Short-term memory, executive control and children's route learning

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Abstract

The aim of this study was to investigate route learning ability in 67 children aged 5 to 11 years and relate route learning performance to the components of Baddeley's (1986) model of working memory. Children carried out tasks that included measures of verbal and visuospatial short-term memory and executive control, and also measures of verbal and visuospatial long-term memory; the route-learning task was conducted using a maze in a virtual environment. In contrast to previous research, correlations were found between both visuospatial and verbal memory tasks – the Corsi task, short-term pattern memory, digit span, and visuospatial long-term memory – and route learning performance. However, further analyses indicated that these relationships were mediated by executive control demands that were common to the tasks, with long-term memory explaining additional unique variance in route learning.

Keywords: Route learning; short-term memory; executive function; task demands

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Route learning – acquiring knowledge about routes through space – has traditionally been understood as developing via three distinct stages, each a precursor of the next: landmark knowledge, route knowledge, and knowledge of distance and direction between landmarks (Siegel &White, 1975). However, more recent investigations have attempted to link route learning to working memory (Garden, Cornoldi, & Logie, 2002; Meilinger, Knauff and Bülthoff , 2008). Working memory – the active maintenance of psychologically-relevant information over the short-term – has been found to relate to diverse aspects of cognition, such as arithmetic (Adams & Hitch, 1998), reading and vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1993), problem solving (Hambrick & Engle, 2003), and educational attainment (Gathercole, Pickering, Knight, & Stegmann, 2004). For the current study, we attempted to assess the components of the much-studied Baddeley (1986) model of working memory and relate them to the development of route learning ability in children. Given the fact that these components are well-characterized, our aim was to use these theoretical constructs to better understand what cognitive functions are involved in route learning. Although there are other models of working memory (e.g., see Shah & Miyake, 1999), Baddeley's model was singled-out as being highly influential in memory research.

The Baddeley (1986) model consists of three main components: the phonological loop, the visuospatial sketchpad, and the central executive. According to this framework, the phonological loop consists of a short-term store, of limited capacity, that stores temporally labile information in a phonological code. The visuospatial sketchpad is a limited-capacity store of visuospatial material, concerned with memoranda such as color, location and shape. More recently, Della Sala and colleagues (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999) have provided evidence for a fractionation of visuospatial short-term memory, into visual and spatial/sequential subcomponents, supported by a selective interference experiment and neuropsychological evidence. The third component, the central executive, acts to direct attention and to coordinate the activity of the other components, is broadly concerned with executive control and is associated with frontal cortex (e.g., Baddeley, Della Sala, Gray, Papagno, & Spinnler, 1997). The Baddeley model has been expanded to include the episodic buffer (Baddeley, 2000; Baddeley, Allen, & Hitch, 2010), a temporary store of multidimensional chunks (cf. Miller, 1956) that are available to conscious experience, originally thought to interact only with the central executive and long-term memory and to actively bind features (Baddeley, 2000), but more recently construed as a passive store of bound features that interacts with *all* the working memory subsystems and also perception (Baddeley et al., 2010). The episodic buffer has been described as having a 'lack of specificity' by its authors (Baddeley et al., 2010); on that basis, though it clearly has explanatory power, it was not considered further in the current study, given our aim to utilize well-understood theoretical constructs.

Working memory and executive control are separable abilities in both children (Gathercole, Pickering, Ambridge, & Wearing, 2004; Luciana & Nelson, 1998; McAuley & White, 2011) and adults (e.g., Borella, Carretti, & De Beni, 2008; Unsworth & Engle, 2007); they therefore may be considered separate potential sources of variation in route learning. However, there is an executive component to the working memory model (i.e., it is part of working memory's definition); for theoretical clarity, therefore, we will not contrast executive control with working memory but with its 'slave systems': phonological and visuospatial short-term memory. This is to minimize overlap of the theoretical constructs measured, which is important when interpreting correlations between measures.

Executive control, then, may be important for successful route learning. Although there have been no published investigations that directly address the relationship between route learning and executive control, Münzer and colleagues (Münzer, Zimmer, Schwalm, Baus, & Aslan, 2006) have argued that the poor spatial knowledge of users of navigation assistance devices (‘Sat-navs’) may be due to a lack of ‘active encoding’. This notion is similar to the concept of ‘depth of processing’ (e.g., Craik & Tulving, 1975) whereby only information that is utilized, transformed or actively memorized is subsequently available for recall. Another suggestion that executive control might be important comes from a study of route learning in Williams syndrome (Farran, Courbois, Van Herwegen & Blades, in press). Farran and colleagues noted that the perseverative errors seen in their sample could be explained with reference to executive dysfunction.

Relevant to the phonological loop and visuospatial sketchpad, Meilinger et al. (2008) investigated the influence of verbal and visuospatial working memory on route learning. Their study involved a dual-task paradigm in a virtual environment (VE), with 24 adults. The simultaneous tasks were performed during the learning phase of the experiment, but not at test. The main task was to learn a route through a virtual mediaeval town centre, presented on a 13 x 3 metre screen. The learning phase was passive, while the test phase required participants to navigate the route with a joystick. There were three types of dual-task: a verbal lexical decision task that required judging whether two-syllable words existed in German; a visual task in which participants were told a certain time and had to say whether the hands of an analogue clock would be in the same or different vertical half of the clockface; and a ‘spatial’ task in which participants had to judge the direction of a sound presented by headphones. The results showed that the verbal and spatial tasks interfered with route learning, whereas the visual task did not. Verbal task performance was impaired on the approach to choice points on the route, leading to the suggestion that participants used a verbal strategy for encoding these. Meilinger et al. interpreted their results as supporting a ‘Dual Coding Theory of Wayfinding’, with both verbal and spatial encoding important for successful route learning. In line with this view, Garden et al. (2002) also found that both verbal and spatial dual-tasks disrupted route learning performance. These studies indicate that verbal and visuospatial *processing* are involved in route learning, but do not directly speak to the issue of whether verbal or visuospatial short-term *storage* is involved. Interpreted within the Baddeley model, these studies could indicate that both storage systems are involved, or only the central executive, or all three components.

Having considered adult studies, we now turn to those involving children. In the only studies known to the authors that directly attempted to relate visuospatial short-term memory to route learning in children, Farran, Blades, Boucher and Tranter (2010) found that large-scale route knowledge correlated with performance on a short-term memory task in children and adults with moderate learning difficulties. This task was based on Gathercole and Pickering (2000), in which participants had to reproduce a route drawn through a maze depicted on a piece of paper. No such relationship was found for a typically-developing group of children, but this was because this group was at ceiling on the memory task. Fenner, Heathcote and Jerrams-Smith (2000) investigated the relationship between verbal and visuospatial abilities, including short-term memory measures, and route learning performance, in a real world environment. Verbal abilities were not associated with route learning performance. However, children who scored higher on the visuospatial measures did perform better at route learning, but Fenner et al. aggregated the visuospatial measures and did not present results from any of the component tasks. Therefore, it is not possible to conclude whether visuospatial short-term memory, rather than general visuospatial skills, was specifically associated with route learning.

In sum, studies with adults suggest that both verbal and visuospatial aspects of working memory are important for route learning. The studies involving children suggest that visuospatial short-term memory might be important and do not provide evidence against a relationship between verbal short-term memory and route learning. The current study was concerned with children aged from 5 to 11 years because children undergo large developmental improvements in tests of executive control and working memory between these ages (Alloway, Gathercole, & Pickering, 2006; Gathercole et al., 2004), with the overarching aim of relating the development of route learning to the development of executive control and short-term memory. If short-term memory or executive control is important for route learning, there may be accompanying changes in route learning across this age range. Gathercole (1999) has shown in a review that children's short-term memory improves rapidly across this age range, slowing after children are 8 years old, both for verbal and visuospatial measures. In a review of executive gains after the age of 5 years, Best, Miller, & Jones (2009) showed marked improvements across a variety of tasks over the same developmental period (although even more rapid gains in executive function are seen in pre-school children, e.g., Garon, Bryson, & Smith, 2008). Alloway and colleagues (Alloway et al., 2006) have found that the components of working memory appear to be in place by 4 years old, and that this theoretical structure (of verbal and visuospatial storage with shared processing) is stable from 4 to 11 years old. Route learning ability is at an adult level by 12 years of age (Cornell, Heth, & Rowat, 1992), so that the age range 5-11 would be expected to be associated with development in this area of cognition.

The selection of appropriate cognitive measures for the current study was based on the Baddeley model components detailed above. Based on Della Sala and colleagues' proposed fractionation of the visuospatial sketchpad (Della Sala et al., 1999), we selected the Visual Patterns Test, a test of visual short-term memory in which the participant must reproduce a matrix of filled and unfilled squares (adapted from Wilson, Scott and Power, 1987), and the Corsi task, which is a spatial/sequential task. We also included digit span for phonological short-term memory and the Go/No Go task, a measure of executive control (e.g., Falkenstein, Hoormann, & Hohnsbein, 1999; similar to Donders's Type C Reaction time task; Donders, 1868/1969).

Motivated by known links between working memory and long-term memory (e.g., Gathercole & Baddeley, 1993) and the fact that remembered routes must be stored in long-term memory, two long-term memory measures were also included: it is possible that short-term memory measures will correlate with route learning simply because they are involved in conveying information to long-term memory. The People and Shapes tests from the Doors and People battery (Baddeley, Emslie, & Nimmo-Smith, 1994), which are measures of verbal and visuospatial long-term memory respectively. The Shapes test is similar to Fenner and colleagues' (Fenner et al., 2000) drawing from immediate memory task, but allows for learning across several trials (as does the People test). To our knowledge, this is the largest battery of memory and executive control measures to be investigated with regard to route learning, in children or in adults (Fenner et al., 2000, used a larger battery, but this was not restricted to measures of memory and executive control).

Route learning took place within a brick wall VE maze. Landmarks were placed within the maze, both near to junctions and away from junctions, but also outside the maze walls as 'distant' landmarks (e.g., mountain, church spire). In addition, there was a 'non-unique' maze object: that is, many instances of the same object type were distributed around the maze. These different landmark/object types were chosen to provide a diverse source of information that could be used by children in encoding and retrieving visual cues (e.g., Jansen-Osmann & Weidenbauer, 2004). All the landmarks were potentially useful for route learning, apart from the non-unique, which were included because the 'real' visual world is full of such objects (post boxes, lamp posts, traffic lights).

Route knowledge has been defined as knowledge of the serial order of landmarks (e.g., Buchner & Jansen-Osmann, 2008), and so route learning performance may be related to serial recall in the digit-span or Corsi tasks. VEs allow routes to be retraced on a number of trials in a short time, and enable the experimenter to control conditions across participants. Navigating VEs involves the same cognitive mechanisms as real-world environments (Richardson, Montello & Hegarty, 1999) and learning in VEs transfers to performance in the real world (Montello, Waller, Hegarty, & Richardson, 2004; Ruddle, Payne, & Jones, 1997; Waller, Montello, Richardson & Hegarty, 2002; Wilson, 1997).

Executive control is necessary for successful route learning (and also for success in short- and long-term memory tasks). To successfully recall memoranda, one must attend to the presentation sufficiently to encode them into memory and subsequently recognize them (see Cornell, Heth, & Alberts, 1994). Similarly, learning a route requires attending to the route. Therefore, we hypothesize that performance on the Go-No Go task will predict route learning.

As discussed above, it is unclear from previous research whether one should expect verbal or visual short-term memory tasks to predict route learning in children. Success on short-term memory tasks requires good verbal and visuospatial sequential processing, both of which might be expected to be involved in route learning. More generally, if verbal learning is important, verbal short-term memory would be expected to correlate with route learning performance. Similarly, visuospatial short-term memory would be expected to correlate with route learning performance if visuospatial learning is important. Given the fact that route learning requires more than a few seconds, we would expect the long term memory measures to predict route learning performance (see Purser & Jarrold, 2010, for a review of the distinction between short-term memory and long-term memory).

Method

Participants

Sixty-seven typically developing (TD) individuals took part in the study. The chronological age of participants ranged from 5;4 to 11;3 years, with at least 10 children in each school year group from UK Year 1 to Year 6.

Maze task

The main experimental task was a maze in a virtual environment, created using Virtools 5.0, a 3D software toolkit. The maze appeared as a network of roads at right angles from each other, lined with brick walls (see Figure 1), with six junctions. Each path section was the same length and each junction led to one correct and one incorrect path section (see Figure 2). Across the six junctions, there were two left, two right, and 2 straight-ahead correct path choices, which were paired with the same balance of incorrect choices. Incorrect path choices ended in a cul-de-sac, or ‘dead-end’, which appeared identical to a T-junction when viewed from the junction that preceded it.

Thirty-two landmarks were placed in or around the maze: eight that were near to junctions (‘junction landmarks’), eight that were not near to junctions (‘path landmarks’), there was one non-unique path landmark on each of the 13 path segments (‘non-unique landmark’), and there were three distant landmarks were outside the maze (see Figure 2 for details of the landmark identities and placements). Each of the three distant landmarks was visible from most locations within the maze, though it was not possible for all three to always be visible, given the height of walls necessary for the maze to be effective (so that the maze solution was not visible to participants). Landmarks within the maze were equally distributed to each side (i.e., left and right) of the path. At the end of the maze was a rotating metallic ball, which elicited the words ‘Well done!” on the computer screen, along with fanfare. Landmark objects were drawn from a range of categories (e.g., animals, tools, furniture) and were chosen for high verbal frequency (Morrison, Chappell, & Ellis, 1997) and also for being easy to recognize by sight.

Procedure. Each participant was first familiarized with the maze environment and control method by completing a short familiarisation maze with no landmarks. In this maze, participants followed a single path which included making two right-angle turns; there were no junctions or direction decisions to be made. Movement through the maze was controlled by a combination of computer keyboard and mouse: the space bar caused forwards movement, while orientation was achieved by the mouse. Participants were able to orient upwards and downwards in addition to orienting left and right.

After the familiarisation maze, the experimenter took over the controls and showed the participant the correct route through the experimental maze, suggesting that the participant pay close attention to the route and also to the various objects that appeared in the ‘maze game’. The participant then attempted to navigate through the maze, with a maximum of 10 trials to complete the maze from start to finish without error. Because the incorrect path sections ended in cul-de-sacs, when the participant made an error, this was self-corrected. Each trial terminated once the participant had completed the route. The dependent variables were the number of trials taken to achieve error-free criterion and the total number of errors made across all trials. An error was a deliberate incursion down an incorrect path. Participants were self-paced and allowed as much time as necessary to complete each trial of the maze.

As a final part of the maze game, participants were asked to complete the two-turn familiarisation maze once more, as quickly as possible. The time taken for this ‘computer control’ served as a measure of keyboard/mouse proficiency.

After the maze game was completed and the participant congratulated, a control naming task was administered. Participants were shown images of each of the 20 landmarks on a computer screen in a pseudorandom order and asked to name each one. This was to ensure that the landmarks selected for the experiment were readily distinguishable for the participants involved. All participants were able to provide a unique name for all 20 of the landmarks, apart from four participants who were able to name 19 (the incorrect landmark differed across participants; there was not one particular landmark that all 4 children failed to name).

Test battery

Participants were assessed on the British Picture Vocabulary Scale III (BPVS; Dunn, Dunn, Styles, & Sewell, 2009), a measure of receptive vocabulary, and also on Raven’s Coloured Progressive Matrices (RCPM; Raven, Raven, & Court, 1998), a test of non-verbal intelligence. These tasks are often used as indices of general cognitive development in verbal and nonverbal domains, so would be expected to correlate with route learning to the extent that it relies on verbal and nonverbal cognition, respectively.

Go/No Go (GNG) task. In GNG, a pseudo-random series of red, green, blue and yellow solid circles was presented on a computer. Participants were instructed to press the space bar as rapidly as possible when they saw each circle, unless it was red, in which case they should refrain from pressing the space bar. If the space bar was pressed on red, a buzzing ‘error’ noise was heard and the circle disappeared. Each circle disappeared after two seconds if the space bar was not pressed. If participants pressed the space bar on two subsequent red trials, they were reminded of the task rules. There were 8 practise trials, followed by 128 experimental trials, with a break after 64. The dependent measures were the average reaction time for correct hits and the number of errors (pressing the space bar for a red circle).

Digit span. Digit span is a verbal short-term memory measure in which participants repeat lists of spoken digits. Digits were presented via computer speakers at a rate of one per second. There were three trials at each list length, beginning with a list length of three. To proceed to the next list length, a participant was required to get at least two out of the three lists correct. However, to optimize the sensitivity of the test, the dependent measure was the number of *items* (i.e., digits) correct across all trials.

Corsi span. Corsi span is a visuospatial analogue of the digit span task in which the experimenter taps out a sequence of spatial locations, then the participant attempts to reproduce that sequence (Corsi, 1972). There were three trials at each list length, starting with a list length of three, with a criterion of two trials correct at each list length to progress to the next. The dependent measure was the number of *items* (i.e., locations) correct across all trials.

Pattern span. Pattern span is a test of visual short-term memory in which participants must recall visual matrix patterns in which half of the cells are filled, adapted from Wilson, Scott and Power (1987). Fish, rather than black squares, were used to fill the target cells to make the task more engaging for young children: matrices made up of 3 cm X 3 cm cells were displayed on a computer screen for 2 seconds each and participants were asked to mark with a pencil dash “where the fish were” on an answer sheet of blank matrices. Similar to the digit span task, there were three trials at each matrix size, beginning with a size of 2 X 3, and the criterion for progressing to the next size (adding two cells) was getting at least two out the three trials correct. The dependent measure was the number of fish correctly placed across all trials. Any superfluous dash marked on the answer sheet (e.g., a fourth dash when there were only three fish presented on that trial) resulted in a mark being deducted from the total score.

People Test. The People Test (Baddeley, Emslie, & Nimmo-Smith, 1994) is a measure of long-term verbal memory functioning. Participants were shown pictures of four people in succession, each paired with a forename and surname (Jim Green, Cuthbert Cattermole, Tom Webster, and Philip Armstrong) which was printed under the picture. The experimenter told the participant the occupation of each person (e.g., “This is the doctor. His name is Jim Green”). After being shown all four people and told their professions, participants were immediately cued with each profession and asked to produce the relevant name (“Can you tell me the name of the doctor?”). This procedure was repeated two more times, or until perfect performance was attained, in which case a maximum score was assumed for the remaining trials. Each forename or surname recalled correctly earned one point and one additional point was granted for successfully recalling a forename and surname together (one point for ‘Jim Heath’ or ‘Tom Green’, 3 points for ‘Jim Green’). The maximum score was 36 (3 points for each name X 4 names X 3 trials).

Shapes Test. The Shapes Test (Baddeley, Emslie, & Nimmo-Smith, 1994) is a measure of long-term visuospatial memory functioning. Participants were shown a succession of four line drawings, which they copied down. They were then required to redraw the figures from memory (trial 1). For trials 2 and 3, participants were shown the drawings, but were not allowed to copy them and were then asked to draw them from memory Points were awarded both for correctly reproducing elements of the target pictures and also for overall shape. If perfect performance was attained on any trial, testing ended and a maximum score was assumed for the remaining trials. The maximum score was 36 (3 points for each shape X 4 shapes X 3 trials).

Results

Associations of variables

Table 1 shows descriptive statistics (mean scores and ranges) for the route learning measure and the items in the test battery. Correlations between the cognitive measures and route learning performance (measured as the number of trials to criterion – two errorless trials in a row – and the total number of errors made across trials, henceforth referred to as trials and errors respectively) are displayed in Table 2, uncorrected for multiple comparisons. GNG error rates were low (M = 4.2, SD =3.0) and did not correlate with other measures so they have been omitted from the tables for clarity. The strongest correlates of route learning were Go/No Go RT (r^2 = .25 for trials; r^2 = .39 for errors) and the People test (r^2 = .25 for trials; r^2 = .34 for errors), suggesting that executive function and (verbal) long-term memory were particularly important factors in determining maze task performance. However, *every* cognitive measure reliably predicted either trials to criterion or errors. We would expect every cognitive function assessed to improve with increasing age (as indeed they did) and hence all to be intercorrelated in this mixed-age sample. Thus, to ascertain which factors determined development of route learning ability, multiple regression analyses were undertaken.

Backwards elimination regressions retain more variables than forwards stepwise regressions and are therefore less likely to spuriously identify only one or two factors as being important in relation to a given dependent variable. They begin by including all variables in the regression equation and then go through a series of iterations, eliminating variables one-by-one that are not significant predictors of the dependent variable. In this case, the criterion for eliminating each variable was having an associated F value of less than 1. Route learning Error was the dependent variable and independent variables were as follows:

chronological age, BPVS, RCPM, Go/No Go RT, digit, Corsi, pattern, People, and Shapes. These variables were selected because they were significantly related to the dependent variable (see Table 2). The measure of computer control proficiency was not included because it did not show a significant correlation with errors. After 8 iterations, the regression model retained two variables: Go/No Go RT (*F* change $p < .001$) and People (*F* change $p = .017$).

This analysis was followed up with a forward stepwise multiple regression with just Go/No Go RT and then People as independent variables. Backward elimination removes some shared variance, so a forward regression can be useful to confirm its findings. Go/No Go RT alone explained 39% of variance in errors made, with People uniquely explaining an additional 5%. With the order of entering independent variables reversed, People accounted for 34% of the variance before Go/No Go RT was added to the model, which explained the other 10%.

A similar set of analyses was also run for trials to criterion. Another backward-elimination multiple regression was run (criterion: $F > 1$), with trials to criterion as the dependent variable and independent variables of chronological age, BPVS, RCPM, Go/No Go RT, digit, Corsi, pattern, People, and Computer control). Again, these variables were selected because they were significantly related to the dependent variable (see Table 2). Shapes was omitted because it did not show a reliable correlation with the dependent variable. This time, Go/No Go RT (*F* change $p = .003$) was retained after 8 iterations. The follow-up forward stepwise multiple regression with Go/No Go RT as the independent variable revealed that Go/No Go RT accounted for 25% of variance in trials to criterion.

Thus, it appeared that two variables were particularly useful for explaining variation in route learning performance: Go/No Go RT and People. Critically, when the variance that the Go/No Go task shared with variance in route learning was accounted for by the regression procedure, none of the memory tasks significantly predicted route learning, apart from the People Test of verbal long-term memory. This indicates that the correlations found between the short-memory tasks and route learning were mediated by executive control.

As previously noted, variation in performance on these tasks was partly determined by chronological age; because of this, attempting to control for age-related variation might be expected to significantly weaken any correlations between scores on any given pair of tasks. Partial correlations, controlling for chronological age, between Go/No Go RT, People, and the route learning measures are given in Table 3. The correlations between Go/No Go RT and People and the measures of route learning remained strong, particularly with the relatively sensitive measure of errors.

Age-related changes in route learning ability

As a complement to the above analyses, children were split into three age-groups: Year 1/2, Year 3/4, and Year 5/6, to investigate any possible discontinuity in age-related changes in route learning ability, to which linear regression would not be sensitive. A one-way ANOVA was conducted, with route learning errors as the dependent variable and age-group as a between-subjects factor (Year 1/2 $M = 11.59$, $SD = 11.43$, Year 3/4 $M = 3.14$, $SD = 4.64$, Year 5/6 $M = 1.92$, $SD = 2.76$). There was a reliable effect of age-group, $F(2, 64) = 11.848$, $p < .001$, $\eta_p^2 = .270$. Bonferroni-adjusted post-hoc tests revealed no significant difference between Year 3/4 and Year 5/6, but more errors in Year 1/2 than both Year 3/4, $p < .001$, and Year 5/6, $p < .001$. A similar analysis based on trials to criterion yielded very similar results. These analyses indicate that there is a large improvement in route learning between 5 and 8 years of age.

To investigate whether executive control or long-term memory mediated this pattern of results, the ANOVA above was repeated twice, again with route learning errors as the dependent variable, but with Go/No Go RT and People as covariates. The difference between Year 1/2 than Year 3/4 was not reliable with either Go/No Go RT or People as the covariate ($p < .10$). This was consistent with the hypotheses that executive control or long-term memory mediated the improvement in route learning between 5 and 8 years of age. To explore this possibility further, an additional ANOVA, this time with Go/No Go RT as the dependent variable, and age group as the between-subjects factor, showed a reliable effect of age-group, $F(2, 64) = 15.930$, $p < .001$, $\eta_p^2 = .332$. Bonferroni-adjusted post-hoc tests revealed no significant difference between Year 3/4 and Year 5/6, but more errors in Year 1/2 than both Year 3/4, $p < .01$, and Year 5/6, $p < .001$, mirroring the ANOVA above of route learning and age group. A further ANOVA, with People as the dependent variable and age group as the between-subjects factor, showed a reliable effect of age-group, $F(2, 64) = 45.135$, $p < .001$, $\eta_p^2 = .585$. However, in this case, there was no sign of discontinuous change, with each age group reliably scoring higher than younger groups, all $p < .001$. Taken together, these analyses are consistent with the notion that improvement in route learning between 5 and 8 years is mediated by executive control and supported by verbal long-term memory.

Discussion

The aim of the study was to understand what cognitive underpinnings support route learning by identifying which components of Baddeley's (1986) working memory model related to route-learning by children. Children's route learning improved with age, most markedly between 5 and 8 years old. Strong correlations were found between all three visuospatial memory tasks – Corsi, pattern memory and the Shapes test – and route learning performance. This is the first clear finding of associations between visuospatial short-term memory tasks and route learning in typically developing children and is consistent with the results of a previous study by Fenner et al. (2000), which showed that children with high visuospatial ability (assessed by a battery that included Corsi) made fewer errors in learning a new environment than children with low visuospatial ability. Verbal short-term memory, indexed by digit span, and the two measures of long-term memory were also associated with route learning performance. Overall, these findings are consistent with adult studies that have found links between both verbal and visuospatial working memory and route learning (Garden et al., 2002; Meilinger et al, 2008), though these studies did not address short-term storage.

We suggest that all of the memory measures and the route learning measures make executive demands: in the memory tasks (e.g., Corsi, pattern and digit span), proactive interference, forgetting due to interfering activity of previously-presented items (e.g., Keppel and Underwood, 1962), must be overcome. In the route learning task, participants must avoid perseverating on any errors made in earlier trials. Moreover, participants must inhibit any desires to look around the room, and must not engage the experimenter in conversation or do anything other than the task itself. Therefore, the appropriate multiple regression models are those that enter Go/No Go as a pure measure of executive control before the other measures, because we would expect executive demands in these other tasks. The error rate for the Go/No Go task was close to floor, so Go/No Go reaction time was used in the analyses.

Having found associations between various short-term memory measures and route learning, subsequent multiple regression analyses showed that the relationships were mediated by executive control, indexed by the Go/No Go task. In other words, when the variance that the Go/No Go task shared with variance in route learning was removed, the remaining variance that each memory task shared with route learning variance was not reliably related, with the exception of the People test of verbal long-term memory. Go/No Go explained 25% of variance in number of trials to criterion and almost 40% of variance in route learning errors. Beyond the executive control demands of Go/No Go, there is little more required of participants aside from remembering the rules of the task (be as quick as possible, do not press the button on red stimuli). Thus, the variance shared by Go/No Go and the route learning measures can confidently be interpreted as variance in executive control.

The finding of a sharp improvement in route learning between the ages of 5 and 8, with no improvement above 8 years, was accompanied by exactly the same pattern in improvements in executive control. Taken together with multiple regression analyses, it would be parsimonious to suggest that executive control mediated the improvement in route learning. There were improvements in verbal long-term memory between 5 and 8, and also between 8 and 11. Therefore, verbal long-term memory improvement may support route learning improvement, but the two do not appear as closely linked as executive control and route learning.

As stated in the results section, we would expect every cognitive function assessed to improve with increasing age and hence all to be intercorrelated in this mixed-age sample. A strict test of the associations of Go/No Go, the People test and route learning performance was undertaken by controlling for chronological age. The associations between Go/No Go and People and route learning remained strong even after controlling for age-related variance. This is a striking result, because we would expect that controlling for age-related variance in a cross-sectional sample would remove much of the variance on which relationships between variables could be established. The fact that Go/No Go and the People test remained strong predictors of route learning after controlling for age is decisive in establishing the importance of executive control and long-term memory in this domain for young school-age children.

The People Test of verbal long-term memory had a significant, albeit modest, additional amount of shared variance with our measures of route learning. It is not surprising that a long-term memory measure partly determines route learning performance because to learn a route, one must attend to the route and subsequently recall it. The finding that a verbal, rather than visuospatial, long-term memory measure was important may reflect verbal coding and recall of named landmarks by participants. However, it should be noted that there was a ceiling effect for the visuospatial long-term memory measure: almost a third of the children tested were at ceiling on the Shapes test thus reducing the variance in performance on this measure, but no child was at ceiling on the People test. Therefore, the finding that a verbal, rather than visuospatial, long-term memory measure was important may owe, at least in part, to this reduced variance in the visuospatial measure. At present, most memory models take long-term memory to be amodal, (though there is a lack of direct evidence for this assumption; see Barsalou, 2008, for a review), so we may take the People test to be a measure of general long-term memory, rather than one of only verbal long-term memory. Using different theoretical frameworks from Baddeley's (1986) working memory model, or alternatively taking a less theoretically-centred psychometric approach, several studies have attempted to link memory tasks and route-learning abilities in various ways (Allen et al., 1996; Fenner at al., 2000; Hegarty at al., 2006; Quaiser-Pohl et al., 2004). In summary of this literature, there have been few clear associations found between individual short-term or working memory tasks and route learning. Those associations that have been found either have not been replicated or did not involve direct measures of route learning. As stated above, other studies (Garden et al., 2002; Meilinger et al., 2008) have found links between 'working memory' processing tasks and route learning, but not between route learning and actual memory tasks.

There are several additional possible reasons why relationships were found between memory tasks and route learning in the current study, even though previous studies have tended not to find such links. First, the sample size (N=67) of the current study was larger than the samples included in many prior studies. Second, there are differences in the types of tasks used across studies. A third reason might be particularly important: sensitive scoring was adopted for all tasks in the current study, which avoided floor effects. Rather than using span procedures for the short-term memory tasks, in which participants are given a score according to the maximum list length or array size they appear to be capable of recalling, scoring was instead based on the total number of individual items (digits/locations) that were correctly recalled across *all* trials. However, as explained above, the relationships between the short-term memory tasks and route learning were mediated by executive control.

The most important point to take from the current study is that researchers should be very cautious in interpreting associations between performances on different tasks. Such associations may be statistically strong, yet mediated by task demands that are considered non-central by the experimenters. In particular, we have shown that executive demands can mediate such relationships; it would seem that such demands are part of most cognitive tasks.

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Table 1.

Descriptive statistics for route learning and the cognitive test battery.

	Mean	SD	Range	Best Possible Score
Age (years;months)	8;2	1;9	5;4 -11;3	N/A
BPVS (raw)	109	25	41-150	168
RCPM (raw)	27	6.1	9-36	36
GNG RT (ms)	677	111	476-1031	N/A
Digit (items correct)	46	17.3	18-108	189
Corsi (items correct)	38	13.2	11-76	189
Pattern (items correct)	42	15.4	21-99	189
People	18	17.7	0-34	36
Shapes	31	5.2	11-36	36
Computer control (seconds)	14	3.8	7-27	N/A
Route learning trials to criterion	4.6	2.6	2-11	2
Route learning errors	5.5	8.3	0-37	0

Note. BPVS = British Picture Vocabulary Scale, RCPM = Raven's Coloured Progressive Matrices, GNG RT = Go/No Go task reaction time, Computer = a measure of mouse/keyboard and eye coordination.

Table 2.

Correlations between cognitive measures and route learning performance.

	Age	BPVS	RCPM	GNG RT	Digit	Corsi	Pattern	People	Shapes	Computer	Trials	Errors
Age	1.0	.70**	.71*	-.63**	.54**	.42**	.47**	.80**	.44**	-.34**	-.46**	-.51**
BPVS		1.0	.77**	-.39**	.58**	.41**	.52**	.69**	.45**	-.29*	-.30*	-.39**
RCPM			1.0	-.44**	-.56*	.49**	.43**	.69**	.44**	-.28*	-.43**	-.47**
GNG RT				1.0	-.35**	-.45**	-.32**	-.65**	-.24*	.26*	.50**	.62**
Digit					1.0	.37**	.56**	.51**	.30*	-.13	-.25*	-.26*
Corsi						1.0	.42**	.48**	.31*	-.15	-.30*	-.31*
Pattern							1.0	.49**	.33**	.00	-.24*	-.31*
People								1.0	.46**	-.21	-.50**	-.58**
Shapes									1.0	-.29*	-.22	-.36**
Computer										1.0	.26*	.19
Trials											1.0	.79**
Errors												1.0

*Note. BPVS = British Picture Vocabulary Scale, RCPM = Raven's Coloured Progressive Matrices, GNG RT = Go/No Go task reaction time, Computer = a measure of mouse/keyboard and eye coordination, Trials = trials to criterion, Errors = total number of incorrect turns taken in the maze. N = 67; *p < .05; **p < .01, uncorrected for multiple comparisons.*

Table 3.

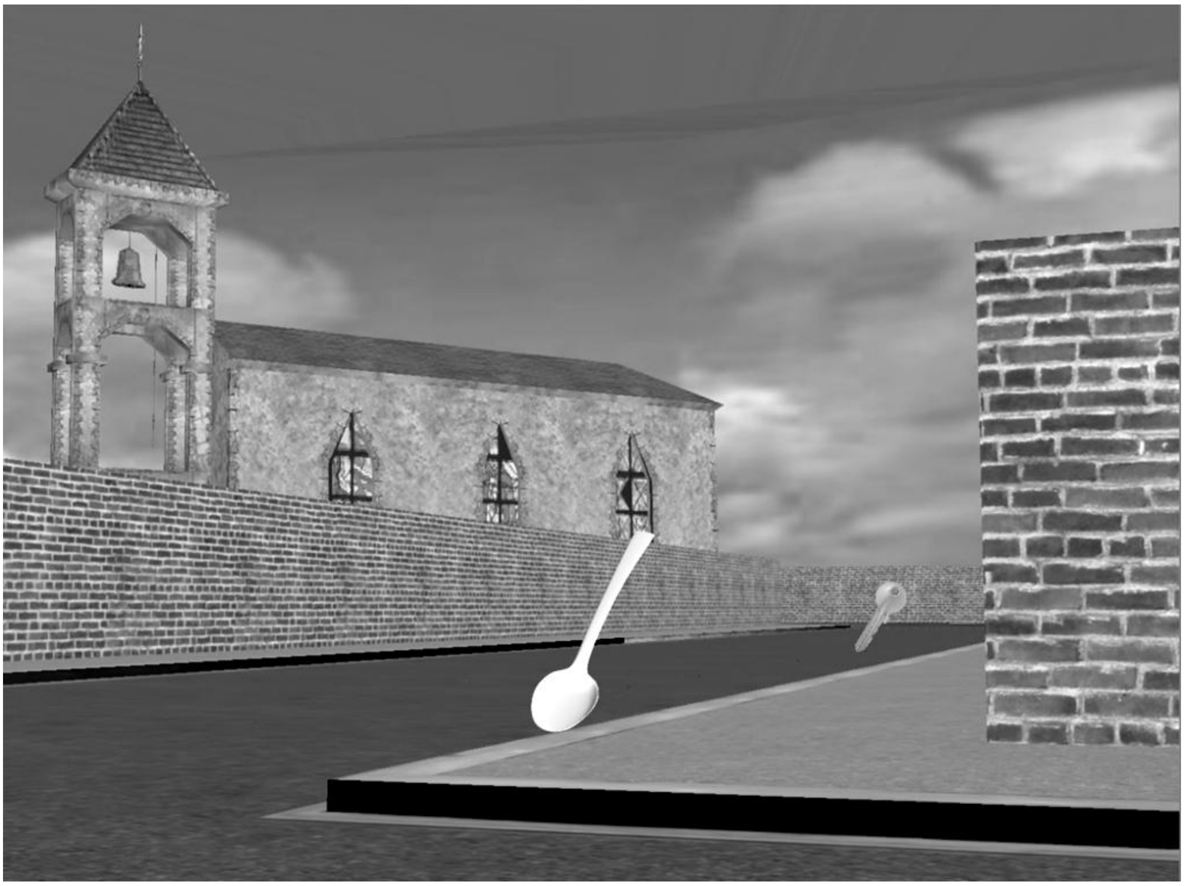
Partial correlations, controlling for age, between Go/No Go task reaction time, People, RCPM and route learning performance.

	GNG RT	People	Trials	Errors
GNG RT	1.0	-.33**	.31*	.46**
People		1.0	-.25*	-.34**
Trials			1.0	.73**
Errors				1.0

*Note: BPVS = British Picture Vocabulary Scale, RCPM = Raven's Coloured Progressive Matrices, GNG RT = Go/No Go task reaction time, Trials = trials to criterion, Errors = total number of incorrect turns taken in the maze. df = 64; *p < .05; **p < .01, uncorrected for multiple comparisons*

Figure 1.

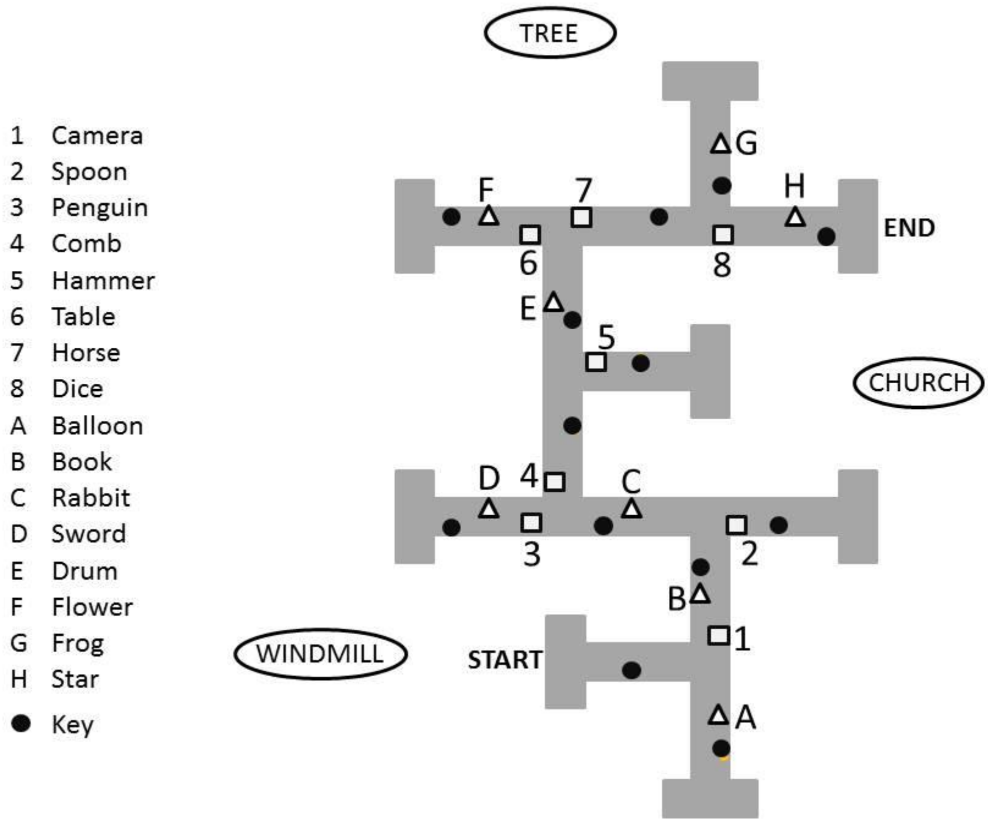
The virtual environment maze.



Note. Note the spoon (junction landmark, key (non-unique landmark) and the church (distant landmark).

Figure 2.

A map of the maze depicting the locations of landmarks.



Note. *1 to 8 are junction landmarks and A to H are path (non-junction) landmarks. The black circles are non-unique landmarks (keys). Distant landmarks (tree, church, windmill) are outside the maze walls.*