How useful are landmarks when learning a route in a virtual environment? Evidence from typical development and Williams syndrome

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Abstract

The ability to learn a route through a virtual environment was assessed in nineteen older children and adults with Williams syndrome (WS) and forty typically developing (TD) children aged six to nine years. In addition to comparing route-learning ability across groups, we were interested in whether participants show an adult-like differentiation between ‘useful’ and ‘less useful’ landmarks when learning a route and the relative salience of landmark position versus landmark identity. Each virtual environment consisted of a brick-wall maze with 6 junctions. There were sixteen landmarks in the maze, half of which were on the correct path and half on incorrect paths. Results showed that both groups could learn each route to criterion (two successful completions of a route without error). In the learning phase, the WS group produced more errors than the TD group and took longer to reach criterion. This was predominantly due to the large number of perseverative errors (errors that were made at the same choicepoint on consecutive learning trials) made by the WS group relative to the TD children. We suggest that this reflects a difficulty with inhibiting erroneous responses in WS. In the test phase, the TD group showed stronger recall of landmarks adjacent to junctions (more useful landmarks) than landmarks along path sections (less useful landmarks), independent of each individual’s level of non-verbal ability. This pattern was also evident in the WS group, but was related to level of non-verbal maturation; the differentiation between recall of junction and path landmarks increased as non-verbal ability increased across WS participants. Overall, the results demonstrate that individuals with WS can learn a route, but that the development of this ability is atypical.

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Route-learning, i.e. the ability to know where you are, to learn your way around a town, or to learn a route from A to B, is a crucial aspect of human development (Rissotto & Giuliani, 2006). Siegel and White (1975) propose that route-learning abilities develop in three stages. The first involves knowledge of the landmarks along a route, defined as landmark knowledge. The second refers to knowledge of the sequential order of the turns and landmarks of a route, defined as route knowledge. The final stage involves the development of a cognitive map, also known as configurational knowledge, by which the spatial relationships between routes and landmarks in an area are understood. More recently, a qualitative difference between the first two stages, landmark knowledge and route knowledge, has been challenged and many now favor a model of continuous development of route-learning ability, with the only qualitative change occurring during the integration of learnt places, to form a cognitive map (Montello, 1998). Furthermore, Jansen-Osmann and colleagues (Jansen-Osmann & Fuchs, 2007; Jansen-Osmann, Schmid & Heil, 2007) differentiate between the cognitive representations formed during the stages described above, and the perceptual-motor learning required to build such representations. They define the cognitive system of internal representations as spatial knowledge, and the perceptual-motor learning as wayfinding behavior.

Route-learning can also be considered in terms of spatial frames of reference. That is, landmark and route knowledge can be accomplished using an egocentric frame of reference, i.e. by encoding the location of a landmark relative to oneself (response learning), and hence involve viewpoint-dependent representations. In contrast, the development of a cognitive map requires an individual to use an environment-based frame of reference, i.e. to encode the locations of objects relative to other objects or elements of the environment (place learning), and is viewpoint-independent (see Burgess, 2006). In typical development, young children rely on egocentric frames of reference for route-learning, with spontaneous use of environment-based representations emerging within the school-age years (e.g., Bullens, Igloi, Berthoz, Postma & Rondi-Reig, 2010; Nardini, Thomas, Knowland, Braddick & Atkinson, 2009).

Learning a sequence of landmarks and turns (route knowledge) is an effective strategy for navigating a new environment, and such a sequence is one aspect of developing a more complete representation of an environment, or a cognitive map (Montello, 1988). In the literature on environmental learning most researchers have focused on the use of a cognitive map, and there has been less emphasis on landmark knowledge and route knowledge (see Buchner & Jansen-Osmann, 2008). In the present study, landmark knowledge and route knowledge were assessed using virtual environments in typically developing (TD) children aged 6 to 9 years, and individuals with Williams syndrome (WS). The study focused on the use of proximal landmarks when learning a route and explored egocentric viewpoint-dependent processing. We were interested in whether participants differentiated between 'useful' and 'less useful' landmarks and the relative salience of landmark position versus landmark identity. Using Jansen-Osmann and colleagues' (Jansen-Osmann & Fuchs, 2007; Jansen-Osmann, Schmid & Heil, 2007) terminology, we measured wayfinding behavior by recording the number of learning trials required and the number of errors made while learning a route, and we assessed landmark knowledge (a feature of spatial knowledge) by measuring participants' recall of landmarks. This study is the first to use virtual environments with people with WS and the first to explore knowledge of landmark usefulness in TD children as young as 6 years old.

Landmarks are an important feature of route-learning, and more generally, are important to the development of spatial cognition. Landmarks can be defined as objects within the environment that are remembered due to their perceptual and contextual salience (see Caduff & Timpf, 2008). They are used as beacons or reference points (e.g., Waller & Lippa, 2007) or to represent a prototype location (Newcombe & Huttenlocher, 2000). Developmentally, landmarks are used as cues from an early age. For example, 11-month-olds, with only a few weeks experience of independent locomotion (i.e. crawling) can use landmarks to take a route to a target that was not directly visible at the start of the route (Clearfield, 2004). By 2 years of age children can combine the location of landmarks with geometric information from a rectangular environment (Learmonth, Newcombe & Huttenlocher, 2001). Older children can use landmarks even when there is no environmental context, for example in a circular enclosure (Newcombe, Ratliff, Shallcross & Twyman, 2010).

The selection of landmarks and the capacity to determine their usefulness when learning a route, changes with development. Allen, Kirasic, Siegal & Herman (1979) used photographs of a route to demonstrate that 10-year-olds, but not 7-year-olds, showed an advantage of using useful over less useful landmarks (usefulness was judged by adult participants) to make distance judgments between places on the route. This is supported by Jansen-Osmann and Wiedenbauer (2004a) who demonstrated that after learning a route in a virtual environment, 11-year-olds recalled more landmarks than 7-year-olds, but both of these groups, as well as an adult group, showed stronger recall for landmarks that were adjacent to a correct path, and thus more useful, than other landmarks. Despite this, it is not until children are 12 years old that they explicitly recognize landmarks near intersections as useful (Cornell, Hadley, Sterling, Chan & Boechler, 2001; Golledge, Smith, Pellegrino, Doherty & Marshal, 1985; Heth, Cornell & Alberts, 1997). By the age of 12 years children can also use distal landmarks, such as tall trees or buildings to aid navigation (Heth, Cornell & Alberts, 1997).

In this study, the ability to determine the usefulness of proximal landmarks was explored in both typical development and in individuals with WS.

WS occurs in approximately 1 in 20,000 births (Morris & Mervis, 1999) and presents with an IQ of ~60 (Udwin & Yule, 1990). However, this comprises an uneven profile of cognitive abilities in which visuo-spatial cognition is weaker than verbal cognition (e.g., Bellugi, Wang & Jernigan, 1994). In small environments individuals with WS can use viewpoint-dependent processing, but show impaired viewpoint-independent processing (Nardini, Atkinson, Braddick & Burgess, 2008). When assessed in spatial reorientation tasks, individuals with WS do not benefit from the geometry of a rectangular room to orient themselves when looking for a toy hidden in one corner of the room, but do show relatively improved performance when there is a unique landmark, like a blue wall in the room (Lakusta, Dessalegn & Landau, 2010). This contrasts to the performance of typically developing children, who may use geometric information from as early as 18 to 24 months (Hermer & Spelke, 1996).

The studies above, although not directly investigating route-learning ability, suggest that individuals with WS can learn a route, but such learning will be based on viewpoint-dependent processing. The impairment in using geometric knowledge in WS (Lakusta et al, 2010) also suggests that individuals with WS will be dependent on landmarks for orientating. Therefore, when individuals with WS learn a route, they might do so as a succession of paired associations between landmarks and turns (response learning), rather than with any greater understanding of the spatial relationships between places in the environment. Our recent research, which is the only study of route-learning in WS, supports this assumption (Farran, Blades, Boucher & Tranter, 2010). In Farran et al. (2010) participants were guided along two unfamiliar 1 km routes in a real-world environment, with 20 junctions, and then asked to retrace the route themselves. WS participants performed less well than a group of individuals with moderate learning difficulties matched for non-verbal ability and chronological age, and a TD group matched for chronological age. The WS group and the moderate-learning-difficulty group failed to show an understanding of the spatial relationship between landmarks along the route, and thus did not make use of viewpoint-independent processing. Despite this, the WS group did show a good knowledge of the sequence of turns along the route, and this knowledge improved through repeated experience of the route and by the use of verbal labeling when learning the route.

As a 1 km route was included in Farran et al. (2010), the opportunity for repeated trials on such a route was limited and therefore we could not determine if the WS group would have eventually learnt the route without making any errors. In addition, although a real-world route has ecological validity, it was not possible to equate the salience of each landmark and each turn along the route. These limitations were avoided in the present study by using virtual environments. By using virtual environments we could also test participants' encoding of the visual and spatial properties of landmarks separately, by removing landmarks and by changing their identity (which is obviously not possible in a real-world context).

Previous researchers have shown that virtual environments tap into the same cognitive mechanisms as real-world environments (Richardson, Montello & Hegarty, 1999), that learning from virtual environments transfers to successful performance in the real world (Montello, Hegarty, Richardson & Waller, 2004; Ruddle, Payne, & Jones, 1997; Waller, Montello, Richardson & Hegarty, 2002; Wilson, 1997) and that it is possible to use virtual environments successfully with individuals with learning difficulties (Stanton, Wilson & Foreman, 1996; Mengue-Topio, Courbois, Farran & Sockeel, 2011). Thus, we were confident that the skills measured in this study were the same as the skills employed when route-learning in the real world.

Within a virtual environment we manipulated the usefulness of landmarks by placing landmarks at junctions (useful) or on path sections (less useful). For the TD children we predicted that junction landmarks would be better recalled than path landmarks and that this would be related to development, with stronger effects with increasing cognitive maturation (Allen et al., 1979). It was possible that such improved recall for junction landmarks would not be found in the WS group because proximity to junctions is a spatial property and visual-spatial memory is weaker than visual-object memory in WS (Vicari, Bellucci & Carlesimo, 2005, 2006), hence the WS group might not show differential recall of junction and path landmarks.

As visual-spatial memory is poorer in WS we predicted that the WS group might have poorer recall of landmark locations (visual-spatial) than landmark identities (visual-object). The relative importance of the visual and spatial information provided by landmarks has not been investigated in typical development. However, TD children's level of visual-spatial memory and visual-object memory are equivalent (Van Leijenhorst, Crone & Van der Molen, 2007) so there was no reason to predict that either property would be more salient to route-learning in typical development.

We also investigated the effects of verbal labeling. We showed the beneficial effects of verbal labeling for learning a route in the real-world (Farran et al., 2010); therefore in the present study we predicted that both groups would show facilitation of verbal labeling for learning the route and for landmark recall.

The study design is based on the developmental trajectory approach (Thomas et al., 2009). Using this approach, rather than considering differences in group means as in a matched group design, one can observe how variance in performance on a task relates to variance in cognitive maturation. In this way, cross-sectional development within each group can be taken into account, rather than considering performance as static (as in a matched group design). The current task was predominantly a non-verbal task and so we measured cognitive maturity using the Raven's Colored Progressive Matrices (Raven, 1993), a standardized measure which taps into similar non-verbal mechanisms in both WS and TD groups (Van Herwegen, Farran & Annaz, 2011). The TD group was chosen so that their range of Raven's Colored Progressive Matrices scores encompassed the range of Raven's Colored Progressive Matrices scores of the WS group.

Method

Participants

Twenty-two participants with Williams syndrome (WS) were recruited via the records of the Williams Syndrome Foundation, UK. All participants had received a positive diagnosis of WS based on phenotypic and genetic information. Genetic diagnosis was based on a Fluorescent insitu Hybridisation (FISH) test (see Lenhoff, Wang, Greenberg & Bellugi, 1997). Three WS participants failed to finish the testing session because they were unwilling to complete the study. The data reported in this study is therefore from 19 participants with WS. All participants with WS had a computer at home and used a mouse and keyboard on at least a weekly basis and had normal or correct-to-normal vision. Verbal ability and non-verbal ability were measured using the British Picture Vocabulary Scale II (Dunn, Dunn, Whetton & Burley, 1997) and Raven's Colored Progressive Matrices (Raven, 1993) respectively. Four groups of 10 typically developing (TD) children of mean ages 6, 7, 8 and 9 years were recruited from a primary school in Middlesex, UK. Participant details can be found in Table 1.

Table 1

Design and Procedure

Four different virtual environments were created using the software program Vizard (www.Worldviz.com). Virtual environments were presented on a 17 inch laptop. Participants navigated using the arrow keys on the keyboard. One virtual environment was used as a practice to familiarize participants with navigation in a virtual environment before the experiment began. This had a similar layout to the three test virtual environments, but did not include landmarks.

Each test virtual environment was a brick-wall maze with 6 junctions (see Figure 1). At each junction, there were two path sections from which to choose. One was a path section of the correct route and led participants to the next junction of the correct route, the other was an incorrect path section which led them to a cul-de-sac (from the junction, this looked like a T-junction, rather than a dead-end). From a first person perspective, the correct route involved two left, two right and two straight ahead decisions at junctions (ordered differently for each virtual environment). The directions of the incorrect path sections at each junction were similarly distributed (two left, two right, two straight ahead). To highlight each junction, the floor at each junction had a square area of pebble texture. The same texture was also used at the end of each cul-de-sac.

Each virtual environment contained 16 landmarks. The landmarks were chosen from categories familiar to children (each virtual environment contained: three toys, one item of furniture, two vehicles, two food objects, two animals, one type of vegetation, and five random objects [e.g., camera, candle, umbrella]). This ensured that the range of distinctiveness across landmarks was similar across virtual environments. Similar types of landmarks have been used in previous virtual environment studies with brick-wall mazes (e.g., Jansen-Osmann & Wiedenbauer, 2004a). There were eight landmarks on incorrect path sections and eight on the correct path sections. For each set of eight landmarks, four of the landmarks were immediately adjacent to a junction (henceforth referred to as junction landmarks) and four were mid-way along a path section and thus not near to a junction (henceforth referred to as path landmarks). If the correct route is considered in terms of six path sections (one section after each junction) two of the path sections included two landmarks (a junction landmark and a path landmark), and four path sections featured one landmark (two had a junction landmark and two had a path landmark). Of the six incorrect path sections which led to cul-de-sacs, two were positioned straight ahead from a junction and so the landmarks featured on these paths were visible on the approach to a junction when walking the correct route. On these incorrect path sections there were two landmarks (a junction landmark and a path landmark). The landmarks on the other incorrect path sections (two left, two right) were only visible if an incorrect decision was made at a junction and each featured one landmark (two featured a junction landmark and two featured a path landmark). Within each virtual environment, half of the landmarks were positioned on the left hand side of the path section and half on the right hand side (from a first person perspective when approaching a junction from start to finish). At the end of each route, participants could see a yellow duck which produced a ‘quack’ noise as the participant passed it. The virtual environment then disappeared indicating the end of the trial.

For each virtual environment, the participant was shown the correct route by the experimenter who used the arrow keys on the keyboard to navigate from start to finish. Participants then learnt the route and were subsequently tested on their knowledge of the landmarks on that route. Two non-labeling conditions were carried out first. In these conditions, when demonstrating the correct route, the experimenter used non-specific dialogue, such as “…and then we go this way…”. Comparisons between performance on the two non-labeling conditions provided an index of practise, i.e. whether participants transfer route-learning performance from one virtual environment to another different virtual environment.

The final condition was the labeling condition in which the experimenter verbally labeled each landmark that was visible when demonstrating the correct route (the eight landmarks on the correct paths and the four visible landmarks on incorrect paths), e.g., "…then we go past the bike…". The labeling condition had to be experienced last, so that carry-over effects of using a verbal strategy could not occur. Each participant experienced all three test virtual environments, but the virtual environments employed for each condition (non-labeling a, non-labeling b, labeling) were counterbalanced across participants.

For each virtual environment, after the participant had been shown the route once, they were asked to navigate their way through the virtual environment with as few errors as possible. When participants chose the wrong path they arrived at a cul-de-sac and were able to self-correct their error by travelling back to the junction. The experimenter gave no additional feedback and there were no time restrictions. At the end of each learning trial, the participant was asked to complete another learning trial (i.e. to walk the route again) until they were able to walk the route without making any errors (travelling down or turning to look down an incorrect path was considered an error). Once the participant had achieved two consecutive successful completions of the route without errors, they were deemed to have learnt the route and the learning phase was complete. Immediately following the learning phase, participants took part in two test phases, as illustrated in Figure 2. They were asked about the location of the objects (test phase 1) and about the identity of the object (test phase 2) in alternating order across the three conditions. The test phase that participants received first (in non-labeling condition a) was counterbalanced across participants.

In test phase 1, all of the landmarks were removed from the virtual environment and the floor of each path was divided into five equal spaces by white lines (Figure 2b). The experimenter navigated through the maze and stopped at the beginning of each of the 6 correct path sections. The experimenter named the landmark that was on that path during the learning phase and asked the participant to point to *where* the landmark had been in the learning phase (when a path section featured two landmarks, the second was named by the experimenter after a response had been elicited from the participant regarding the first landmark). Responses were coded as correct if they were on the correct side (left or right side of the path) and in the correct space (of the five possible spaces). After each response had been given, the participant was shown an image of that path section with the landmark visible, in the correct location as feedback (when there were two objects on the path in the learning phase, only the landmark in question was shown as feedback in the test phase).

In test phase 2, each landmark was replaced by a red ball, presented in the correct location (Figure 2c). Again the experimenter navigated through the virtual environment and stopped at the beginning of each of the six correct path sections. For each red ball, participants were asked to verbally recall *what* landmark had been at that location in the learning phase. In cases where the participants used an ambiguous label for the landmark, we referred to the labels that they used for that landmark in a subsequent naming task described below to determine accuracy. As in test phase 1 after each response had been given the participant was shown an image of the original landmark as feedback (as in test phase 1, when there were two landmarks on the path in the learning phase, only the landmark that the participant was responding about was shown as feedback in the test phase).

Between the two test phases, the participant was shown the correct route through the virtual environment again by the experimenter (all landmarks were present, as in the learning trials). This was included because in the test phases the route was disjointed relative to a normal walk of the route. By experiencing the route in a normal way before the second test phase, participants could re-familiarize themselves with the correct route through the virtual environment.

The naming task was completed at the end of each session. Participants were shown images of all the landmarks from the virtual environment and asked to name them. This was employed so that, if a participant had used the label ‘light’ or ‘lamp’ in test phase 2, we could establish, for example, that they were referring to the ‘lamppost’.

After each condition, a recognition task was administered. The participant was shown images of 16 landmarks. Half of these landmarks had featured in the original virtual environment, while the other half depicted previously unseen objects. For the landmarks that had featured in the original virtual environment, four depicted a landmark that had been on an incorrect path and the remaining four had been on the correct path. The participant was requested to say whether or not the object had featured in the original virtual environment. The correct response for the landmarks on incorrect paths was individually tailored to whether a participant had taken that incorrect path (and thus seen the landmark) or not during learning.

Figures 1 and 2

Results

To take development into account, first WS performance was compared to typical development by entering the TD group into ANOVAs as four groups split by chronological age (6-, 7-, 8-, and 9-year-olds). Second, based on the developmental trajectory approach (Thomas et al., 2009), ANCOVA was employed for each group as a whole (WS and all TD children). For this method, a measure of cognitive ability is employed as the covariate, which enables one to characterize the linear developmental trajectory of performance on the experimental task, as driven by individual differences in underlying cognitive ability. For these analyses we took a theoretically driven approach which assumed that non-verbal ability, as measured by Raven's Colored Progressive Matrices performance, would provide an index of the cognitive abilities associated with route-learning performance for each group, and thus Raven's Colored Progressive Matrices raw score was employed as the covariate.

Learning phase: measures of wayfinding behavior

Participants completed as many learning trials (walks of the route) as were required for them to walk the route without making any errors (if a participant turned to look down an incorrect path or travelled down an incorrect path, this was classed as an error) on two consecutive learning trials. The number of learning trials required to learn each route was noted (including the two error-free criterion trials). In addition, we counted the cumulative number of errors made in each learning phase (errors were summed across all learning trials for each condition separately). Group means for each of these dependent variables are displayed in Table 2.

Number of learning trials required to learn each route. Analysis of Variance (ANOVA) was carried out with a within-participants factor of condition (3 levels: non-labeling a, non-labeling b, labeling) and a between participants factor of group (5 levels: 6-, 7-, 8-, and 9-year-olds, WS). This revealed a main effect of group, $F(4, 54)=3.47$, $p=.01$, $\eta_p^2 =.21$; Tukey pairwise comparisons revealed that the WS group were significantly weaker than the 9-year-olds ($p<.05$), but at the same level as 6- to 8-year-olds (means: 5.47[WS], 5.30 [6 years], 5.23 [7 years], 4.53 [8 years], 3.70 [9 years]). A significant effect of condition was explained as a linear contrast, $F(1, 108)=20.64$, $p<.001$, $\eta_p^2 =.28$ (means: 5.61 [non-labeling a], 4.90 [non-labeling b], 4.03 [labeling]), and reflected task practise effects across all three VEs, and thus that verbal labeling had no additional impact on performance over and above practise effects. This effect was not modulated by group, $F(8, 108)=1.15$, $p=.33$, $\eta_p^2=.08$.

Analysis of Covariance (ANCOVA) was carried out for TD and WS groups separately to explore developmental trajectories of performance. Each ANCOVA had a repeated measures factor of condition (non-labeling a, non-labeling b, labeling), and Raven's Colored Progressive Matrices raw score as the covariate. For the TD group, the higher an individual's Raven's Colored Progressive Matrices score, the fewer learning trials were required to reach criteria, $F(1, 38)=6.68$, $p=.01$, $\eta_p^2=.15$. This relationship was consistent across conditions, $F(2, 76)=1.48$, $p=.23$, $\eta_p^2=.04$. For the WS group, Raven's Colored Progressive Matrices score was not a good predictor of the number of learning trials required to learn a route: $F<1$; 4% of variance in performance explained. Chronological Age showed a similar lack of predictive ability, $F(1, 17)=1.82$, $p=.20$, $\eta_p^2=.10$.

Errors made in the learning phase. Within each condition we recorded the number of errors made across learning trials. Errors across learning trials is a more sensitive measure than the number of learning trials themselves. A factor of error type was also added to the analysis, which differentiated errors into three categories: 1) errors made at a junction just once across all learning trials for that virtual environment (single errors); 2) errors that were made at the same junction repeatedly on consecutive learning trials (perseverative errors); 3) errors that were made at the same junction on more than one learning trial, but not on consecutive learning trials (consolidation errors).

Error data is displayed in Figure 3. ANOVA was carried with within participants factors of condition (non-labeling a, non-labeling b, labeling) and error type (3 levels) and a between participants factor of group (6-, 7-, 8-, 9-year-olds, WS). The main effects of group, $F(4, 54)$ -4.18, $p=.01$, $\eta_p^2=.24$, and condition, $F(1, 54)=26.71$, $p<.001$, $\eta_p^2=.33$, were consistent with the analysis of the number of learning trials above. That is, the number of errors reduced linearly across conditions (means: 2.00 [non-labeling a], 1.49 [non-labeling b], 0.86 [labeling]) and, based on Tukey paired comparisons, the WS group performed at a lower level than the TD 9-year-olds only (means: 2.09 [WS], 1.60 [6 years], 1.63 [7 years], 1.22 [8 years], 0.70 [9 years]). There was a main effect of error type, $F(2, 108)=7.99$, $p=.001$, $\eta_p^2=.13$, due to significantly fewer consolidation errors (mean: 0.89) than perseverative (mean: 1.98, $p<.001$) or single errors (mean: 1.48, $p=.001$) and similar numbers of single and perseverative errors ($p=.16$). This interacted with condition, $F(4, 216)=3.04$, $p=.02$, $\eta_p^2=.05$, due to a gradual shift in error patterns which was driven by a stronger linear reduction in perseverative errors across conditions than other error types (single errors: $p=.03$; perseverative errors: $p<.001$; consolidation errors, $p=.01$). Group also interacted with error type, $F(8, 216)=2.64$, $p=.01$, $\eta_p^2=.16$. This was due to an effect of group for perseverative errors only, $F(4, 54)=3.67$, $p=.01$, $\eta_p^2=.21$, on account of the WS group making more of these errors than 9-year-olds ($p=.01$), and marginally more than 8-year-olds ($p=.06$). Group did not interact with condition, and there was no significant 3-way interaction.

For the TD group, a relationship between number of errors and Raven's Colored Progressive Matrices score, $F(1, 38)=8.45$, $p=.01$, $\eta_p^2=.18$ was modulated by error type, $F(2, 76) = 5.85$, $p=.004$, $\eta_p^2=.13$. This was due to a reduction in errors with increasing Raven's Colored Progressive Matrices score for perseverative errors only, $F(1, 38)=10.35$, $p=.003$, $\eta_p^2=.21$ (single errors, $F<1$; consolidation errors, $F(1, 38)=1.22$, $p=.28$, $\eta_p^2=.03$). For the WS group, number of errors was not significantly predicted by Raven's Colored Progressive Matrices score, $F(1, 17)=2.11$, $p=.17$, $\eta_p^2=.11$. The relationship between performance and Raven's Colored Progressive Matrices score marginally differed according to error type, $F(2, 34)=2.87$, $p=.07$, $\eta_p^2=.15$. Although effect sizes are low, analysis points to different pattern than that observed in the TD group. For the WS group there was a marginal increase in the number of single errors with increasing Raven's Colored Progressive Matrices score only (single errors, $F(1, 17)=3.68$, $p=.07$, $\eta_p^2=.18$; consolidation errors, $F(1, 17)=2.69$, $p=.12$, $\eta_p^2=.14$: perseverative errors, $F(1, 17)=1.85$, $p=.19$, $\eta_p^2=.10$).

Table 2, Figures 2 and 3 about here

Test phase: measures of landmark knowledge

Participants were asked to recall the location (test phase 1) and the identity (test phase 2) of each of the eight landmarks (four junction and four path landmarks) that featured on the correct path, in each condition. At the end of each condition, participants' recognition of 'old' versus 'new' landmarks was measured.

Recall of landmarks. Initial analysis showed order effects for the order in which they completed test phases one and two; participants showed stronger memory on their second test phase than their first test phase (Order x Memory Type: $F(1, 48) = 12.82$, $p=.001$, $\eta_p^2 =.21$). However, as the memory type assessed in each of the two test phases was counterbalanced and the order effect did not significantly interact with condition, group or type of landmark, it was not considered problematic. Figures 4 and 5 illustrate recall performance for WS and TD groups. ANOVA was carried out with three within participant factors: condition (non-labeling a and b, labeling); memory type (2 levels: the ability to recall the location and the identity of the landmarks); and type of landmark (2 levels: junction landmarks and path landmarks) and a between participant factor of group (5 levels: 6-, 7-, 8-, and 9-year-olds, WS). A main effect of group, $F(4, 53)=3.32$, $p=.02$, partial $\eta^2 =.20$, was explored using Tukey pairwise comparison; the WS group (mean: 1.81) performed significantly below the 9-year-olds (mean: 2.58, $p=.01$), but at the level of the 6- to 8-year-olds (means: 2.06 [6 years], 2.17 [7 years], 2.19 [8 years]). Recall of junction landmarks (mean: 2.23) was stronger than for path landmarks (mean: 2.09), $F(1, 53)=60.14$, $p<.001$, $\eta_p^2 =.53$. The main effects of condition and memory type were not significant. All other interactions were not significant.

For the TD group performance was not significantly related to Raven's Colored Progressive Matrices, $F(1, 37)=2.05$, $p=.16$, $\eta_p^2=.05$, but was related to CA, $F(1, 37)=7.57$,

p=.01, η_p^2 =.17. Patterns of performance were the same for both variables; neither Raven's Colored Progressive Matrices nor CA interacted with any other factors. Performance of the WS group significantly improved with increasing Raven's Colored Progressive Matrices score, $F(1, 17)=8.62$, $p=.01$, $\eta_p^2=.37$. Raven's Colored Progressive Matrices score predicted performance differently according to condition, $F(2, 34)=3.27$, $p=.05$, $\eta_p^2=.16$. This was because the rate of increase in memory score with increasing Raven's Colored Progressive Matrices score became weaker after the first condition. Although marginal, the interaction between Raven's Colored Progressive Matrices score and type of landmark, $F(1, 17)=3.22$, $p=.09$, $\eta_p^2=.16$, was explored. We know from the ANOVA above, that the effect of type of landmark did not interact with group. To emphasize, as a group the participants with WS recalled significantly more junction landmarks than path landmarks, $F(1, 18)=9.14$, $p=.01$, η_p^2 =.34. Analysis of the linear trajectories explores individual differences in this effect. This analysis showed no difference between recall of junction and path landmarks at the beginning of the trajectories, $F<1$, but there was a much steeper trajectory for recall of junction landmarks than path landmarks. This suggests that the main effect of type of landmark was related to increasing Raven's Colored Progressive Matrices score in the WS group, as illustrated in Figure 5.

Figures 4 and 5

Recognition of landmarks. TD and WS groups showed ceiling effects for recognizing landmarks that had been on the correct path, and for new objects, suggesting that any difficulties with recall were not due to a lack of attention to landmarks. Recognition of objects that were on incorrect paths was significantly above chance (50%) ($p<.001$), but not always at ceiling (mean accuracy, non-labeling a: 93%; non-labeling b: 96%; labeling: 95%).

Discussion

We have shown that individuals with WS are able to navigate through virtual environments. This is an important finding for the success of this and future virtual environment research with individuals with WS. Our results demonstrated that with sufficient repetition and experience, individuals with WS can learn a route without making errors. This extends Nardini et al.'s (2008) finding that individuals with WS can use viewer-dependent spatial representations in a table-top task, and shows that route-learning is also possible within this frame of reference.

By categorizing route-learning errors, we found a different pattern of errors in WS, relative to typical development, which we relate below to group differences in inhibitory processes. From the assessment of landmark knowledge we demonstrated that typical children differentiate between junction and path landmarks from at least 6 years and that individuals with WS also show this differentiation. This finding suggests that individuals with WS use landmarks as a cue, as in typical development (Newcombe & Huttenlocher, 2000).

Errors in the learning phase demonstrated that the WS group produced a similar number of errors as TD 6- to 8-year-olds, but that they made a large number of perseverative errors relative to single or consolidation errors. This pattern was not observed in the TD group and by 7 years all error types were observed to a similar extent. To learn a route the participant needed to make an association at each junction between the visual scene information and the correct direction of travel (response learning; Newcombe & Huttenlocher, 2000) for a sequence of six junctions. This association requires a type of binding (Treisman, 1996). The difficulty in WS was not due to a memory limitation in binding ability as such a limitation would have resulted in a large number of consolidation errors. Rather, we suggest that when a visual scene became associated with an incorrect spatial direction, participants had difficulty inhibiting these incorrect bindings across learning trials. The group difference in the number of perseverative errors might therefore relate to group differences in inhibition ability.

Mobbs et al. (2007) and Menghini, Addona, Costanzo and Vicari (2010) showed impaired performance in WS on the Go / No Go inhibition task in which participants press a button in response to all stimuli that appear (e.g., different colored circles), except for one (e.g., a red circle) when they must inhibit responding. Inhibition is also poor in WS when measured by the Opposite World task (Manly et al., 1999) in which the participants is presented with a path of digits (1s and 2s) and must say ‘1’ when they read a ‘2’ and vice versa (Menghini et al., 2010), and a counterpointing task (Atkinson et al., 2003). These results support the notion that in the current study the higher number of perseveration errors in the WS group were due to a difficulty in inhibiting erroneous responses. Nardini et al. (2008) have also suggested weak inhibition as a possible contributor to poor viewer-independent responses by WS in a frames of reference task.

For the TD group, the number of perseverative errors reduced substantially at a micro-developmental level with repeated experience of the task. This was not the case for the WS group. It is possible that the two groups had different strategies for learning because Raven’s Colored Progressive Matrices score was related to error scores in the TD group, but not in the WS group. Jansen-Osmann and Fuchs (2006) define wayfinding behavior as the perceptual-motor learning required to build representations, which is more vulnerable to perseveration errors, and is relatively independent of level of cognitive ability. This would explain the perseveration errors and the lack of a relationship between error scores and Raven’s Colored Progressive Matrices scores, as found in the WS group. It is possible, that while the learning phase was predominantly a measure of wayfinding behavior in the WS group, that the TD group began to form cognitive representations of the landmarks, i.e. landmark knowledge (a feature of spatial knowledge) and used this during this phase to facilitate learning. If this was the case, a contribution from landmark knowledge would result in relatively few perseverative errors and a relatively strong relationship between error scores and Raven's Colored Progressive Matrices score. This was observed in the TD group. Thus, we tentatively suggest that, with repeated experience of the task, during the learning phase the TD group began to rely more on landmark knowledge relative to wayfinding behavior, but that this did not occur for the WS group, at least not to the same extent.

The test phase used recall of landmarks as an index of encoding preferences. That is, we could observe whether participants' cognitive representations of junction landmarks (landmark knowledge) were more salient to participants and thus better remembered than path landmarks. The TD group recalled junction landmarks better than path landmarks and this indicates that they recognized the usefulness of junction landmarks and relied on those more to learn each route than on path landmarks. Jansen-Osmann and Wiedenbauer (2004a) used a similar virtual environment to the one we employed and reported stronger recall of junction landmarks than non-junction landmarks from 7 years of age. In the present study, we showed that children differentiated between junction and path landmarks even earlier, from 6 years, and that the distinction made at 6 years was just as strong as that made by children at 9 years. The current virtual environment and that used by Jansen-Osmann and Weidenbauer (2004) were relatively sparse, whilst Allen et al. (1979), who did not find differential effects of landmarks until 10 years, used a richer real-world environment. Taken together, we suggest that children understand the difference between useful and less useful landmarks from at least 6 years, but that they might not be able to benefit from this in complex environments. This is an issue for future research because it has implications for the success of using landmark knowledge training with young children.

As a group, landmark recall performance of the WS participants did not differ from that of 6- to 8-year-old TD children, but was below the 9-year-old level. This demonstrates that individuals with WS do form cognitive representations of the landmarks in an environment when learning a route. WS recall ability was positively related to level of non-verbal ability. While both groups showed a distinction between junction and path landmarks when assessed at a whole group level, marginal evidence showed that this was consistent across development for the TD group, but emerged with increasing non-verbal ability in WS. Thus at the lower levels of non-verbal ability individuals with WS did not differentiate between junction and path landmarks, but by higher levels of non-verbal ability, individuals with WS group showed a typical pattern of stronger memory for junction than path landmarks. This difference in patterns across the groups is despite the same range of Raven's colored progressive matrices scores for WS and TD groups. The poor recall of landmarks at relatively immature levels of non-verbal ability for the WS group, suggests that individuals with WS with relatively poor non-verbal ability learn a route with little input from landmark knowledge (a feature of spatial knowledge; see Jansen-Osmann & Fuchs, 2007) and might use a wayfinding strategy which relies more on the sequence of turns than the landmarks themselves. Thus, whilst Lakusta et al. (2010) demonstrated that individuals with WS can use landmarks to spatially orient, our results demonstrate that this ability is dependent on the maturity of each individual's non-verbal abilities.

The prediction for the WS group in relation to visual-object and visual-spatial memory in the test phase was not supported; visual and spatial landmark properties were encoded to a similar extent by WS and TD groups. Although Vicari et al. (2005, 2006) report weaker visual-spatial than visual-object memory in WS, Jarrold et al. (2007) and O'Hearn et al. (2009) found no difference between these two memory types in WS. The lack of consistency across studies suggests that memory ability in WS is sensitive to differences in task demands. The current task differs from previous tasks in that participants were not explicitly asked to commit the landmarks and their properties to memory. Further research is required to elucidate the nature of visual and spatial memory in WS.

In the final condition, the experimenter verbally labeled the landmarks when demonstrating the route. To avoid carryover effects, this condition had to be administered last. Because this fixed order introduced the possible confound of practise effects, improvement that was unique to practise was measured by including two non-labeling conditions. For the learning phase, the improvement in learning across conditions was best explained by a linear improvement across all three conditions indicating that the improvement in performance reflected practise, and verbal labeling did not impact learning. At the test phase, recall did not differ across conditions, which also indicates that verbal labeling did not facilitate memory performance. These findings contrasts to the benefits of verbal labeling observed in our real-world study (Farran et al, 2010). The only salient features of the virtual environments were the 16 landmarks, 8 of which were on the correct route, and so it is likely that each landmark on the correct route was spontaneously attended to by participants. The ceiling recognition memory scores for landmarks support this. In the real-world study (Farran et al., 2010) the environment was rich with numerous potential landmarks of varying levels of salience and so verbal labeling also served to select an appropriate subset of salient landmarks to facilitate route-learning. Comparing the two studies indicates that verbal labeling in the real-world might reduce cognitive load by highlighting salient information. Investigation using virtual environments with sparse versus rich information could explore this hypothesis.

Typical route-learning studies use just one virtual environment. By using three different virtual environments we were able to demonstrate micro-development of route-learning ability across different virtual environments and routes in both TD and WS. We suggest that a route-learning strategy developed with experience, which participants transferred from one condition to the next. The strategy was related to learning the route only, as landmark knowledge was consistent across VEs. This distinction supports Jansen-Osmann and colleagues' distinction between wayfinding behavior and spatial knowledge. They report that the use of color and symmetry in a virtual environment affects wayfinding behavior, but not spatial knowledge (Jansen-Osmann, Schmid & Heil, 2007; Jansen-Osmann & Wiedenbauer, 2004b). In our study, we suggest that binding ability, i.e. the ability to associate visual scene information with spatial direction information, is learnt across conditions and that the TD group, but not the WS group, also learned to inhibit erroneous responses (perseverative errors) across conditions for this group. Thus, with practice, wayfinding behavior becomes more efficient, such that equally sufficient cognitive representations (spatial knowledge) can develop with progressively less experience of each new environment. This unexpectedly rapid improvement in route-learning ability across conditions and therefore different routes is an important finding as it suggests that route-learning strategies can develop within one route, with the expectation that participants will be able to transfer this strategy to their route-learning abilities to other virtual environments (and also to the real world). This suggestion is supported by previous studies who have successfully achieved this goal (Montello et al., 2004; Ruddle et al., 1997; Waller et al., 2002; Wilson, 1997).

In summary, route-learning in WS is hampered by a high frequency of errors relative to typical participants with the same level of non-verbal ability. These errors can be accounted for by WS difficulty in inhibiting previously made erroneous responses. TD children from 6 years distinguish between junction and path landmarks. For the WS group this distinction emerged with increasing maturation in non-verbal ability. In the current study, geometric knowledge, or viewer-independent spatial representations were not assessed. The impairments reported by Lakusta et al. (2010) and Nardini et al. (2008), as well as in Farran et al., (2010) predict that, when navigating an environment these individuals would not be able to determine short-cuts, or point in the direction of landmarks that are not directly visible. This could be investigated by exploring the understanding of spatial relationships between places within a virtual environment in WS.

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Table 1

Participant details for Williams syndrome (WS) and typically developing (TD) groups: Chronological age (CA), British Picture Vocabulary Scale (BPVS) raw scores and Raven's Colored Progressive Matrices (RCPM) raw scores.

	CA in years; months	BPVS raw score	RCPM raw score
	Mean (standard deviation; range)		
WS	22;04 (9;00, 11;01-41;05)	96.32 (18.82; 73-142)	17.16 (4.67; 10-26)
TD 6 years	6;03 (0;04, 5;10-6;09)	52.40 (11.84; 39-73)	17.40 (6.24; 9-32)
TD 7 years	7;05 (0;03, 7;00-7;09)	61.40 (8.26; 49-73)	21.40 (4.03; 15-28)
TD 8 years	8;02 (0;02, 7;11-8;06)	73.70 (13.3; 51-95)	25.30 (2.54; 23-30)
TD 9 years	9;06 (0;04, 9;00-9;11)	87.50 (20.64; 60-127)	26.30 (6.82; 12-36)

Table 2

Total number of learning trials and total number of errors for William syndrome (WS) and typically developing (TD) children by condition presented as group means (standard deviations in parentheses)

		condition		
		Non-labeling a	Non-labeling b	labeling
	Group	Mean (standard deviation)		
Total number of learning trials	WS	6.26 (2.88)	5.00(2.31)	5.15(1.74)
	TD	5.43(2.21)	4.88(1.99)	3.75(1.56)
Total number of errors	WS	8.42(7.05)	5.74(5.06)	4.63(3.24)
	TD	5.38(4.02)	4.13(3.35)	2.01(1.95)

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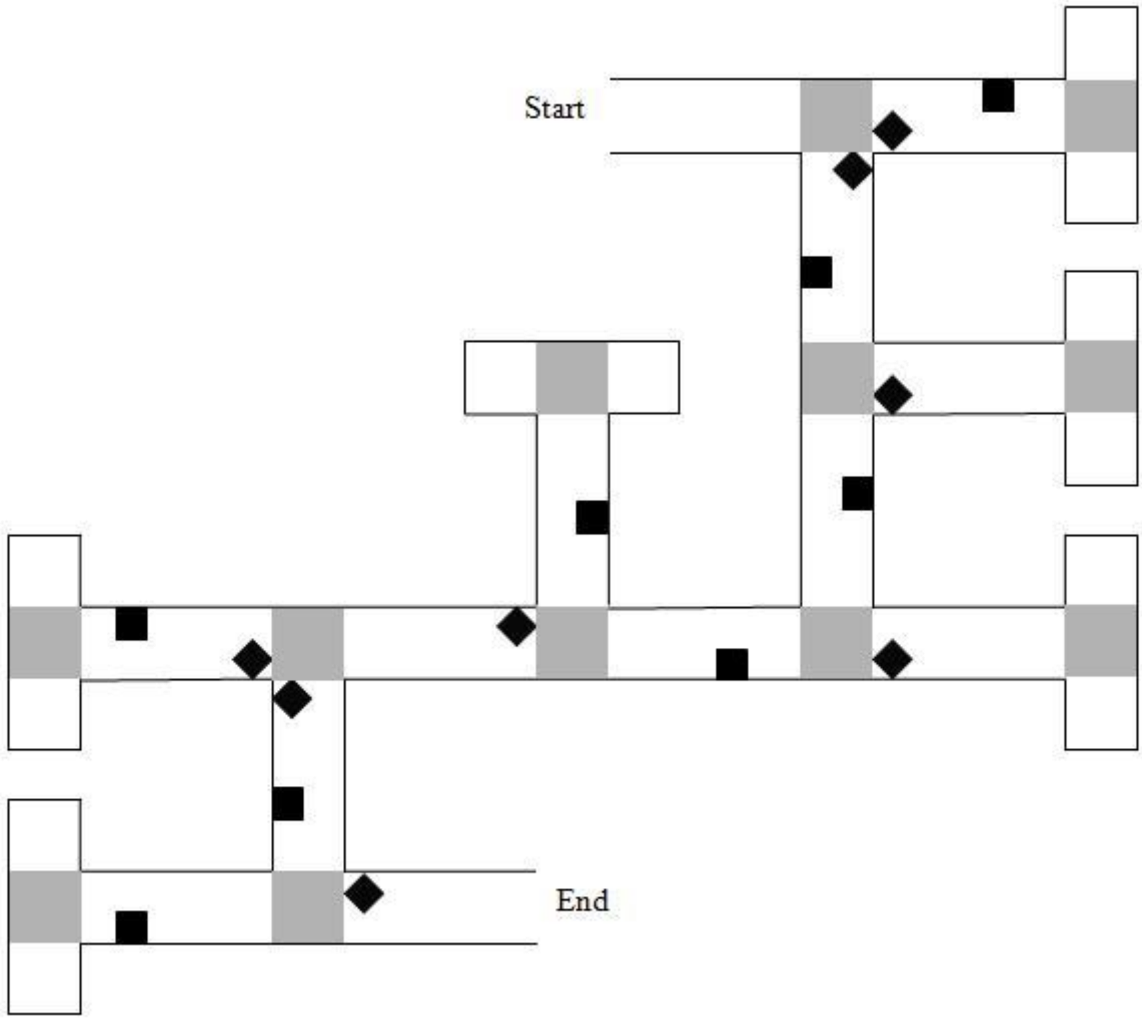
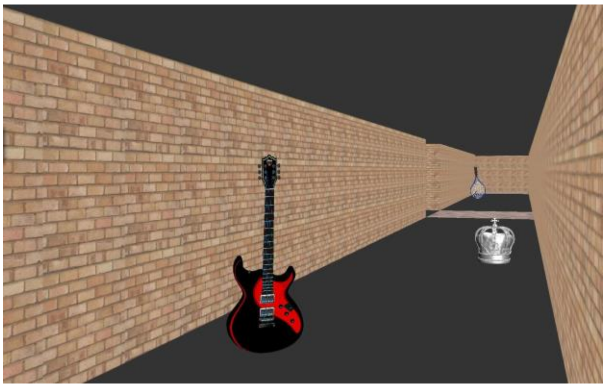
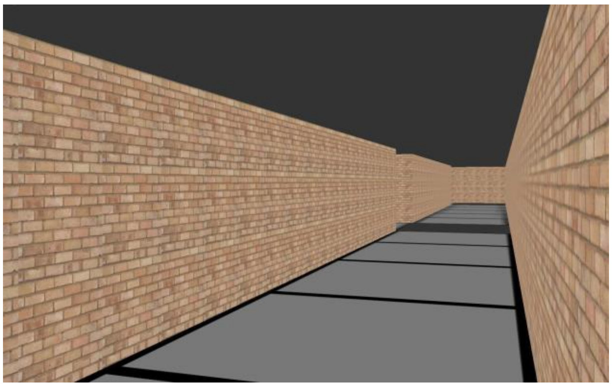


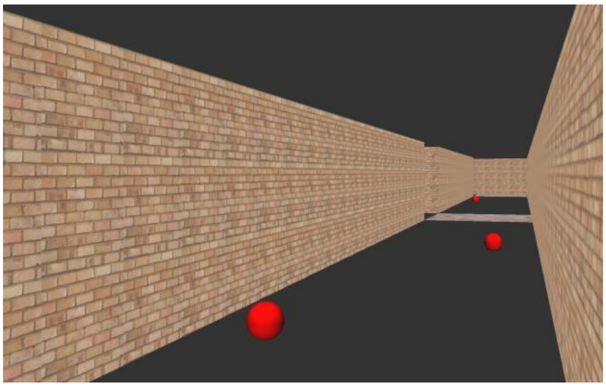
Figure 1. A map of a virtual environment maze layout. Grey squares on route represent 'pebble' texture which featured at junctions and at the end of cul-de-sacs. Black diamonds indicate junction landmarks. Black squares indicate path landmarks.



a. learning phase



b. test phase 1: recall of landmark location



c. test phase 2: recall of landmark identity

Figure 2. A view of a virtual environment during learning trials (a) and at each test phase (b and c).

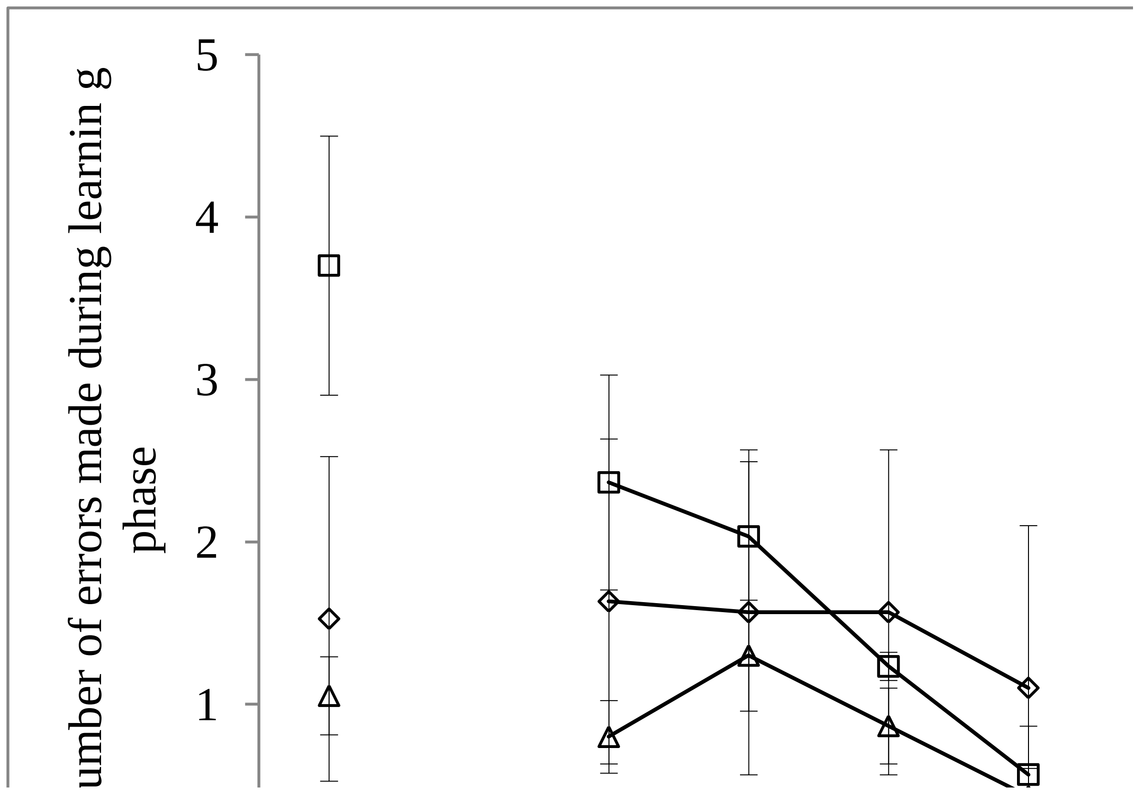


Figure 3. Mean number of errors made during learning phase, collapsed across condition.

Error bars represent standard error.

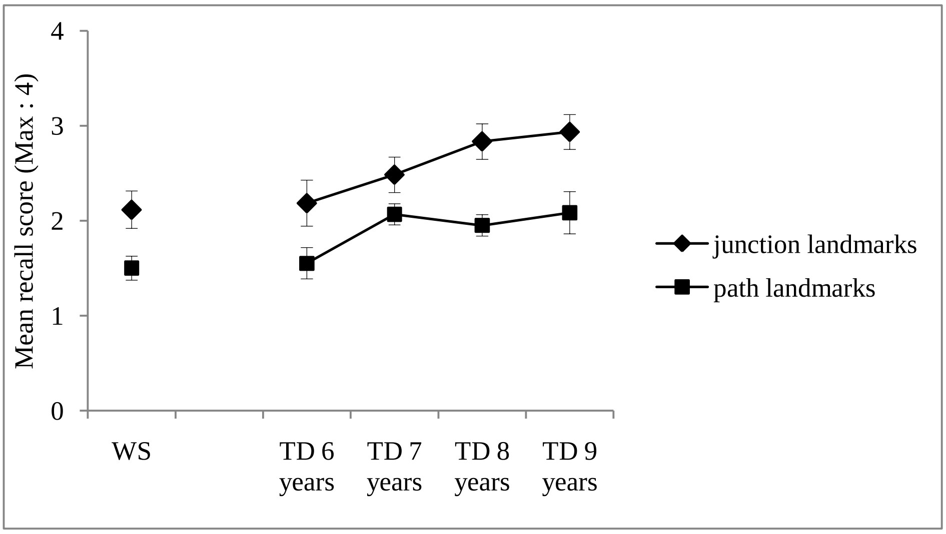


Figure 4. Mean number of junction and path landmarks correctly recalled during test phase. Error bars represent standard error.

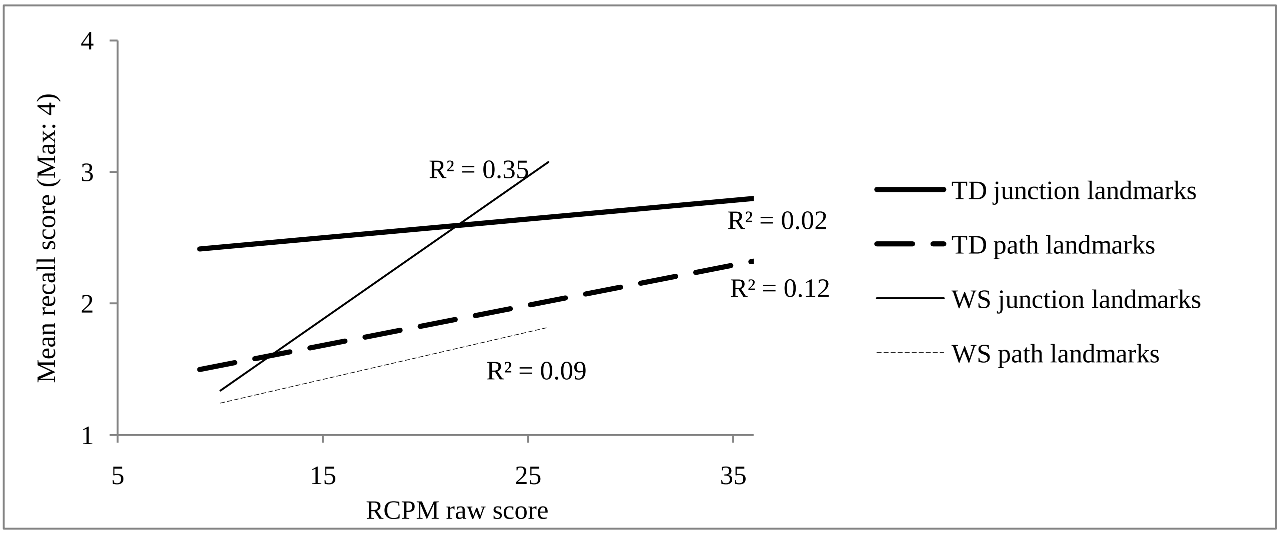


Figure 5. WS and TD trajectories of the mean number of correctly recalled junction landmarks and path landmarks when plotted against Raven's Colored Progressive Matrices (RCPM) raw scores.