Route-learning strategies in typical and atypical development; eye tracking reveals atypical landmark selection in Williams syndrome.

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Abstract

Background: Successful navigation is crucial to everyday life. Individuals with Williams Syndrome (WS) have impaired spatial abilities. This includes a deficit in spatial navigation abilities such as learning the route from A to B. To-date, to determine whether participants attend to landmarks when learning a route, landmark recall tasks have been employed *after* the route learning experience. Here, we combined virtual reality and eye tracking technologies, for the first time, to measure landmark use in typically developing (TD) children and participants with WS *during* route-learning. Method: Nineteen individuals with WS were asked to learn a route in a sparse environment (few landmarks) and in a rich environment (many landmarks) whilst their eye movements were recorded. Looking times towards landmarks were compared to typically developing (TD) children aged 6, 8 and 10 years. Changes in attention to landmarks during the learning process were also recorded. Results: The WS group made fewer looks to landmarks overall, but all participants looked for longer at landmarks that were at junctions and along the paths of the maze than landmarks that were in the distance. Few differences were observed in route learning between the sparse and rich environments. In contrast to the TD groups, those in the WS group were as likely to look at non-unique landmarks as landmarks at junctions and on paths. Discussion: The current results demonstrate that attention to landmarks during route learning reflects the types of landmarks remembered in memory tasks, that individuals with WS can learn a route if given sufficient exposure, but that this is accomplished within the context of an impaired ability to select appropriate landmarks.

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Introduction

Our ability to navigate successfully in large-scale space is crucial to everyday living (Rissotto & Giuliani 2006). Navigation skills enable one to, for example, travel to work or find your classroom and to re-orient if lost. In childhood, these skills are vital for developing independence. Developmentally, three stages of route learning have been proposed (Siegel & White 1975). The first stage involves knowledge of the landmarks along a route (landmark knowledge). This is followed by route knowledge, in which an individual can find their way from A to B by following a fixed sequence of turns, using landmarks as reference points. The final stage involves understanding the spatial relationships between places within an environment or configural knowledge. Configural knowledge is more flexible than route knowledge when navigating as it allows for short cuts and to re-orient when lost (Siegel & White 1975; also see Chrastil 2013). Whilst this theory remains a useful framework, it is now realised that landmark knowledge and route knowledge develop in tandem, rather than as sequential stages (Montello 1998).

To-date, landmark use has usually been assessed by measuring memory (recall/ recognition) of landmarks after a route-learning experience. Although this is a valid method, it relies on the assumption that variations in participants' memory for landmarks are a reliable index for variations in landmark use during route learning. Eye movements have been argued to be an overt indicator of what information is being attended to and thus can provide insight into the cognitive strategies employed by individuals during a certain task (Ballard et al. 1997). In this study, for the first time, we combined the use of virtual environments (VEs) with eye tracking to assess attention to landmarks during the learning process itself in both typical developing (TD) children and participants with Williams syndrome (WS).

Landmarks can be categorised as proximal landmarks, which feature on the route itself, or distant landmarks. From 6 years, TD children have stronger recall of proximal landmarks that feature at junctions (junction landmarks) than those that do not (path landmarks) on account of their relative usefulness for route learning (e.g. Farran et al. 2012). The use of distant landmarks emerges later (7-10 years; Bullens et al. 2010), and is useful for the development of configural knowledge (Broadbent, Farran & Tolmie 2014). The current study did not require configural knowledge of the environment for successful task completion, and thus distant landmarks were relatively less useful than proximal landmarks. The current study explored whether the pattern of landmark use as indicated by memory tasks is replicated when measured using eye tracking.

We were interested in route learning in TD children, but also in Williams syndrome (WS), a genetic disorder in which, within the context of moderate learning difficulties, visuo-spatial abilities are impaired relative to verbal abilities (Mervis et al. 1999). Studies have reported behavioural impairments in route learning in WS (Broadbent et al. 2014; Farran et al. 2010; 2012a,b), as well as neural impairments in the hippocampus (Meyer-Lindenberg et al. 2004), an area associated with navigation in typical adults (Burgess 2008). Nardini et al. (2008) reported poor use of landmarks to locate a hidden object in WS in a small-scale task. Recall of landmarks immediately after a route-learning task in a VE is poor but shows a typical pattern (Farran et al. 2012a). This begs the question as to whether participants with WS can use proximal landmarks in a typical way, but only for those landmarks that they have actually attended to. Purser et al. (2015) demonstrated that participants with WS could learn a 6-turn route with three distant landmarks only. However, whilst TD 5- to 11-year-olds showed a detriment in the distant landmark only condition relative to conditions with 16 proximal landmarks only, this impairment was not evident in the WS group, which is suggestive of atypical landmark use in WS. Both Purser et al. (2015) and Broadbent et al. (2014), who also used distant landmarks only, suggest that their WS group were using a visual recognition view-matching strategy in which they evaluate whether the visual scene (including landmarks) had been seen before and is part of the correct route, rather than pairing a landmark with a directional decision (e.g. turn left after the bench).

Previous studies of participants with WS and TD children have mainly focused on VEs with relatively few landmarks. Real-world environments are rich in potential landmarks and one has to determine which landmarks are most useful to learning a route. The current study examined looking behaviours to landmarks in both sparse and rich environments. In addition to junction and path landmarks, the rich environment included a non-unique landmark (a dustbin) that featured numerous times and therefore was not useful for navigation. In addition to these proximal landmarks, distant landmarks featured around the periphery of the environment.

We predicted that, with increasing age, TD children would: 1) require fewer learning trials to learn the route; 2) show increased attention to landmarks; 3) that time spent looking at landmarks would increasingly differentiate usefulness (junction>path>non-unique); 4) that attention to distant landmarks would be minimal and evident in older children only; and that 5) strategy efficiency would develop over repeated trials. The direction of any effects of route learning in a sparse compared to a rich maze was difficult to predict. One could argue that an increase in visual information (the rich environment) is conducive to stronger encoding of the route due to the salience and uniqueness of each path, and thus route learning would be stronger in a rich than a sparse environment. Or, that a rich environment increases the attentional and cognitive demands required to learn the route and thus route learning would be weaker in a rich than a sparse environment.

With reference to the WS group, previous eye tracking studies have shown that participants with WS show atypical attention and scanning patterns and that this atypical looking pattern is stronger for complex compared to simple stimuli (Hoffman et al. 2003; for a review see Van Herwegen 2015). Thus, we tentatively predicted that: 1) the increased attentional demands of the rich environment might be detrimental to performance in the WS group, relative to the sparse environment. We also predicted that the WS group would: 2) take longer to learn each route than at least the oldest TD children; 3) but that, based on previous studies, the pattern of looking to junction and path landmarks would be typical in the sparse maze. With reference to distant landmarks, we know that individuals with WS can use distant landmarks (Broadbent et al. 2014; Purser et al. 2015), but we do not know whether the weighting of these landmarks relative to proximal ones is any different from the typical population. Given that distant landmarks are only used in the typical population from seven years of age, we predict: 5) minimal attention to distant landmarks in WS. Attention to non-unique landmarks provided an index of whether individuals with WS are able to select appropriate landmarks. If individuals with WS can select appropriate landmarks, we predict: 6) minimal attention to non-unique landmarks in this group.

Method

Participants

Participants with WS (N = 19) were recruited from the WS Foundation (UK). All participants received genetic and phenotypic diagnosis of WS. Two participants with WS were excluded from the analyses as their glasses reflected and no eye movements could be recorded and one participant with WS withdrew due to fatigue. In total, sixteen WS participants took part (aged 14 to 48 years; Table 1). Seven of this group had participated in one (N=4) or two (N=3) different navigation studies within the previous 12 months. As the design of these previous studies differed (distant landmark use only / assessment of configural knowledge), we were confident of minimal interference or practice effects on performance in the current study. Thirty-two TD children took part (6 year-olds: N=10; 8 year-olds: N=10; 10 year-olds: N=12). This age range was chosen because the verbal and non-verbal ability of the WS group, measured using the British Picture Vocabulary Scales III (BPVS: Dunn & Dunn 2009) and the Raven's Coloured Progressive Matrices (RCPM: Raven 1993), would fall within the ranges of these TD groups. For the RCPM, the WS group performed similarly to the 6-year-olds, while for BPVS performance was comparable to the 8-year-olds ($p > .05$ for both) (Table 1). Although the groups differ by chronological age and thus level of experience with route learning, based on previous studies, we do not predict an experience related advantage in WS.

Table 1

Design and Procedure

Virtual environments (VEs) were created using Vizard (http://www.worldviz.com) (see Figure 1 for screenshots). Eye tracking was measured using Tobii T120 presented on a 17 inch LCD monitor set to a resolution of 640*480.

The binocular eye-tracker sampled the position of the participant’s eyes at the rate of 120 Hz.

Each VE was a brick wall six-junction maze. Two maze layouts (A and B) were used (Figure 2). At each junction there were two paths, a correct path that led to the next section of the maze and an incorrect path that led to a dead end. The correct route involved two left, two right and two straight ahead decisions at junctions, the order of which varied across maze A and B.

Table 2, Figures 1 and 2

Participants were presented with either rich maze A and sparse maze B, or rich maze B and sparse maze A (counterbalanced). Different landmarks were used for maze A and maze B, with landmark membership in each proximal category (path or junction) counterbalanced across the two maze As and the two maze Bs.

Landmarks were chosen from categories that are familiar to children (see Table 2 for a list of landmarks used). Our priority was that all landmarks were distinct and recognisable to the participants, hence it was necessary to use objects that were not ecologically valid. Item by item analysis demonstrated that this did not present the problem of any of the groups selectively ignoring any particular class of object (e.g. objects that move in the real world). Landmarks were located adjacent to junctions (junction landmarks), along paths (path landmarks) or outside of the maze walls (distant landmarks). Proximal landmarks were distributed equally on correct and incorrect paths and to the left and right side of the path. Sparse mazes contained 11 landmarks (4 junction, 4 path, 3 distant). Rich mazes contained 42 landmarks (14 junction, 14 path, 8 non-unique, 6 distant). The non-unique landmark in the rich mazes (a grey bin) appeared eight times (4 path, 4 junction).

Participants were seated 60cm from the computer monitor within a quiet room. A nine-point calibration was completed at the start of each maze. Participants viewed a dynamic presentation (a video) of the correct route through each maze from start to finish. Following this presentation, participants took part in learning trials in which they viewed a video of the same route, but the video stopped at each junction (N=6). Participants were then asked “Which way do we go now?”. To avoid directional errors (Landau & Hoffman 2005), participants responded by pointing to the screen to indicate the direction of the route, rather than verbally responding. Feedback was given (i.e. “well done, that’s correct” or “good try, but we went this way”) and the video presentation continued along the correct route to the next junction / the end of the route. Learning trials were repeated to a criterion of two consecutive error-free learning trials or until a maximum of 10 learning trials had been completed.

Participants’ ability to recognise each landmark was measured using a sparse and a rich landmark recognition task. This was presented immediately after the participant had completed each route-learning task. In the sparse recognition task, images of 22 landmarks (11 landmarks, 11 novel landmarks) were presented in a fixed random order. In the rich maze 70 landmarks (35 landmarks, 35 novel landmarks) were presented in a fixed random order, which included one presentation of the non-unique landmark. Participants were told that they would be shown some pictures of objects, and to verbally respond (“yes” or “no”) to each object as to whether they had seen it in the maze that they had just completed. Participants completed RCPM and BPVS tasks in between the mazes.

Ethics committees of the universities of the first and last author approved this study. Written consent was obtained from the adults and parents and verbal assent was obtained from all children.

Results

Behavioural Analysis

Learning Phase

The TD groups made very few errors. It is possible therefore that ceiling effects are reducing variation in the TD behavioural data. Two dependent variables were measured: the number of learning trials required to reach criterion (not including the two zero-error criterion trials) and an arguably more sensitive measure, the cumulative number of errors made across those learning trials. Two two-way ANOVAs were conducted with Maze Type (sparse, rich) and Group (WS, TD6, TD8) as factors. Both ANOVAs showed the same pattern. There was an effect of Group (Learning trials: $F(3,44) = 11.07$, $p < .001$, $\eta_P^2 = .43$; Errors: $F(3,44) = 9.97$, $p < .001$, $\eta_P^2 = .41$. For both ANOVAs: WS> all TD groups: Tukey, $p < .05$ for all; no differences across the TD groups: Tukey, $p > .05$ for all) (Table 3). For both ANOVAs there was no effect for Maze Type (Learning trials: $F < 1$; Errors: $F(1,44) = 1.64$, $p = .21$, $\eta_P^2 = .04$) or interaction between Maze Type and Group ($F < 1$ for both ANOVAs).

Recognition tasks

The proportion of correct responses was calculated for the junction, path and distant landmarks separately, whilst for the unique landmark participants received a score of 0 or 1 (Table 4). Proportion correct was first compared to chance performance of 0.50 using one-sample t-tests. This demonstrated that the recognition task in the Rich maze was too difficult. With the exception of the TD 10-year-olds who could recognise non-unique landmarks (p<.05), performance was either at chance (p > .05) or demonstrated a 'no' response bias (WS group only, for distant and path landmark recognition, p < .05). A 'no' response bias indicates that the rich maze contained more landmarks than could be attended to and/or committed to (recognition) memory, and thus participant awareness that they were unlikely to recognise each presented landmark. Performance was above chance for the Sparse maze, with the exception of distant landmarks for all groups (TD groups: p>.05; WS group: p<.05 ['no' response bias]), and the junction landmarks for the WS group (p=.06).

Due to poor performance on the Rich maze, ANOVA was carried out on the Sparse maze data only, with Landmark Type as a within participant factor and Group as a between participant factor. There was a main effect of Group, $F(3, 44)=4.86$, $p=.01$, $\eta_p^2=.25$ (WS< all TD groups: Tukey, p<.05 for all), with no differences in recognition across the TD groups (Tukey, p>.05 for all). The main effect of Landmark Type, $F(2, 88)=31.73$, $p<.001$, $\eta_p^2=.42$ was due to weaker recognition for distant than junction and path landmarks (p<.05 for both), but no differentiation between junction and path landmarks (p>.05). The interaction between Landmark type and Group was not significant, F<1.

To determine whether there was a relationship between the number of times a participant experienced the maze and their ability to recognise the landmarks, correlational analyses were carried out between the number of learning trials required to learn each maze with the corresponding landmark recognition score for each maze, for each group. This demonstrated no significant correlations (p>.05 for all). This demonstrates that landmark recognition is not related to the amount of exposure to those landmarks.

Eye tracking

Landmarks were coded as visible when more than 50% of the object was visible (non-occluded by other landmarks or junctions). Eye movements were mapped by integrating a log of the eye-movement data and of the locations of landmarks generated using MATLAB, which was used to define dynamic areas of interest (dAOIs). Standard fixation filters do not work well with dynamic stimuli due to their inability to separate fixations from smooth pursuit (tracking) eye-movements (Holmqvist et al. 2011). Consequently, we report time spent in dAOI based on matching the raw (x,y) coordinates of the gaze to the coordinates of the moving AOI.

Frequency of looks

The data was coded binomially in terms of whether a participant looked at a landmark. Since different pathways had a different number of visible landmarks, a proportional frequency of looks was calculated for each category. Given that looks to landmarks on the correct path are most informative, ANOVAs were only carried out for landmarks on the correct route as well as the distant landmarks.

ANOVA of Group (6 years, 8 years, 10 years, WS) by Landmark Type (path, junction, distant) by Maze Type (rich, sparse) by Time (first learning trial, last learning trial) revealed a main effect of Group, $F(3, 44)=3.72$, $p=.02$, $\eta_p^2=.20$ due to fewer looks by the WS group than the 6-year-olds ($p=.01$) and 10-year-olds ($p=.001$) (Figure 3). There was a main effect of Maze Type, $F(1, 44)=22.92$, $p<.001$, $\eta_p^2=.34$ due to more looks at landmarks in the sparse maze than the rich maze. This is not surprising given that this is proportional data; it does not reflect fewer looks to landmarks in the rich maze in absolute terms. There was a main effect of Landmark

Type, $F(2, 88)=144.24$, $p<.001$, $\eta_p^2 = .77$, which also interacted with Maze Type, $F(2, 88)=34.47$, $p<.001$, $\eta_p^2 = .44$ (Figure 4). Overall, participants looked less frequently at distant landmarks than the other two landmark types ($p<.05$ for both); however, there was a difference between junction and path landmarks (path > junction, $p<.05$). This was driven by the rich maze only (path > junction > distant; $p<.001$ for all), whilst in the sparse maze, distant landmarks were looked at less frequently than path and junction landmarks ($p<.001$ for both), with no difference between path and junction landmarks ($p=.17$). There was also an interaction of Landmark Type by Maze Type by Time, $F(2, 88)=3.33$, $p=.04$, $\eta_p^2 = .07$. This demonstrated that learning was evident, although marginally, for distant landmarks in the sparse maze, $F(1, 44)=3.86$, $p=.056$, $\eta_p^2 = .08$, and for path landmarks in the rich maze, $F(1, 44)=3.90$, $p=.054$, $\eta_p^2 = .08$, due to higher frequency of looks in the final trial compared to the first trial.

There were marginal interactions of Group by Time, $F(3, 44) = 2.74$, $p=.055$, $\eta_p^2 = .16$ and Group by Landmark Type, $F(6, 88)=1.92$, $p=.087$, $\eta_p^2 = .12$. The Group by Time interaction showed that the TD 10-year-olds were the only group to show overall learning from the first to last trial (TD10, $F(1, 11=11.52$, $p=.01$, $\eta_p^2 = .51$; TD6, TD8 and WS: $F<1$). The Group by Landmark Type interaction demonstrated that the main effect of Group was predominantly driven by distant landmarks (junction landmarks, $p=.27$; path landmark, $p=.06$ [WS<TD6, $p=.095$]; distant landmarks, $p<.001$ [WS<TD6, TD8, TD10]). The main effect of Time was non-significant, $F<1$. All other interactions were non-significant: Group by Maze Type by Time, $F(3, 44)=1.34$, $p=.27$, $\eta_p^2 = .08$; all other interactions, F<1.

To determine the frequency of looks to non-unique landmarks in the rich maze relative to other landmark types, another ANOVA was carried out for the rich maze only with four Landmark Types. The main effect of Landmark Type remained, F(3, 132)=27.55, p<.001, η_p^2=.39, with non-unique landmarks looked at as frequency as distant landmarks (p=.28), and less frequently than path and junction landmarks (p<.001 for both). The Group by Landmark Type interaction became significant, F(9, 132)=2.27, p=.02, η_p^2=.13. The TD6 and TD8 year olds showed a linear progression with more looks to path landmarks, followed by junction landmarks (p<05), followed by unique and distant landmarks (p<.05) which were looked at to a similar extent (p>.05). The TD10 year olds showed the same pattern, with the exception of no differentiation between path and junction landmarks (p>.05) (path = junction > distant = non-unique). However, the WS group looked at non-unique, path and junction landmarks to the same extent (p>.05 for all) and significantly more than distant landmarks (p<.05 for all). All other interactions with Landmark Type were non-significant (Landmark Type by Time, F(3, 132)=2.19, p=.09, η_p^2=.05; Landmark Type by Time by Group, F<1).

Figures 3 and 4

Looking patterns

It is possible that participants did not use the landmarks to navigate. This would be reflected in their looking time to areas of the screen where objects did not feature. We calculated the mean time spent looking at landmarks and non-landmark areas of the screen across all exposures to the maze (viewing the video, and all learning trials) for each participant (Table 5). ANOVA of Group by Looking type (landmark vs. non-landmark) by Maze type revealed a significant main effect of Looking type, F(1, 50)=117.50, p<.001, η_p^2=.70, and a main effect of Group, F(3, 50)=3.27, p=.03, η_p^2 =16. These two Factors interacted with one another, F(3, 50)=5.71, p=.002, η_p^2 =.26. To unpack this, all Groups looked at the non-landmark areas more than the landmark areas. This is understandable given that we used raw x, y coordinates to accommodate the dynamic nature of our stimuli, and that a higher proportion of the screen displayed non-landmark information than landmarks. However, of interest, the WS group spent more time looking at non-landmarks than the TD6 and TD8 years olds (F(3, 50)=4.33, p=.01, η_p^2 =.21 [Tukey, WS>TD6 and TD8, p<.05; all other comparisons, p>.05]), but there was no Group difference for looking time to landmarks, F<1. To explain further, the WS group spent proportionally more time looking at non-landmarks than landmarks, when compared to the pattern of the majority of the TD children; this could suggest an atypical strategy in WS. All other main effects and interactions were non-significant: Maze type by Looking type, F(1, 50)=1.64, p=.21, η_p^2 =.03; Maze type, Maze type by Group; Maze type by Group by Looking type: F<1 for all.

Tables 4 and 5

Discussion

All participants were able to learn routes in a small number of trials, but the WS group required significantly more trials and made more errors, even compared to TD 6-year-olds. This is surprising given previous findings that route learning is typically at or above the 6-year-old level in WS (Farran et al. 2012a,b). This most likely reflects the superior performance of the TD children, relative to previous studies, caused by the immediate feedback provided at decision points in the current study. In previous studies, participants did not discover their error until they reached a cul-de-sac or dead-end. This difference in TD performance across studies in itself was surprising and points towards an immediate feedback strategy for teaching route knowledge in the typical population. Indeed, this method rendered the task too easy to differentiate differences in absolute performance across TD groups. The WS group may not have benefited from this difference in feedback on account of the characteristic impaired memory associated with this group (Vicari et al. 2006). Even if the WS group could benefit from immediate feedback, the passive presentation in the current study prevented participants from looking down each path at junctions and using a view-matching decision making strategy, the preferred strategy for individuals with WS in active navigation tasks (Broadbent et al. 2014, Purser et al. 2015). Thus, participants were forced to rely on the information preceding the junction to make their decision, which could have hindered the WS group.

No differences were observed in the ability to learn a route in rich versus sparse environments, and there was little evidence from the eye tracking data of differences in strategy-use between the two maze types. This suggests that participants were equally able to select the required information to attend to in the rich maze as in the sparse maze. Thus, for the WS group, despite evidence from previous studies of a negative impact of task complexity on looking patterns (Hoffman et al. 2003), in this study for both the TD and WS groups, there was no evidence of a negative impact of the increased attentional demands of the rich maze, with reference to their ability to learn the route.

Participants’ recognition memory for landmarks was hindered by poor performance in the rich maze. For the sparse maze, recognition memory and eye tracking data largely mirrored one another. That is, distant landmarks were looked at less frequently and were not easily recognised, relative to proximal landmarks on paths or at junctions. The consistency across recognition memory and eye tracking data is encouraging and suggests that memory measures (as used in most previous studies) are a valid measure of attention to landmarks. Furthermore, the eye tracking data enabled a richer picture of online processing whilst learning a route, and uncovered group differences that would not have been possible to determine from behavioural data alone. We unpack group differences and similarities below.

Eye tracking data indicated that the WS group looked at fewer landmarks during the trials overall and (presumably as a consequence) recognised fewer landmarks in the subsequent memory test. This could also explain the 'no' response bias for some landmark types in the recognition tasks, which was specific to the WS group. One could argue that looking at fewer landmarks relates to attentional mechanisms, but this does not sit well with data that indicates that selective attention in WS is at the level expected for their mental age (Breckenridge, Atkinson & Braddick, 2012). Individuals with WS are purported to have a local or featural processing style for some types of spatial tasks (see Farran & Jarrold 2003). Reduced attention to distant landmarks in the WS group fits with this hypothesis, and suggests that when the WS group were attending to landmarks, they rarely focussed their attention beyond the route itself (although see Purser et al. 2015). Furthermore, our data suggests that the strategy of using landmarks as a facilitator to route learning might not have been as strong as in the TD group; the WS group spent more time looking at areas of the screen that did not contain landmarks than the two youngest TD groups.

A further differentiation between the WS and TD groups relates to the profile of looks to each category of landmarks. With reference to path, junction and distant landmarks, all groups showed a similar pattern of fewer looks to distant landmarks than junction and path landmarks. This suggests that, although individuals with WS might not be as reliant on proximal landmarks as TD children (Purser et al. 2015), they nevertheless show a typical preference towards proximal over distant landmarks when they are presented within the same VE. This pattern is also consistent with previous research and was predicted based on the age of our TD participants (Bullens et al. 2010), and reflects an efficient strategy for the development of route knowledge. Interestingly, and in contrast to the TD groups, the WS group did not appear to recognise that it was not strategically effective to look at the non-unique landmarks, i.e. the bin that featured on every path. This is reminiscent of Courbois, Blades, Farran and Sockeel (2012) who demonstrated that individuals with learning difficulties selected significantly more non-unique landmarks as useful during a real-world route experience, than chronological age matched TD participants. Thus, this behaviour may not be specific to WS, but relate to learning difficulties in general.

The use of eye tracking also enabled us to assess the development of an effective looking strategy across trials. We compared participant's performance in the first and last trials. This did not reveal any learning in the WS group. However, this was similar to most of the TD groups; the exception being the TD 10-year-olds who looked at more landmarks in the final trial relative to the first trial. Given the proficiency of this group (<1 error across trials), it is unlikely that this reflects any change in strategy, but perhaps reflects changes in the availability of attentional resources once the route had been committed to memory.

In summary, the current study shows that in TD children attention to landmarks during route learning reflected the types of landmarks remembered in recognition tasks, which confirms that memory tasks are a valid way of accessing attention to landmarks. Consistent with previous studies, the WS group demonstrated the ability to acquire route knowledge. Still, their atypical looking pattern to non-unique landmarks suggests that this group have not fully developed the capacity to select appropriate landmarks. This is important in real-world environments, which often have a larger number of landmarks and thus the selection of appropriate landmarks is particularly crucial to navigating the environment. Or course, our VEs are less complex than any real-world environment. However, evidence that VEs tap into the same cognitive mechanisms as real-world environments (Richardson et al., 1999) suggest that we can be confident that our findings can translate to the real world. Finally, individuals with WS looked at fewer landmarks, particularly distant landmarks. Fewer looks to distant landmarks is not detrimental to this task, as configural knowledge is not required; one could even argue that is strategic. Further research could investigate whether a similar pattern would be observed in a task where configural knowledge is required, in an effort to determine why configural knowledge is so difficult to acquire in WS (Farran et al. 2015).

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Table 1: Participant details

Group	Chronological age (years; months)	BPVS raw score	RCPM raw score
WS (N = 16)	27;2 (0;9, 14;5-47;11)	118.38 (20.72, 70-152)	18.75 (4.30, 13-29)
TD 6 (N =10)	6;2 (0;3, 5;3-7;4)	95.70 (12.59, 84-120)	22.10 (6.21, 11-31)
TD 8 (N =10)	8;00 (0;6 ; 7;6-8;3)	118.00 (10.15, 103-129)	31.40 (3.92, 22-34)
TD 10 (N =12)	9;10 (9;07, 9;3-10;8)	141.42 (7.87, 129-155)	32.75 (2.53, 28-36)

Standard deviation and ranges are in parentheses. BPVS, British Picture Vocabulary Scale; RCPM, Raven's Coloured Progressive Matrices

Table 2: List of landmarks used

Path/ Junction landmarks	**Distant landmarks**
Bin (non-unique landmark)	Lamppost 1
Teapot	Lamppost 2
Mug	Tree 1
Cow	Tree 2
Elephant	Tower
Helicopter	Fountain
Boat	Playground
Car	Circus
School bus	Building
Flower	
Plant	
Bench	
Chair	
Clock	
Camera	
Guitar	
Robot	
Lamp	
Lightbulb	
Grapes	
Apple	
Snowman	
Aeroplane	
Ball	
Table	
Glasses	
Torch	
Umbrella	
Scissors	
Bird	
Slide	
Bike	
Jeep	
Horse	
Trumpet	
Dice	
Ice cream	

Table 3: Number of learning trials (excluding the two criterion, zero-error, trials) and cumulative errors across learning trials for each group.

Maze	Group	Learning trials to criterion	Cumulative errors across learning trials
Sparse	WS	5.00 (2.31)	3.75 (3.26)
	TD 6	2.90 (1.10)	1.00 (1.33)
	TD 8	2.30 (.48)	0.40 (.70)
	TD 10	2.33 (.65)	0.33 (.65)
Rich	WS	5.00 (3.12)	6.13 (7.49)
	TD 6	3.40 (.84)	1.70 (1.57)
	TD 8	2.60 (.70)	0.50 (.53)
	TD 10	2.67 (.78)	0.75 (.97)

Means are reported with standard deviation in parentheses

Table 4: Landmark recognition task: proportion correct

	Rich maze landmark types				Sparse maze landmark types		
	Junction	Path	Distant	Non-unique	Junction	Path	Distant
WS	0.42 (0.21)	0.29 (0.19)	0.26 (0.18)	0.50 (0.52)	0.69 (0.37)	0.69 (0.30)	0.25 (0.29)
TD 6	0.53 (0.19)	0.47 (0.20)	0.52 (0.27)	0.70 (0.48)	0.88 (0.27)	0.78 (0.27)	0.50 (0.36)
TD 8	0.49 (0.13)	0.41 (0.15)	0.60 (0.21)	0.60 (0.52)	0.90 (0.21)	0.85 (0.13)	0.40 (0.26)
TD 10	0.54 (0.17)	0.43 (0.17)	0.44 (0.19)	0.83 (0.39)	0.85 (0.17)	0.85 (0.25)	0.42 (0.32)

Means are reported with standard deviation in parentheses

Table 5: Time (msecs) spent looking at non-landmark and landmark areas of the screen across all maze exposures.

Group	Non-landmark	Landmark
WS	34306.17 (16380.52)	5495.7583 (2904.60)
TD 6	18573.35 (12937.30)	4809.1098(2762.29)
TD 8	19846.19 (11410.52)	6315.3819(3295.59)
TD 10	23510.42 (11416.76)	6537.7488 (2366.38)

Means are reported with standard deviation in parentheses

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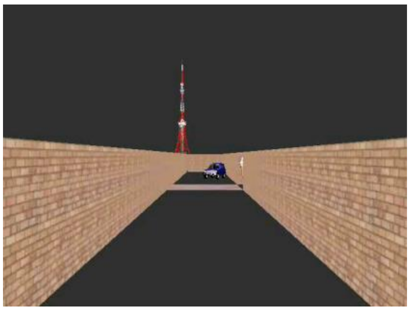
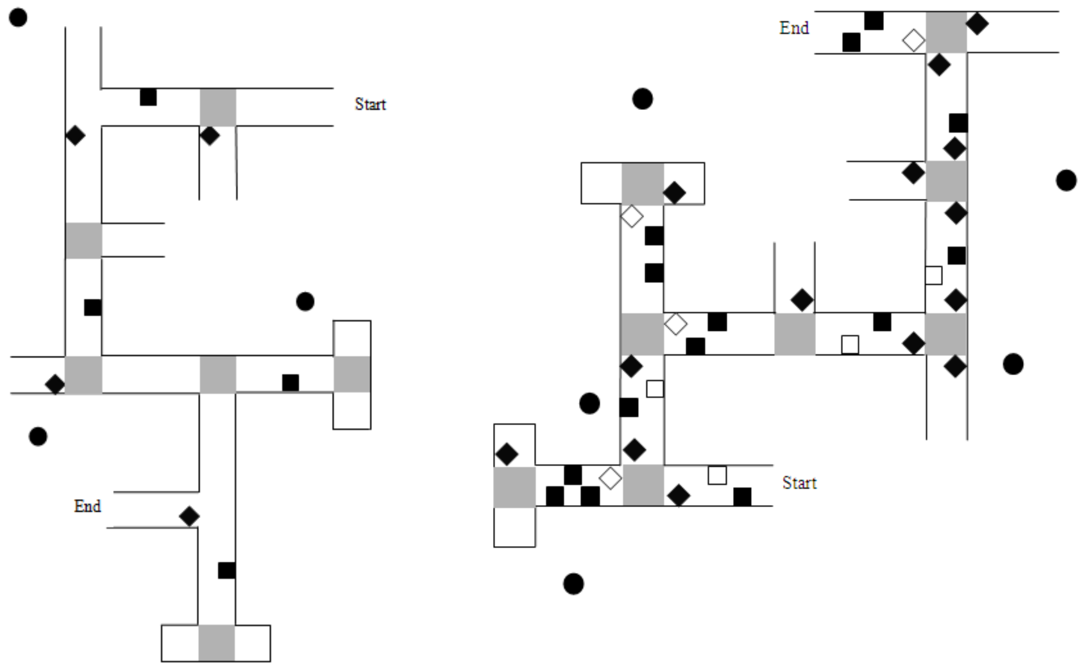
Figure 1: Screenshots of rich and sparse mazes



Rich maze (42 landmarks)

Sparse maze (11 landmarks)

Figure 2: Map of virtual environment maze layouts (maze A with sparse landmarks and maze B with rich landmarks). Grey squares on route represent “pebble” texture that featured at junctions and at the end of cul-de-sacs (required for straight ahead paths that were not on the correct route). Black diamonds, squares and circles indicate junction, path and distant landmarks respectively. Open diamonds and squares (rich maze only) represent nonunique junction (diamonds) and path (squares landmarks).



Sparse maze using Maze layout A　　　Rich maze using Maze layout B

Figure 3. Mean (s.e.) frequency of looks to landmarks as a proportion of visible landmarks, for each Landmark Type and Group.

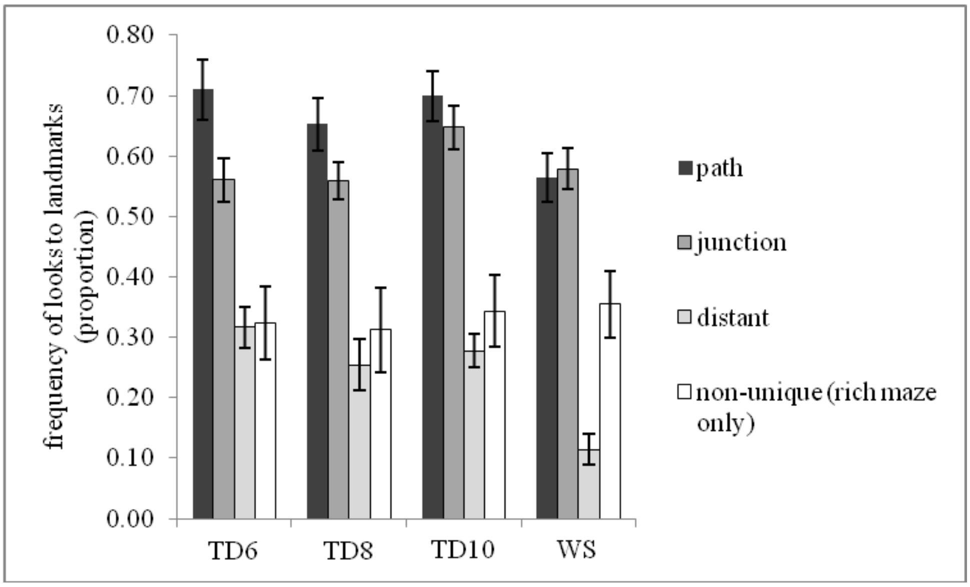


Figure 4 Mean (s.e.) frequency of looks to landmarks as a proportion of visible landmarks, for each Maze type and Landmark type.