Studying Children's Navigation in Virtual Reality

Aimilia Tzanavari[1(✉)], Chris Christou[2], Kyriakos Herakleous[3], and Charalambos Poullis[3]

[1] PROTOIO Inc., San Francisco, USA
aimiliatzanavari@gmail.com
[2] Department of Design and Multimedia, University of Nicosia, Nicosia, Cyprus
christou.ch@unic.ac.cy
[3] Immersive and Creative Technologies Lab, Concordia University, Montreal, Canada
kyriakosv2005@hotmail.com, charalambos@poullis.org

Abstract. Navigation in large-scale virtual environments is composed of locomotion and wayfinding. We compared two locomotion techniques in an immersive CAVE-like display in order to determine which one promotes better performance in children in a wayfinding task. A 'treasure hunt' game scenario was devised in which participants had to navigate to various houses of a virtual village that was previously seen only on a map. The 2D coordinates of paths taken by participants were recorded together with their success rates in finding the targets, and the time taken to reach their destination. Children showed that although the pointing method allowed them better control in locomotion, neither method was preferred in terms of success rates and timing.

Keywords: Navigation · Virtual reality · CAVE · Children

1 Introduction

Navigation in virtual environments consists of two components: Locomotion and wayfinding [1, 2]. The aim of all locomotion (travel) methods is to allow the user to explore virtual environments easily and naturally while supporting spatial awareness and reducing cognitive load [3]. Maintaining spatial awareness is especially important for wayfinding, which in itself is a cognitively challenging task. Knowing where one is in relation to a destination is essential for effective wayfinding.

The most natural techniques of simulating locomotion are ones in which the user receives proprioceptive and vestibular inputs from their body movements. In this respect Slater et al. [4] devised a technique whereby the user walks in place and makes normal head movements. Their movements were interpreted by a neural network classifier in order to update their viewpoint in the scene. A similar method was employed by Adamo-Villani and Jones [5] in a comparison between different immersive travel methods designed for children. More recently there have been developments in omnidirectional treadmills (e.g. [6, 7]), which can be used mainly in

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conjunction with HMDs. These allow the user to walk normally on the treadmill and these movements are monitored in order to update the view of the virtual world.

The importance of real walking in spatial cognition was highlighted by a series of experiments by Ruddle and Lessels [8] in which participants performed a search task in a room-sized virtual environment. The experiments compared gaze-directed travel using either a desktop display, a HMD with joystick or physical walking using a HMD. They found that only in the latter condition (real walking with HMD) was performance comparable to the same task conducted in the real world. The other two methods produced more errors with around 50 % of real-world performance. Their conditions differed in the amount of body-based information provided: In the first scenario (desktop display) no body-based information was provided, whereas gaze-directed travel with HMD provided rotational body information only and the free walking with HMD condition provided both rotational and translation body information.

These results were interpreted as supporting the use of physical walking interfaces in navigation through virtual environments. However, walking devices have limited scope and applicability. For example, they are large because they have to provide an area for the user to walk, they are difficult to physically move around, and it may not always be appropriate to have physical walking during exploration: larger virtual environments are more easily explored using simulated translation. Addressing these issues Riecke et al. [9] performed the same experiment but requiring all participants to wear a HMD to navigate. Again body-based information was none, rotation only or rotation and translation (real walking). They found that although walking with a HMD produced the best results, rotation only performance was comparable to real walking and better than no body-based information at all. This suggests that allowing a user to perform physical rotations in a virtual environment is more important than providing physical translation.

The results of Riecke et al. [9] suggest that a combination of head-tracked orientation changes with translation controlled using a joystick may be the most versatile method of locomotion which still supports spatial awareness. This can be accomplished using a steering method. Two steering methods commonly used are the *gaze-directed* method and the *pointing* method [10]. Bowman et al. [11] identified these two as the most general and efficient for spatial navigation. They allow for rotational head movements while enabling translation using a hand-held device. They differ only in that the gaze-directed method couples the translation direction with the viewing direction. The pointing method allows the user to pick the translation direction by pointing (with a tracked hand or pointing device).

These two methods have also been the subjected to comparative evaluations to find which is preferred by users. Asking users to walk along a line to a target object Bowman et al. [12] found that the gaze-directed method produced slightly better performance in terms of speed and accuracy (staying close to the line). However, this difference was not statistically significant. In another task in which participants had to move to a point relative to an object they found that the pointing method produced better performance using the same metrics. These experiments utilized a sparse virtual environment consisting of rectangular spaces defined only by concentric lines. Each method appeared to have its advantages and disadvantages (listed in Table 1). They noted that more significant differences between the two motion techniques might be found with more complex navigation tasks and in richer 3D contexts. Such a scenario for example might involve someone steering themselves along a city street with all the visual cues that we normally experience in the real world.

Table 1. Advantages and disadvantages of gaze-directed and pointing methods of travel. From [12]

	Advantages	Disadvantages
Gaze-directed	Steering and view are coupled	User's head can stay relatively still
	Ease of use/learning	More comfortable
	Easier to travel in a straight line	Can look and move in different directions
	Slightly more accurate	
Pointing	User's head can stay relatively still	Can lead to overcorrection
	More comfortable	More cognitive load
	Can look and move in different directions	Harder to learn for most users
		Slightly less accurate

In other studies Suma et al. [13] compared real walking with gaze-directed and pointing motion control in spatial cognition tasks using a HMD. They found a trend for better performance with real walking but no difference between the other two methods. Adamo-Villani and Jones [5] reported a study in which child participants had to navigate to fixed targets in a virtual environment displayed in a CAVE. They compared travel using either a wand device (pointing method with uncoupled gaze) with a gesture-based interface consisting of a pair of tracked data gloves and a body-centered interface utilizing a dance platform which used stepping as a locomotion metaphor. They found that, in terms of time to reach the targets, the wand and gesture conditions produced the fastest results. The wand method also yielded the lowest error-rate (incorrect turns en route to the target).

These latter findings may indicate that performance with gaze-directed and pointing methods may be dependent on the type of display used. All of the comparative studies above used a HMD except for Adamo-Villani and Jones [5] which took place in a CAVE-like display. Theoretically, the display device may have an impact as the HMD with its limited field of view will have different requirements and entail different user strategies than, say, a CAVE display which can provide a wider field of view.

2 Motivation and Objectives

Our aim was to determine whether there exists a preference for either the gaze-directed and pointing methods of travel implemented in a CAVE environment displaying a realistic scene, taking the special user group of children as participants. Although Bowman et al. [12] found minor differences between these methods under certain circumstances, we hypothesized that the reason for this was the sparseness of the environment they used, the nature of their tasks and the limited field of view available. We decided to test these methods using a realistic task requiring spatial awareness and high cognitive load while maintaining precise control of locomotion. Wayfinding requires that decisions be constantly made according to where the subject believes they are in the environment and in relation to their goal. It is also a common task that is easily comprehensible to children. Our experiment therefore differs from previous studies in the following respects:

- Using a CAVE-like display that provides peripheral visual information.
- A natural yet complex task of wayfinding under cognitive load.
- A more realistic environment where destinations are shielded from the start position.

These three factors may all influence preference for motion control. The CAVE display provides peripheral vision that was not available in traditional HMDs. Bowman et al. [12] for example, used a HMD with a field of view of 60 degrees. A CAVE display provides a field of view of 200 degrees. A complex environment will also result in obstructions of the line of sight between the subject and their destination, forcing them to store their route in working memory. An efficient motion control technique would not interfere with this information and allow them to find their target successfully.

3 Experimental Design

The virtual setting for our experiments was a village populated with distinctive buildings serving different social functions such as a school and a bakery. We placed signs around the village to identify the direction to various places (excluding buildings that served as targets in the experiment). The task involved a wayfinding exercise in which users were initially shown a map of their current location in the village and the location of a building that contained a large gold treasure chest (Fig. 1). Their task was to proceed as quickly as possible to the building while staying on the path. Travel speed was kept constant for all trials.

Fig. 1. The maps presented during the four trials

The two travel modes used in these tests differed only in that the pointing method allowed gaze in a direction independent of the direction of travel. From previous experiments described in the literature we identified accuracy, efficiency and control as often used parameters that encompass Bowman et al.'s [12] guidelines for travel methodologies. Accuracy in our case was measured by the number of times participants found the treasure. Efficiency was determined by the time it took to reach the target destination. Finally, control was measured by asking participants to keep to the center of the paths running between the buildings.

4 Experiment

The wayfinding ability in children and their development of mental representations of routes has been studied extensively (see [14] for review). However, relatively few studies have been conducted regarding map use in larger-scale environments. Developmental psychologists have suggested that children's abilities to represent environments follow a developmental sequence from egocentric representations to abstract allocentric representations [15, 16]. Recent studies have shown that there is a developmental progression in children aged 6 to 10 in route learning with younger children's wayfinding being more dependent on landmarks [17]. These developmental studies suggest that by 12 years of age children are able to encode a route procedurally. Comparison of way-finding ability between children of this age and adults of 22 years of age have shown no appreciable difference between them in real world experiments [18].

We were motivated to see how children navigate in VR. Interaction methods should be inclusive if VR technology is to benefit a wide range of societal needs. Even though children at the age of 11 can find their way in the real world using directions it remains to be seen if navigating in a virtual environment with the added cognitive load of using a motion control device is as straightforward.

We used a between-subjects design and each child participant had four trials using one or other of the two travel modes.

4.1 Participants

We contacted a local school to organize a class visit to the CAVE facility in order to test whether children demonstrated any preference for either one of the two travel methods described. Twenty-six (26) children (13 male and 13 female) aged between 11 and 12 years of age took part in the study. The children's parents signed informed consent forms that had been forwarded to them a week before the visit.

Summarizing the demographic data, in terms of computer use the majority of children (54.2 %) said they used a computer several times daily and 29.2 % said they used a computer during each week. In terms of computer games 45.8 % said they played computer games sometime during each week and 45.8 % said they played several times daily. None of the children had been in a CAVE display before. 80 % of the children owned either a Nintendo Wii or Sony Playstation. It is therefore reasonable to assume that the majority had experience with some form of game control device.

4.2 Design

We used a between-subjects design to test the two travel modes with the routes depicted in Fig. 1. Thus each child performed 4 trials using one of the two travel modes on an alternately assigned basis. The accuracy metric was the number of successful trials. Efficiency being measured by the time taken to complete a route. Control of movements was assessed by the mean square deviation from the center of the path during travel. Recording terminated when the participant reached within a fixed distance of the target entrance or after 80 s, in which case the trial was considered unsuccessful.

4.3 Procedure

The children completed an adult-supervised pre-test questionnaire and were alternately assigned to one of the two travel modes. They were individually familiarized with the CAVE, fitted with the stereo glasses and instructed as to the use of the wand according to their prescribed condition. They were allowed a short time to familiarize themselves with the motion control device and the experiment commenced when they were ready.

4.4 Results

Data from 2 children (1 male, 1 female) was discarded owing to inability to complete all four trials. Figure 2(a) shows the mean time taken to traverse each route for each mode of travel (for both successful and unsuccessful trials). On inspection, the average trial times appear to correlate with the length of each route although, interestingly, the travel times for routes 1 and 3 appear longer than routes 2 and 4. In these trials the participant's start point and direction violates Levine's (1984) forward-up equivalence principle and indicates perhaps an increased cognitive effort required to encode and traverse the route.

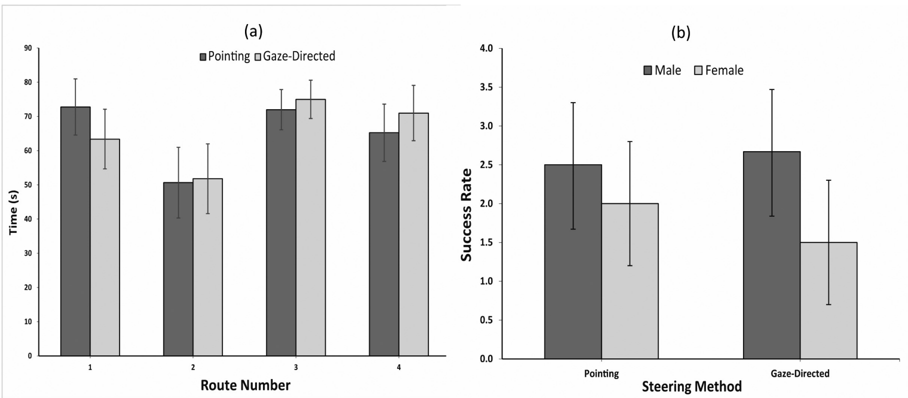

Fig. 2. (a) Children's mean trial duration (for all trials) for each treasure route. N = 12 for each condition, error bars are 0.95 confidence intervals. (b) Mean number of successful trials for children according to gender as function of steering mode. Error bars denote 0.95 confidence intervals.

In terms of the two motion control methods under consideration, trial times appear similar for the two travel conditions. We performed a repeated measures ANOVA with mode of travel as between subject's factor. This showed that there was no significant difference between the modes of travel in terms of trial time [$F(3, 22) = 1.77$, $p = 0.16$]. In terms of timeouts (time limit being reached before reaching target) the pointing condition produced 21 in total (relative frequency = 0.44) and the gaze-directed condition produced 23 (relative frequency = 0.48).

We summed the number of successful trials for each participant and performed a factorial ANOVA. Since we had a balanced design with equal numbers of males and females performing each of the primed searches with both modes of travel we could take gender into account. The ANOVA therefore consisted of two factors (Gender and Travel Mode) with number of successful trials as the dependent variable. Figure 2(b) shows the mean number of successful route traversals as a function of travel mode for the two genders. Results of the ANOVA show that gender was significant [$F(1, 20) = 4.55$, $p < 0.05$] with boys having greater success than girls. The mode of travel was not significant [$F(1, 20) = 0.18$, $p = 0.67$] and the interaction between these two factors was not significant [$F(1, 20) = 0.73$, $p = 0.4$].

Fig. 3. The routes taken by child participants. Large deviations have been removed. Inset picture shows all data. (Color figure online)

Finally, we look at the level of control afforded by each of the two travel methods. We found that some participants used at least one 'illegal' route to reach the primed destination (see inset in Fig. 3). These trials were removed from the comparison data. We see from the overlays of the paths followed in Fig. 3 that the pointing method allowed participants to stay closer to the center of the path. Figure 4 shows the mean square deviation (from the ideal path) for all 24 children. For all routes participants had lower mean deviations when using the pointing method of steering. A repeated measures ANOVA with 4 levels (corresponding to each route) and steering method (pointing, gaze-directed) as between-subjects factor showed that this difference was significant [$F(1, 22) = 5.72$, $p < 0.05$].

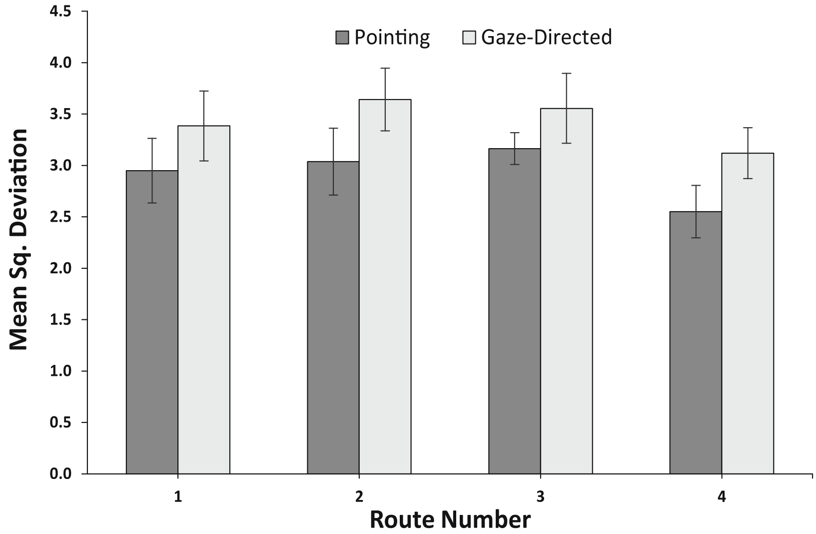

Fig. 4. Mean square deviations from the center of the path (in virtual world units) derived from children's navigation data. Error bars show standard error of the mean, N = 12 for each condition.

Because of the elevated number of timeouts we considered that this may have masked any difference between mode of travel and if enough time was given a preference for one method or the other would have been revealed. In order to further compare the two methods, regardless of whether participants reached the treasure location, we subdivided each route into a series of 10 equidistant waypoints and counted the number of waypoints reached for each route. A waypoint was considered to be reached if the user came within 15 world units of it (corresponding to 3 times the width of the path). Averaging across routes, we found that children using the pointing method reached 7.56 (SD = 1.45) waypoints and children using the gaze-directed method reached 7.79 (SD = 1.54). A t-test for independent samples by group showed no significant difference between the number of waypoints reached [$t(22) = -0.37$, $p = 0.7$].

4.5 Summary and Discussion

In terms of our measure of accuracy using each travel method we found no difference between the pointing method and the gaze-directed method. Similarly there was no significant difference between trial times for the two groups. However children were able to control their movements better with the pointing method than with the gaze-directed method.

The increased number of timeouts initially suggests that children did not have enough time to complete the path traversals, although a closer look at the data in terms of the waypoints covered regardless of whether they reached their target similarly suggested no difference between the two travel modes. The increase in timeouts reduced the amount of available data and so the results remain inconclusive. The fact that children found the task difficult may be explained by one of two possibilities. Firstly, it may be that children required more time to complete the routes and the time allowed was insufficient to do so. Secondly, it may be the case that children in many cases did not encode their route through the environment sufficiently to allow them to reach the target and got lost. In the former case the mode of travel may have made a difference, but not in the latter. Our analysis of waypoints reached for both groups shows that travel mode was not a significant factor regardless of the time allowed. Furthermore, visual inspection of path traversal behaviour of individual participants who did not complete their routes showed that they had good control over their navigation but simply made wrong turns and got lost. Nevertheless, further experiments would be required to investigate this more comprehensively.

5 Conclusion

In this experiment we compared two commonly used steering methods in a wayfinding task where the participants were children. In the gaze-directed method movements through the environment occur along the direction in which the user is looking. In the pointing method movement occurs in the direction of a hand-held pointing device allowing independent head movements. Both methods have their advantages. For example, the pointing method allows the users' head to stay relatively still making it more comfortable. On the other hand, the gaze-directed method allows changes in direction simply by rotating one's head and the user does not have to point with an interaction device which may reduce arm strain.

Previous comparisons of these two methods have measured accuracy, efficiency and control by measuring time to complete particular tasks correctly and the ability of users to follow paths. These tasks however were carried out using head mounted displays and have involved rather contrived tasks in non-realistic immersive environments. We were motivated to carry out experiments in a CAVE display that does not restrict the users head movements and in which the peripheral vision of the user is much greater. We also used a realistic wayfinding task requiring the user to make head-movements to assess where they were and where they were going. Wayfinding is a cognitively challenging task in itself and any intrinsic benefits of either travel mode would be reflected in the objective measures that we made. We were principally concerned with timing to reach a destination, the number of successful route completions and the ability to maintain trajectories along fixed paths. These measures, as well as the wayfinding task itself, can be seen as encompassing the several parameters identified by Bowman et al. [12] as the qualities of an effective motion control method; namely accuracy, spatial awareness, ease of learning, ease of use and information gathering.

From our own subjective impressions the task was surprisingly difficult considering the simplicity of the topology. The main confounding factor in navigation through a large-scale environment is that buildings can obscure the line of sight and the task becomes one of using a cognitive map to encode where one is in relation to one's destination and to control how to get there. On presentation of the map we found that the best strategy was to imagine facing the direction of travel and then navigating the intended route by encoding which way to turn at each junction.

The data from our child participants shows that they found wayfinding in VR difficult. They reached the target destination on approximately half of their trials using either control method. Also, data from two children had to be discarded and this inevitably made the comparison between the two travel modes difficult. However, with the data available we can at least draw the conclusion that the pointing method allowed greater control in path following.

The fact that our sample of children found this task difficult is intriguing. However, on a trial by trial basis child participants appear more likely not to have had enough time to reach the target destination suggesting that they either found motion control more difficult in general or they did not encode their route sufficiently. The latter would conflict with, for example, the results of Cornell et al. [18] who compared wayfinding behaviour between 11 and 22 year olds. In Cornell's experiment, children were walked through a campus grounds and asked to find their way back. They therefore had prior exposure to the scene they had to navigate. The cognitive demands of our task were somewhat greater. The children had no prior exposure to the environment they had to navigate in. They were shown a map and asked to navigate from one location to another. A more suitable paradigm might have shown participants the routes to be traversed in advance, perhaps using a virtual fly-through, rather than a map. This would have provided them with additional information such as landmarks, which appear to be important for children's wayfinding [17] and thus a fairer comparison between travel methods is possible.

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