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Using virtual environments to investigate wayfinding in 8- to 12-year-olds and adults

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ABSTRACT

Wayfinding is the ability to learn and recall a route through an environment. Theories of wayfinding suggest that for children to learn a route successfully, they must have repeated experience of it, but in this experiment we investigated whether children could learn a route after only a single experience of the route. A total of 80 participants from the United Kingdom in four groups of 20 8-year-olds, 10-year-olds, 12-year-olds, and adults were shown a route through a 12-turn maze in a virtual environment. At each junction, there was a unique object that could be used as a landmark. Participants were "walked" along the route just once (without any verbal prompts) and then were asked to retrace the route from the start without any help. Nearly three quarters of the 12-year-olds, half of the 10-year-olds, and a third of the 8-year-olds retraced the route without any errors the first time they traveled it on their own. This finding suggests that many young children can learn routes, even with as many as 12 turns, very quickly and without the need for repeated experience. The implications for theories of wayfinding that emphasize the need for extensive experience are discussed.

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Introduction

Researchers have long been interested in how navigation develops (Bullens, Iglói, Berthoz, Postma, & Rondi-Reig, 2010; Karimpur & Hamburger, 2016; Purser et al., 2015). Navigational abilities such as route learning are used by most people every day as they travel from one place to another place. Route learning refers to the ability to encode spatial and other information along a route well enough to retrace that route on future occasions (Merrill, Yang, Roskos, & Steele, 2016; Rissotto & Giuliani, 2006).

Adults can often learn routes quickly and effectively after only one or two experiences of the route (Gärling, Böök, Lindberg, & Nilsson, 1981; Montello, 1998), and this is the case even when the routes are 1 or 2 km long and/or include a large number of choice points at junctions (Farran, Blades, Boucher, & Tranter, 2010; Karimpur & Hamburger, 2016). The ease with which adults learn routes suggests that adults have developed appropriate strategies for encoding routes (Montello, 2017). One important strategy is encoding turns in relation to landmarks (e.g., "the left turn after the school"). Adults may be particularly well adapted to focus on landmarks and turns, and there is evidence for distinct brain activation for landmarks and routes (Wegman & Janzen, 2011). Adults show increased activity in the parahippocampal gyrus when attending to landmarks at decision points (Janzen, Wagensveld, & van Turennout, 2007), and the anterior cingulate gyrus and the right caudate nucleus are activated when adults learn the turns along a route (Janzen & Weststeijn, 2007).

In contrast to adults' competence in learning new routes after only brief experience, the evidence about children's ability to learn new routes after only brief experience is less clear. Siegel and White (1975) argued that children's route learning requires repeated experience because children first need to learn individual landmarks along a route; only then do they associate those landmarks with particular decisions (e.g., left or right turns) before they can combine a series of landmarks and turns into a fully learned route. There is evidence that children do, like adults, focus on landmarks (Jansen-Osmann & Wiedenbauer, 2004; Lingwood, Blades, Farran, Courbois, & Matthews, 2015a, 2015b). van Ekert, Wegman, and Janzen (2015) found that similar regions of networks involving the hippocampus and the inferior/middle frontal gyrus were activated during a memory test for previously seen landmarks in both children and adults.

Despite children's focus on landmarks, children do not always learn routes as well as adults (Jansen-Osmann & Wiedenbauer, 2004). This may be because in real life or in complex environments, children may be less good at identifying what is an effective landmark. Younger children may be especially dependent on landmarks that are nearby or next to turns, whereas older children tend to use distant landmarks for wayfinding (Cornell, Hadley, Sterling, Chan, & Boechler, 2001; Purser et al., 2012). Older children are also more likely than younger children to use verbal strategies such as counting the number of steps taken or number of buildings passed when retracing a route (Duroisin & Demeuse, 2015). Having better strategies for learning landmarks or estimating distances along routes means that children's route learning does improve with age and may account for reports of age-related improvements in wayfinding in complex environments (Cornell, Heth, & Alberts, 1994; Cornell, Heth, & Broda, 1989; Heth, Cornell, & Alberts, 1997).

In contrast to the studies showing that children do need repeated experience of a route to learn the route, researchers have found that preschoolers can learn a route without error after only a single experience (Spencer & Darvizeh, 1983), and Cornell and Hay (1984) reported that 6- and 8-year-olds who had seen a route only once were able to retrace the route with an average of less than one error. The latter finding implies that a number of children retraced the route without error at all. Cousins, Siegel, and Maxwell (1983) showed that 7-, 10-, and 13-year-olds could retrace a route after one experience of it. The fact that even very young children can retrace novel routes after one experience goes against the suggestion that children need multiple experiences of a route before they can learn it successfully. Rather, it seems that children can encode a route as effectively as adults and do not need to progress through "stages" of route leaning such as learning landmarks, turns, and then completed routes. The latter would support Montello's (2017) argument that there is no qualitative difference between "landmark" and "route" knowledge. According to Montello, knowledge of landmarks and knowledge of a route develop in unison and are inseparable aspects of route learning rather than sequential stages in learning a route.

However, when children have learned routes after one experience in the studies cited above, the routes were short with seven or fewer turns (Cornell & Hay, 1984; Spencer & Darvizeh, 1983), and even though the children may have been unfamiliar with the particular test route, they were very familiar with the environment that the test route ran through (Cousins et al., 1983; Spencer & Darvizeh, 1983). Therefore, these studies indicated the possibility that young children might be able to retrace routes after one experience. However, given the nature of the routes (which were limited) and the children's advantage in already knowing the general environments of the routes, the results need to be treated cautiously. It may well be the case that young children can learn routes straight away and without multiple experiences, but this needs to be demonstrated in a more demanding context with longer routes in completely unfamiliar environments. Therefore, we investigated whether children could learn a route after just one experience of the route, but we did so in a more rigorous context and with a longer route than in the previous studies. We tested four age groups, including adults, so that we could make developmental comparisons.

To maintain a perfectly consistent and safe environment for all participants, including the youngest ones, we tested participants in a virtual environment (VE). VEs are an alternative to studying wayfinding in the real world because they allow children the opportunity to walk a route several times without the physical demands of a real environment (Broadbent, Farran, & Tolmie, 2014). VEs can be used successfully with very young children (Lingwood et al., 2015a, 2015b), and they also allow children to retrace routes without the need to be accompanied by an adult. VEs can depict visual and spatial information from a three-dimensional first-person perspective (Jansen-Osmann, 2002; Richardson, Montello, & Hegarty, 1999), and successful route learning in VEs transfers to real environments (Ruddle, Payne, & Jones, 1997). Therefore, VEs are a very appropriate way to assess young children's abilities.

Our study compared the ability of 8-, 10-, and 12-year-olds and adults to retrace a route with 12 decision points in a VE. Participants were guided along the correct route just once and then were asked to retrace the route, from the start, on their own. The primary research question was whether the participants could learn the whole route after a single experience of it. A second research question was to consider when children's performance was equivalent to the performance of adults.

Method

Participants

Child participants were 20 8-year-olds (*M* = 7;11 [years;months], *SD* = 3.84 months), 20 10-year-olds (*M* = 10;2, *SD* = 6.04 months), and 20 12-year-olds (*M* = 12;9, *SD* = 4.91 months) who were recruited from primary and secondary schools in the United Kingdom. There were 10 boys and 10 girls in each age group. Adult participants were 20 students at the University of Sheffield (*M* = 23;8, *SD* = 2;2), with an age range of 18;0 to 29;10 (11 women and 9 men). Ethical approval was granted by the University of Sheffield ethics committee.

Apparatus and materials

Virtual environments

Two different VEs were created using Vizard, a software program that uses Python scripting. VEs were presented to participants on a 17-in. Dell laptop that was placed on a desk. Participants sat in a chair at the desk and were approximately 50 cm from the screen. Participants navigated through the maze using the arrow keys on the keyboard.

Practice maze

One maze (Maze A) was used as a practice maze to familiarize participants with moving in a VE. This maze was a similar but different layout compared with the test maze. It did not contain any landmarks.

Test maze

Maze B was used to test the children and adults (see Fig. 1). The test maze was a brick wall maze with 12 junctions. The junctions were "L" shaped. Each junction had two paths: a correct path and an incorrect path. Of 24 landmarks, 12 landmarks were placed on the correct paths (junction landmarks) and 12 landmarks were placed on incorrect paths (off-route landmarks). As in previous studies, all landmarks were placed in the middle of the paths (Jansen-Osmann & Wiedenbauer, 2004; Lingwood et al., 2015a, 2015b). Landmarks were placed in the middle of paths in case participants interpreted a landmark that was placed on the left hand side of the path as one that indicated a left turn or a landmark on the right as one that indicated a right turn.

An incorrect path always ended in a cul-de-sac, but from each junction a cul-de-sac looked like a typical path rather than a dead end. Therefore, participants could not tell that they had made an error until they had actually committed to walking down a chosen path. There were four right, four left, and four straight ahead correct choices that were balanced with the same number and types of incorrect choices. All of the path lengths between junctions were equal. A white duck marked the start of the maze, and a gray duck marked the end of the maze. When retracing a route from the start, participants were told to find the route back to the gray duck. The gray duck provided a salient target that was always the end point of the route and did not move. When participants reached the gray duck, the maze disappeared, indicating the end of a trial.

All of the landmarks were objects with names that would be familiar to children (and adults) such as ball, playground slide, street lamp, and umbrella. These items were chosen because they had distinctive names, were easily recognizable, and could be distinguished from each other without

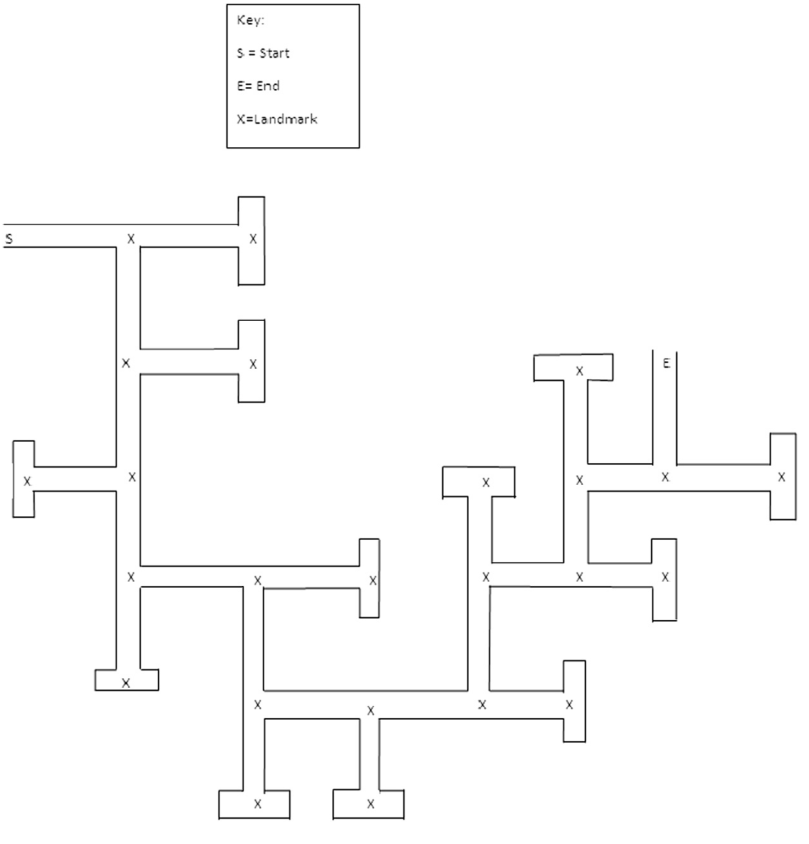

Fig. 1. Plan of Maze B layout with each "X" depicting a different landmark. Participants began at "S" and traveled to "E".

difficulty. All of the landmarks were static because they did not change position during the experiment. When being shown the route, participants passed close to the landmarks at junctions, and the off-route landmarks were not so close but were easily recognizable from the distance that participants saw them.

Procedure

All participants were tested individually. Children completed the experiment in a quiet room in their school. Informed consent was obtained from all of the children's parents, and all children were asked whether they wanted to take part. None of the children refused to take part. Adults completed the experiment in a quiet office in a university department.

Participants sat at the desk facing a computer, and the experimenter sat beside them. The experimenter spent 2 min talking to the children informally to establish rapport. Then the experimenter introduced the task by saying, "This computer has got some mazes on it that we are going to use. First, we're going to practice using the computer to walk around a maze. I'll go first and show you how, and then you can have a turn." The experimenter then demonstrated how to navigate through the practice maze using the arrow keys. The practice maze was the same design as the experimental maze, but it was a different layout. Participants were given time to walk around the maze until they were confident about using the arrow keys, at which point the experimenter ended the practice phase by saying, "Well done, I think you've had enough practice now. Let's have a go at another maze now."

Participants were first given a single experience of the correct route, guided by the experimenter. During this initial experience, the experimenter guided participants by moving forward or turning along the correct route (without looking down any of the incorrect paths). All participants were given preliminary instructions for the test phase: "Now I'm going to show you the way through a new maze. Somewhere in this maze, there is a little gray duck to find. I'll show you the way to the gray duck once, and then you can have a go." The experimenter demonstrated the correct route from the start to the end of the maze. The experimenter used generic terms such as "You go past here, then you turn this way, and then you turn this way." The experimenter never used any directional language such as "turn right." At the end of the demonstration, the experimenter said, "Hooray, we've found the duck!" and the screen went blank.

Participants were then asked to retrace the route they had been shown from the start of the maze to the gray duck that was always in the same place. No participant ever queried this instruction or asked whether the duck had moved. Participants navigated through the maze using the arrow keys on the keyboard. The experimenter sat behind participants and traced the exact route they took on a paper copy of the maze out of participants' sight. The experimenter timed how long it took participants to complete the maze.

If a participant had not reached the end of a maze after 5 min, the experimenter ended that attempt by saying, "Oops, it looks like you've got a bit lost. Not to worry, let's start back from the beginning, shall we?" Only one 8-year-old did not reach the end of the maze on the first attempt. Participants did not receive any help in finding their way after the initial demonstration of the correct route. If participants asked which way to go, the experimenter said, "I want you to show me the way to go. Just try your best." If participants returned to the start position but thought that they had reached the end, they were told, "You're back at the beginning of the maze now. Let's turn around and try again to remember the way I showed you to the little gray duck." Participants then made a second attempt to follow the correct route but did not get to see the original route again.

When participants reached the end of the maze, this was the end of one trial. The experimenter congratulated the participants and asked them to walk the route again from the start. This procedure was repeated until participants had walked the route to a criterion of two consecutive completions without error. The reason for the criterion of two consecutive routes without error is given in the section on scoring (below). At the end of the final trial, all participants were thanked and the children, regardless of their performance, received a sticker.

If participants had not walked the route successfully on two consecutive attempts after 20 min or after eight attempts, the experiment was stopped and the children were given a sticker. This was based on the procedure used by previous researchers (Farran, Courbois, Herwegen, & Blades, 2012;

Lingwood et al., 2015a, 2015b). Only two 8-year-olds did not walk the route successfully on two consecutive occasions.

Results

Retracing the route

The probability of retracing the route correctly, without any mistakes, by guessing at each junction was $p < .00025$. The number of participants who completed the route without errors on their first attempt is shown in Table 1.

The findings from Table 1 show that some children can learn a route consisting of 12 turns immediately, having viewed it only once. Nearly a third of 8-year-olds, half of 10-year-olds and nearly three quarters of 12-year-olds successfully retraced the route on their first attempt without making any errors.

Not all participants retraced the route on their first attempt without error, and so in the following analyses we included only those participants who made one or more errors when retracing the route for the first time. This included 14 8-year-olds, 10 10-year-olds, 6 12-year-olds, and 5 adults.

Reaching the learning criterion

To avoid overestimating participants' performance, we defined a criterion of successful learning as follows: two consecutive completions of the route without error. To achieve this criterion, participants needed to walk the route without walking down any incorrect paths on two consecutive trials. Walking down an incorrect path was classed as an error. Participants needed to fully walk down a path in order for it to be counted as an error. Looking down an incorrect path was not classed as an error. The total number of learning attempts to reach criterion excluded the final two perfect attempts. For example, if participants made an error on Attempt 1, but then walked the route without error on Attempts 2 and 3, they would be scored as having required 1 attempt before reaching criterion. A lower score indicated better performance.

If participants never achieved the criterion, we calculated the number of completed attempts. For example, if participants completed 6 attempts within the 20-min cutoff time but did not complete 2 consecutive attempts without error, they scored 6. Three of the 8-year-olds did not complete two consecutive attempts without error within the 20-min cutoff time.

Table 2 shows that participants who made one or more errors when retracing the route on their first attempt required a similar number of trials to reach learning criterion irrespective of age. This was confirmed by non-parametric statistics, $H(3) = 1.45$, $p = .69$.

Errors during route retracing to criterion

Participants received a mark of 1 for every error they made during an attempt. On each attempt, a proportional error score was calculated as the number of errors divided by the number of decisions made. Fig. 2 shows the route taken by one participant. This participant made 2 errors out of a total of 12 decisions, producing a proportional error score of .17. This scoring captured participants' wayfinding behavior every time they made a decision. This scoring method accounted for occasions when participants doubled back and returned to the same junction more than once within a trial. Some participants who got lost did not reach the later junctions, so any junctions not reached were also scored as errors at decision points. A mean proportional error score was calculated for each participant across each attempt.

Table 1
Number of participants who retraced the route on their first attempt without error for each age group.

8-year-olds	10-year-olds	12-year-olds	Adults
6/20	10/20	14/20	15/20

Table 2
Mean number of attempts to reach criterion for each age group.

8-year-olds	10-year-olds	12-year-olds	Adults
1.86 (1.61)	1.50 (1.27)	1.67 (0.82)	1.40 (0.89)

Note. Standard deviations are in parentheses.

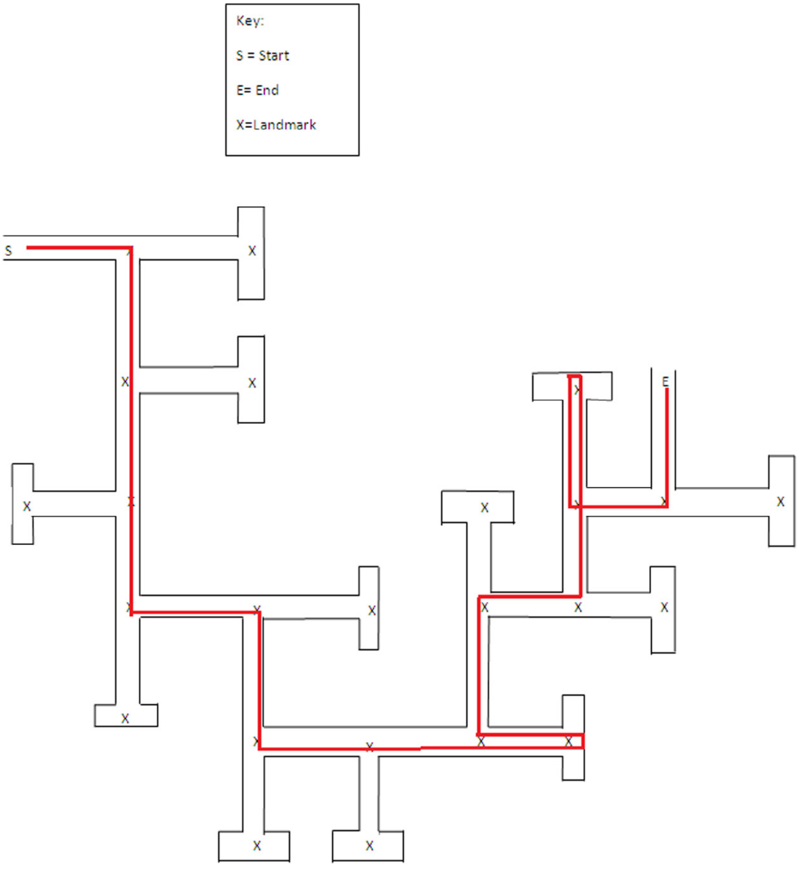

Fig. 2. Wayfinding performance was scored by dividing the number of errors made by the number of potential correct turns. In this example, there were 2 errors divided by 12 potential correct turns, giving a proportional error score of .17.

We note that alternative coding criteria produced the same patterns of performance. For example, we coded just the decisions made the first time participants approached a junction in each attempt. Participants scored 0 if they chose the correct path or 1 if they chose the incorrect path, and any junctions not reached were counted as errors. Therefore, 6 indicated the worse performance and 0 indicated perfect performance. When this scoring was compared with the proportional error score (above), there were no differences in the results. Therefore, in this Results section we report only the proportional error scores.

The mean proportional error scores made by each age group before participants achieved criterion are shown in Table 3. The trend of these results suggests that, irrespective of age, children and adults made a similar number of errors. This was confirmed by non-parametric statistics, $F(3) = 3.49$, $p = .32$.

Table 3
Mean proportion of errors made to achieve criterion for each age group.

8-year-olds	10-year-olds	12-year-olds	Adults
0.10 (0.09)	0.08 (0.04)	0.08 (0.06)	0.04 (0.03)

Note. Standard deviations are in parentheses.

Table 4
Mean (and standard deviation) number of "looking" behaviors made to achieve criterion for each age group.

8-year-olds	10-year-olds	12-year-olds	Adults
1.43 (1.79)	0.70 (0.82)	1.67 (1.75)	1.40 (0.89)

Note. Standard deviations are in parentheses.

We also coded "looking" behaviors when participants retraced the maze. Every time participants used the arrow keys to turn left or right to look down a junction, this was coded as a looking behavior. Table 4 displays the mean number of looking behaviors across age group. This shows that looking behaviors were similar across all age groups, although 10-year-olds produced the fewest number of looks during the learning trials. This was confirmed by non-parametric statistics, $H(3) = 2.38$, $p = .50$.

Discussion

This experiment addressed two research aims. Our primary aim was to find out whether children could successfully retrace a novel route, having experienced that route only once. The findings showed that some of the children, irrespective of age, were able to successfully retrace a 12-turn maze in a VE. Nearly three quarters of the 12-year-olds, half of the 10-year-olds, and a third of the 8-year-olds retraced the route without any errors the first time they traveled it on their own. We emphasize that the route had 12 turns and, therefore, was challenging; nonetheless, some participants in each age group retraced it successfully and without errors the first time they traveled it on their own. We consider the implications of this aspect of children's performance first.

Past evidence for young children's route learning ability is limited, probably because of the practical difficulties of testing children along safe routes in the real environment. Although past researchers have demonstrated that young children can encode short routes of up to seven turns in real environments (Cornell & Hay, 1984), there has been no previous research into young children's ability to learn longer routes. The current study is the first to compare several age groups on a long route (with 12 turns). In the current study, the proportion of 12-year-olds who retraced the route after one trial was similar to the proportion of adults who did so (see Table 1). Although the similarity between the 12-year-olds' performance and the performance of the adults confirms past research (Cornell et al., 1989; Jansen-Osmann & Wiedenbauer, 2004), we note that the past research routes were shorter (e.g., Jansen-Osmann & Wiedenbauer, 2004) or already familiar to children (e.g., Cornell et al., 2001). Therefore, the findings from the current study give a fuller account of children's wayfinding abilities by demonstrating that 12-year-olds have similar route learning capabilities to adults, with many showing the ability to learn a long route immediately. A second novel finding in the current study was that the 10-year-olds also performed well, with half of the children in that age group retracing the route on their first attempt.

The youngest children, the 8-year-olds, were noticeably poorer than the older age groups, and we note that this was the only group in which not all of the children reached criterion (three children did not). Nonetheless, most children in this age group did achieve criterion, and one third of the 8-year-olds retraced the route after seeing it just once. This indicated the potential of even younger children to remember the route successfully. Previous researchers have found that young children can recall routes (Cornell & Hay, 1984; Spencer & Darvizeh, 1983) but tested children only over comparatively short routes or through areas that might have been familiar to the children. Finding that some children as young as 8 years can retrace a completely novel 12-turn route after experiencing it just once was unexpected.

Although most participants were able to successfully retrace the route, there were different trends in performance across different age groups. Although not significant at the statistical level, based on the mean scores (see Tables 2 and 3), younger children (8-year-olds) made more errors and required more trials to reach criterion than older children (10- and 12-year-olds), a finding consistent with previous research (Cornell et al., 1989; Farran et al., 2012; Heth et al., 1997; Jansen-Osmann & Wiedenbauer, 2004). These findings were also consistent with a six-turn VE used by Lingwood et al. (2015a) in which older children (10-year-olds) made fewer errors and required fewer trials to reach criterion than younger children (6-year-olds). Younger children may have less mature cognitive abilities required for learning routes. Evidence from previous studies suggests that children with better attention and long-term memory tend to perform better when learning novel routes (Purser et al., 2012, 2015). In addition, younger children may have less experience in retracing novel routes than older children (Kitchin & Blades, 2002; Lingwood et al., 2015a).

In the current study, participants needed to avoid making repeated errors on more than one trial (perseverative errors) if they were to succeed in reaching the learning criterion. This may have been more difficult for younger children (Farran et al., 2012; Purser et al., 2012). There were also other demands extraneous to the route following task that children needed to avoid to ensure they sustained attention (such as inhibiting any desire to look away from the screen, engage in conversation with the experimenter, or freely explore the VE). Participants also needed to inhibit the desire to navigate toward irrelevant off-route landmarks. Children who can inhibit inappropriate responses on other tasks (e.g., a Go/No-Go task) do perform better on route learning tasks (Purser et al., 2012). Furthermore, focusing on non-useful landmarks (i.e., the off-route landmarks in this study) during route learning is associated with poorer navigational strategies (Broadbent et al., 2014; Farran et al., 2010). This suggests that a variety of spatial working memory skills may be important for wayfinding, particularly for younger children.

The second aim was to investigate at what age children demonstrated route learning abilities similar to adults. Based on the mean scores (see Table 2), it was found that from 8 years of age onward children made a similar number of errors and required a similar number of additional learning trials as adults. Our results extend findings from previous studies (Cornell et al., 1989, 1994; Jansen-Osmann & Wiedenbauer, 2004). Cornell and colleagues found that children did not become adult-like in their route learning abilities until 12 years of age rather than 8 years of age (as our data suggest). However, in Cornell and colleagues' studies children were either 6 or 12 years of age, and so it was unclear whether children under age 12 but over age 6 would perform at the same level as adults. Jansen-Osmann and Wiedenbauer (2004) found that children as young as 11 years performed similarly to adults when asked to find their way out of a VE maze. However, the children and adults who participated in Jansen-Osmann and Wiedenbauer's study explored a maze rather than learned a specific route. Our results extend previous research findings and suggest that children are able to learn and remember a route similarly to adults from 8 years of age onward.

It was not possible to determine precisely how children and adults retraced the route and made few (if any) mistakes. For example, it is unclear whether participants relied on a particular strategy when retracing the route such as recalling the left–right sequence or focusing on landmarks at particular junctions. Nonetheless, we argue that being able to accurately encode the correct left–right sequence of 12 turns independently of the route would have been too cognitively taxing for participants, especially the younger children (Hayashi, Fujii, & Inui, 1990). Therefore, we suggest that participants' success depended on recognizing landmarks as they were traveling along the route and that such recognition then led to the recall of the appropriate action at a choice point. Adults may be adapted to recognize landmarks given that neuroimaging studies have shown increased activity in the parahippocampal place area associated with the recognition of landmarks (Epstein & Vass, 2014; Marchette, Vass, Ryan, & Epstein, 2015).

We note that some off-route landmarks could also be viewed from the correct route direction heading. Therefore, there was a possibility that participants used off-route landmarks to retrace the route. However, evidence from neuroimaging studies suggests that we respond to on- and off-route landmarks differently. For example, immediately after learning a route, the parahippocampal gyrus shows increased activity only for on-route, as opposed to off-route, landmarks (Janzen & van Turennout, 2004; Janzen et al., 2007). This suggests that the ability to identify previously seen on-route landmarks may be particularly crucial for route learning.

Cornell et al. (1994) suggested that individuals used ''place recognition'' to help find their way. For instance, when approaching a junction, individuals could look down the various paths before deciding which path was most familiar to them. In this sense, the landmark would be a ''beacon'' (Waller & Lippa, 2007), the assumption being that only one of the paths was likely to contain landmarks or features previously seen when walking the route. However, in the current study, we found that children and adults did not frequently look down the alternative path when deciding which way to go. This may have been because they could always see a landmark ahead of them. By always being able to view this landmark, this may have helped them to differentiate between the correct and incorrect paths, and so in most cases participants would not need to look down the alternative junction. We acknowledge that in our experiments the junctions were made up of two path intersections and that each junction was visually uncluttered. These types of junctions are easy to describe (Asher, Tolhurst, Troscianko, & Gilchrist, 2013; Clarke, Elsner, & Rohde, 2013; Klippel, Tenbrink, & Montello, 2013; Montello, 2005) and, therefore, may be easier to recognize or recall in comparison with the visually complex junctions that are more likely to be found in real environments.

VEs have been shown to tap into similar cognitive mechanisms as the same tasks in the real world (Richardson et al., 1999), and route learning in a VE can be transferred to real-world environments (Montello, Waller, Hegarty, & Richardson, 2004; Ruddle et al., 1997). Therefore, we predict that the current findings will generalize to an environment in the ''real'' world, and future research could investigate this. However, we note that proprioceptive and vestibular information is absent in desktop VEs (Taube, Valerio, & Yoder, 2013). Such idiothetic features require consideration by employing environments in which participants are more active (Chrastil & Warren, 2012). Given the very good performance of some of the youngest children (the 8-year-olds), any further examination of this age group, or indeed younger age groups in real environments, should consider testing young children on routes that are much longer than have been used in previous real-world environments.

Previous studies have shown that adults are generally good at learning a route (Karimpur & Hamburger, 2016), and this was confirmed by the performance of the adult group in the current study. Three quarters of the adult participants learned the 12-turn route after a single experience of the route. Adults' success in the current experiment confirms that most adults can retrace a long route without error after just a single exposure to that route. Because such a large proportion of adults succeeded straightaway, it is unlikely that 12 turns is the maximum length of a route that adults can encode in one experience; therefore, future researchers should consider testing adults over much longer routes.

The fact that many of the participants learned the 12-turn route after just one experience of it does not support theories of wayfinding that emphasize the need for route learners to construct a representation of a route only slowly by first learning some or all of the landmarks along a route and then combining these with actions at landmarks to form a route (Siegel & White, 1975). Rather, the rapid learning demonstrated by many participants suggests that some children and most adults can integrate landmark and turn information into a complete route on the basis of a single experience, and this would accord with Montello (2017) that there are not separate stages of landmark and route learning. The current study considered only one route and, therefore, did not examine how multiple routes might be integrated into larger representations of the environment, and so this study does not rule out the possibility of other stages in learning more complex environments.

To summarize, the current study showed that most 8-year-olds (85%) and every one of the 10- and 12-year-olds and adults learned a route consisting of 12 turns. Many participants did so without making any mistakes. However, 8-year-olds made more errors and required more attempts to reach criterion than the other groups, whereas these differences among the 10-year-olds, 12-year-olds, and adults were less pronounced. These findings suggest that children from 8 years of age can learn routes, even with as many as 12 turns, very quickly. The perfectly accurate performance of even some of the youngest children, the 8-year-olds, when retracing the route after just one experience demonstrated the potential of very young children to learn a long route straightaway. Such successful performance has not been noted before; therefore, more research with younger children over longer routes would be a useful focus for future research.

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