More recently, research examining the functional development of the hippocampus suggests increased hippocampal connectivity during childhood (Blankenship et al., 2017), specifically from 11 to 14 years of age, which may underlie the age-related improvements in hippocampal-dependent navigation skills and the gradual transition toward adult proficiency at around 12 years.

On the experiential level, navigation skills may benefit from the fact that children are allowed increasing navigational range with age, traveling more frequently and farther away from home (Anooshian & Young, 1981). These experiences may have helped older children to develop various strategies, for example, to notice non-target buildings at specific changes in heading direction along the four routes. Of course, on the other hand, adults may allow children larger spatial ranges as they see evidence that children are developing better wayfinding skills, so the relation is likely to be bidirectional.

The developmental trajectories of the cognitive, neural, and experiential factors driving navigational proficiency all tend to increase during middle childhood, making it difficult to unravel causal relations. Indeed, they are likely to be intertwined, facilitating and supporting each other, as with the intuitively appealing feedback relation between home range and spatial skills but also as involving neural maturation and working memory. For instance, it is easy to imagine that increased environmental pressure to perform well might lead to enhancement of skills, supported by enhancement of relevant neural areas and of working memory. Conversely, ongoing neural maturation might lead to the appearance of skills that support increased confidence and independent wayfinding. Longitudinal work that assesses these relevant factors at successive ages may help to illuminate how these processes occur and interact and how individual differences emerge as well as how stable they are.

Finally, on a methodological note, our data show that Silcton appears to be well-suited as a tool to examine navigational skills and spatial representations for children as young as 8 years. Our results are in congruence with prior research conducted in natural environments (Allen et al., 1979; Cornell et al., 1994; Heth et al., 1997; Jansen-Osmann & Wiedenbauer, 2004; Laurance et al., 2003; Liben et al., 2013; Overman et al., 1996), The congruence in age-related change curves found in real-world environments and in VE provides further validation of VE testing and suggests that Silcton could be used in future studies of developmental questions, such as correlational work examining the relation of performance to environmental or personality variables or examining atypical development, an area in which there is ongoing investigation (e.g., Farran, Courbois, Van Herwegen, & Blades, 2012). Silcton can also be used to investigate the possibility of change during adolescence in other kinds of exploration or testing conditions. Indeed, using Silcton, Sutton et al. (2015, 2016) found age-related changes between 12 years (the youngest age group tested) and 19 years when participants did not explore the environment on experimenter-determined routes but rather wandered freely.

Whether children younger than 8 years would not complete the task due to lack of comprehension, lack of interest, lower attention span, inability to use the computer controls to navigate, or possibly lower navigation skills is uncertain. Prior research in natural environments suggests that they have some relevant navigation skills, however, so devising simpler and more motivating VE environments might allow for investigation of younger children (Laurance et al., 2003).

Limitations

One of the disadvantages of VEs is a loss of vestibular information (Hegarty et al., 2006; Richardson, Montello, & Hegarty, 1999; Wiener-Vacher, Hamilton, & Wiener, 2013; Yoder & Taube, 2014). The integration of the vestibular, visual, and somatosensory systems develops gradually during childhood, with adults having an added advantage of "reweighting" sensory inputs based on their reliability (Nardini, Cowie, Bremner, Lewkowicz, & Spence, 2012). Thus, younger children may record a lower navigation proficiency in a VE as compared with a real-world paradigm. Furthermore, time taken to explore a scaled VE is comparatively shorter than time taken to explore an equivalent real-world environment. This could result in an underestimation of the role of working memory in navigation performance, particularly in young developing children. A second limitation of the study was a lack of information about participant video game experience. Boys and girls within each age group may have different levels of video game experience that could influence their spatial performance in a VE (Feng, Spence, & Pratt, 2007; Subrahmanyam & Greenfield, 1994; Terlecki & Newcombe, 2005). It is also important to keep in mind participants' limited exposure to the VE. Prolonged exposure to the VE may have resulted in different navigator profiles for the same age groups. In addition, the cross-sectional research design may have failed to capture children's hypothesized transitions between navigator profiles. Finally, the small-scale MR and PT measures were selected to accommodate the large developmental age range and might not have been age appropriate for younger children. However, the investigator took care to ensure that even the youngest children understood each task well and demonstrated comprehension through sample problems before moving them to the test items. Differences in test format for the MRT (multiple-choice) and PT (open-ended) tasks could potentially influence responses due to differences in available test-taking strategies (e.g., selection by elimination in multiple choice).

Conclusion

This article contributes to our understanding of spatial development in several important ways. First, we delineated the developmental trajectories of component navigation skills in children between 8 and 16 years of age and demonstrated that rate of development in children's route representations is faster than but concurrent with their development in route integration. Second, we showed that children move closer to adult levels of performance at around 12 years of age, when they perform significantly better than younger children. Thus, it is during early adolescence when we see the dawn of individual differences. Third, we found that mental rotation and perspective-taking skills correlate with these lines of spatial development but, importantly, that perspective-taking skills play a more central role. Finally, the novel virtual navigation paradigm used in the current research was found to be a viable tool that allows for the accumulation of comparable large-scale navigation data across labs.

Acknowledgments

Work on this project was funded by Spatial Intelligence and Learning Center Grants SBE-0541957 and SBE-1041707 from the National Science Foundation.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jecp.2018.01.009.

References

Acredolo, L. P., Pick, H. L., & Olsen, M. G. (1975). Environmental differentiation and familiarity as determinants of children's memory for spatial location. *Developmental Psychology, 11*, 495–501.

Allen, G. L., Kirasic, K. C., Siegel, A. W., & Herman, J. F. (1979). Developmental issues in cognitive mapping: The selection and utilization of environmental landmarks. *Child Development, 50*, 1062–1070.

Alloway, T. P., Pickering, S. J., & Gathercole, S. E. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development, 77*, 1698–1716.

Anooshian, L. J., & Young, D. (1981). Developmental changes in cognitive maps of a familiar neighborhood. *Child Development, 52*, 341–348.

Belmonti, V., Cioni, G., & Berthoz, A. (2015). Switching from reaching to navigation: Differential cognitive strategies for spatial memory in children and adults. *Developmental Science, 18*, 569–586.

Blankenship, S. L., Redcay, E., Dougherty, L. R., & Riggins, T. (2017). Development of hippocampal functional connectivity during childhood. *Human Brain Mapping, 38*, 182–201.

Chrastil, E. R., & Warren, W. H. (2014). From cognitive maps to cognitive graphs. *PLoS ONE, 9*(11), e112544.

Cornell, E. H., Heth, C. D., & Alberts, D. M. (1994). Place recognition and way finding by children and adults. *Memory & Cognition, 22*, 633–643.

Cowan, N. (2014). Working memory underpins cognitive development, learning, and education. *Educational Psychology Review, 26*, 197–223.

Cowan, N., Saults, J. S., & Morey, C. C. (2006). Development of working memory for verbal–spatial associations. *Journal of Memory and Language, 55*, 274–289.

Cumming, G. (2009). Inference by eye: Reading the overlap of independent confidence intervals. *Statistics in Medicine, 28*, 205–220.

Dekker, T. M., Ban, H., van der Velde, B., Sereno, M. I., Welchman, A. E., & Nardini, M. (2015). Late development of cue integration is linked to sensory fusion in cortex. *Current Biology, 25*, 2856–2861.

Farran, E. K., Courbois, Y., Van Herwegen, J., & Blades, M. (2012). How useful are landmarks when learning a route in a virtual environment? Evidence from typical development and Williams syndrome. *Journal of Experimental Child Psychology, 111*, 571–586.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*, 850–855.

Fields, A. W., & Shelton, A. L. (2006). Individual skill differences and large-scale environmental learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 506–515.

Frick, A., Möhring, W., & Newcombe, N. S. (2014). Picturing perspectives: Development of perspective-taking abilities in 4- to 8-year-olds. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00386.

Friedman, A., & Kohler, B. (2003). Bidimensional regression: Assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. *Psychological Methods, 8*, 468–491.

Gilmore, R. O., Thomas, A. L., & Fesi, J. (2016). Children's brain responses to optic flow vary by pattern type and motion speed. *PLoS ONE, 11*(6), e0157911.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*, 151–176.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*, 175–191.

Heth, C. D., Cornell, E. H., & Alberts, D. M. (1997). Differential use of landmarks by 8- and 12-year-old children during route reversal navigation. *Journal of Environmental Psychology, 17*, 199–213.

Heth, C. D., Cornell, E. H., & Flood, T. L. (2002). Self-ratings of sense of direction and route reversal performance. *Applied Cognitive Psychology, 16*, 309–324.

Hund, A. M., & Plumert, J. M. (2005). The stability and flexibility of spatial categories. *Cognitive Psychology, 50*, 1–44.

Huttenlocher, J., & Presson, C. C. (1973). Mental rotation and the perspective problem. *Cognitive Psychology, 4*, 277–299.

Huttenlocher, J., & Presson, C. C. (1979). The coding and transformation of spatial information. *Cognitive Psychology, 11*, 375–394.

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology, 52*, 93–129.

Jacobs, L. F., & Schenk, F. (2003). Unpacking the cognitive map: The parallel map theory of hippocampal function. *Psychological Review, 110*, 285–315.

Jansen-Osmann, P., & Wiedenbauer, G. (2004). The representation of landmarks and routes in children and adults: A study in a virtual environment. *Journal of Environmental Psychology, 24*, 347–357.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*, 745–756.

Kozhevnikov, M., Motes, M. A., Rasch, B., & Blajenkova, O. (2006). Perspective-taking vs. mental rotation transformations and how they predict spatial navigation performance. *Applied Cognitive Psychology, 20*, 397–417.

Kuipers, B. (2000). The spatial semantic hierarchy. *Artificial Intelligence, 119*, 191–233.

Lambrey, S., Doeller, C., Berthoz, A., & Burgess, N. (2012). Imagining being somewhere else: Neural basis of changing perspective in space. *Cerebral Cortex, 22*, 166–174.

Laurance, H. E., Learmonth, A. E., Nadel, L., & Jacobs, W. J. (2003). Maturation of spatial navigation strategies: Convergent findings from computerized spatial environments and self-report. *Journal of Cognition and Development, 4*, 211–238.

Liben, L. S., Myers, L. J., Christensen, A. E., & Bower, C. A. (2013). Environmental-scale map use in middle childhood: Links to spatial skills, strategies, and gender. *Child Development, 84*, 2047–2063.

Lingwood, J., Blades, M., Farran, E. K., Courbois, Y., & Matthews, D. (2015). The development of wayfinding abilities in children: Learning routes with and without landmarks. *Journal of Environmental Psychology, 41*, 74–80.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*, 1479–1498.

Maccoby, E. E., & Jacklin, C. N. (1974). *The psychology of sex differences* (Vol. 1) Stanford, CA: Stanford University Press.

Maguire, E. A., Burgess, N., & O'Keefe, J. (1999). Human spatial navigation: Cognitive maps, sexual dimorphism, and neural substrates. *Current Opinion in Neurobiology, 9*, 171–177.

McNamara, T. P. (1986). Mental representations of spatial relations. *Cognitive Psychology, 18*, 87–121.

Nardini, M., Burgess, N., Breckenridge, K., & Atkinson, J. (2006). Differential developmental trajectories for egocentric, environmental, and intrinsic frames of reference in spatial memory. *Cognition, 101*, 153–172.

Nardini, M., Cowie, D., Bremner, A. J., Lewkowicz, D. J., & Spence, C. (2012). The development of multisensory balance, locomotion, orientation, and navigation. In A. J. Bremner, D. J. Lewkowicz, & C. Spence (Eds.), *Multisensory development* (pp. 137–158). Oxford, UK: Oxford University Press.

Nazareth, A., Herrera, A., & Pruden, S. M. (2013). Explaining sex differences in mental rotation: Role of spatial activity experience. *Cognitive Processing, 14*, 201–204.

Negen, J., Heywood-Everett, E., Roome, H. E., & Nardini, M. (2016). Development of allocentric spatial recall from new viewpoints in virtual reality. *Developmental Science, 21*. https://doi.org/10.1111/desc.12496.

Newcombe, N., & Huttenlocher, J. (1992). Children's early ability to solve perspective-taking problems. *Developmental Psychology, 28*, 635–643.

Newcombe, N. S., & Huttenlocher, J. (2006). Development of spatial cognition. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology* (6th ed., pp. 734–776). New York: John Wiley.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In J. S. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 179–192). Dordrecht, The Netherlands: Springer.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. New York: Oxford University Press.

Overman, W. H., Pate, B. J., Moore, K., & Peuster, A. (1996). Ontogeny of place learning in children as measured in the radial arm maze, Morris search task, and open field task. *Behavioral Neuroscience, 110*, 1205–1228.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse mental rotations test—Different versions and factors that affect performance. *Brain and Cognition, 28*, 39–58.
Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition, 27*, 741–750.
Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2013). Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus, 23*, 515–528.
Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. *Advances in Child Development and Behavior, 10*, 9–55.
Subrahmanyam, K., & Greenfield, P. M. (1994). Effect of video game practice on spatial skills in girls and boys. *Journal of Applied Developmental Psychology, 15*, 13–32.
Sutton, J. E., Keller, M., & Vollebregt, M. (2015, October). Mental representations of the environment across adolescence. In Poster presented at the spatial thinking pre-conference of the 9th biennial meeting of the cognitive development society. Columbus, OH.
Sutton, J. E., Keller, M., & Vollebregt, M. (2016, September). Cognitive maps in adolescence. In N. S. Newcombe (Chair), Spatial thinking and STEM education. Symposium conducted at the meeting of the international mind, brain, and education society. Toronto, Canada.
Terlecki, M. S., & Newcombe, N. S. (2005). How important is the digital divide? The relation of computer and videogame usage to gender differences in mental rotation ability. *Sex Roles, 53*, 433–441.
Tobler, W. R. (1994). Bidimensional regression. *Geographical Analysis, 26*, 187–212.
Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55*, 189–208.
Uematsu, A., Matsui, M., Tanaka, C., Takahashi, T., Noguchi, K., Suzuki, M., & Nishijo, H. (2012). Developmental trajectories of amygdala and hippocampus from infancy to early adulthood in healthy individuals. *PLoS ONE, 7*, e46970.
Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599–604.
Vander Heyden, K. M., Huizinga, M., Raijmakers, M. E., & Jolles, J. (2017). Children's representations of another person's spatial perspective: Different strategies for different viewpoints? *Journal of Experimental Child Psychology, 153*, 57–73.
Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*, 250–270.
Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition, 77*, 215–250.
Wang, R. F., & Spelke, E. S. (2002). Human spatial representation: Insights from animals. *Trends in Cognitive Sciences, 6*, 376–382.
Wang, R. F., & Spelke, E. S. (2003). Comparative approaches to human navigation. In K. J. Jeffrey (Ed.), *Neurobiology of spatial behaviour* (pp. 119–143). Oxford, UK: Oxford University Press.
Weisberg, S. M., & Newcombe, N. S. (2016). How do (some) people make a cognitive map? Routes, places, and working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*, 768–785.
Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 669–682.
Wiener-Vacher, S. R., Hamilton, D. A., & Wiener, S. I. (2013). Vestibular activity and cognitive development in children: Perspectives. *Frontiers in Integrative Neuroscience, 7*. https://doi.org/10.3389/fnint.2013.00092.
Wierenga, L. M., Langen, M., Oranje, B., & Durston, S. (2014). Unique developmental trajectories of cortical thickness and surface area. *NeuroImage, 87*, 120–126.
Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences, 14*, 138–146.
Yoder, R. M., & Taube, J. S. (2014). The vestibular contribution to the head direction signal and navigation. *Frontiers in Integrative Neuroscience, 8*. https://doi.org/10.3389/fnint.2014.00032.