Navigation in Virtual Reality

Comparison of Gaze-Directed and Pointing Motion Control

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***Abstract*—We compared two locomotion techniques in an immersive CAVE-like display in order to determine which one promotes better performance in a wayfinding task. One method, commonly found in computer games, allows participants to steer through the 3D scene according to their gaze direction while the other uncouples the gaze direction from the direction of travel. In both cases tracked physical head movements determined the gaze direction. In order to provide a realistic scenario for comparing these methods we devised a task in which participants had to navigate to various houses of a virtual village that was previously seen 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. Participants showed better results with the pointing method of motion control, reaching the targets faster and with fewer errors. Results are interpreted with respect to the benefits afforded by large field of view displays.**

Keywords—virtual reality; navigation; wayfinding; motion control; steering

I. INTRODUCTION

Virtual Reality (VR) systems facilitate the depiction, manipulation and exploration of immersive 3D computer generated virtual environments. The main components are sensory feedback coupled with user interaction. Sensory feedback almost always includes a visual display and, if the environment is large-scale, some means of locomotion so that the user can move from place to place. This paper concerns a comparison of two methods of locomotion which can be used in the absence of physical walking through a virtual environment. We begin with a consideration of the displays that serve as visual feedback as we believe these have an impact on the success of the particular locomotion method employed in any given VR installation.

Visual displays can be head-mounted or projection-based. With a head mounted display (HMD) the user sees the virtual world through an optical system mounted on their head. Tracking of head-movements allows the virtual camera associated with the user's view of the virtual world to be updated giving the impression of immersion within the environment. Because of technological restrictions original HMDs were limited in their field of view and this gave rise to the impression of being 'blinkered' and exploration required more head-movements than would be required in the real world.

In projection-based systems the user is situated in front of large screens on which the virtual world is projected. Stereo viewing is provided by means of shutter glasses synced to the refresh of left and right views of the scene and head movements are tracked by reflectors on these glasses. Examples include the CAVE [1] consisting of 3 rear-projected walls and a top-projected floor. Projection based systems such as this offer greater field of view as the shutter glasses are less restrictive and peripheral vision is available from the surrounding screens.

Both HMDs and CAVE displays offer immersion within the depicted environment. Immersion is the replacement of real-world sensory information with synthetic stimuli such that the user is enveloped in the depicted environment [2]. The benefits of immersion have been demonstrated in industrial design [3] and in data analysis [4], although one can imagine potential benefits in many contexts especially architectural visualization and emergency rescue training.

With respect to interaction in VR one of the most important considerations is that of motion control, also known as locomotion or travel. This is the ability to move from point to point in virtual space. Non-immersive desktop VR systems require the user to control movement using the buttons of a mouse, keyboard or joystick. Visual feedback is provided only on a 2D screen which has a fixed position. The view of the world changes only when the user performs translation and rotation using an input device. This is the case for many first-person computer games in which the camera position and viewing direction coincides with the users' head. Motion control in this case is usually gaze-directed; that is, translation is in the direction of the viewing camera and the user has to rotate the camera in the direction they wish to perform translation. Because of limited field of view provided by the screen, translation in a direction other than the gaze direction is problematic because it can lead to collision with objects in the scene.

In immersive displays the user is not restricted to looking in one direction in physical space. They can use head and body rotations to change orientation within the simulation. Translation can still be initiated by key presses although in some implementations locomotion is also possible by physical walking or using a treadmill for walking in place. The ability to make independent head movements while walking provides an alternative travel method to gaze-directed motion control. Using a suitable travel metaphor even non-walking interfaces can allow the user to make translations in one direction while looking in another. This is facilitated by pointing methods in

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which the user indicates their direction of travel using a hand-held device.

In the past, adoption of travel metaphors was done on an ad-hoc basis. However, given the increasing use of VR in training and basic research and also the recent surge of interest in immersive gaming, it is important to determine which of these methods is more beneficial for navigation in VR.

II. BACKGROUND

Navigation in virtual environments consists of two components: locomotion and wayfinding [6, 7]. The aim of all motion control is to allow the user to explore easily and naturally while supporting spatial awareness and reducing cognitive load [8]. 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.

A. Wayfinding in Real & Virtual Environments

The process of wayfinding encompasses all the cognitive skills which allow people to orient themselves in a 3D space in order to get from one place to another. Ref [9] identified three types of knowledge that people may use in wayfinding: survey knowledge, procedural knowledge and landmark knowledge:

Survey knowledge involves a map-like view of spatial layout and contains spatial information including locations, orientations, and distances between objects. Survey knowledge is geocentric in nature and develops over a prolonged period of familiarization with an environment.

Procedural knowledge characterizes a given space by memorized egocentric sequences of actions that allow the individual to get from one place to another. Thus, the route between any two locations is represented as a sequence of actions (e.g. turn left at X, turn right at Y) performed at particular locations or landmarks.

Landmark knowledge records distinctive objects or buildings that have a particular location in space in relation to other objects. It can be used in conjunction with procedural knowledge to aid navigation.

Survey-type knowledge may also be acquired directly from a map [10, 11]. This process has the benefit that it is faster than requiring multiple explorations of an environment. However, distance estimation and orientation judgements have been found to be inferior in individuals who have gained their spatial knowledge in this manner [10, 12]. One possibility for this is that survey-type knowledge derived from maps is still somewhat egocentric in nature, being dependent on the orientation of the user in relation to the map used. This orientation-dependency was studied by [13] in terms of map design. They found that in order to facilitate efficient map use, the map must be congruent with the environment it represents. This is illustrated in their forward-up equivalence principle, which states that the upward direction of a map must correspond with what is in front of the viewer for them to make efficient use of it and proceed from where they are to where they wish to go.

Initial experiments that studied navigation using VR found that it was more difficult than in the real world e.g. [14, 15]. Commonly, subjects became disorientated and lost their way. This was originally attributed to impoverished visual cues or a lack of fidelity with the real-world [16]. Other research suggests that visual fidelity is not entirely the problem. Instead, it has been argued that the lack of proprioceptive and vestibular feedback during locomotion makes navigation in virtual environments more difficult [17, 18, 19]. Proprioceptive feedback informs us of the position and orientation of our limbs and head. Vestibular feedback gives us a sense of linear acceleration (translation) and rotation in space. Original studies of wayfinding in VR lacked head-tracking and the ability to physically walk in the depicted environment. This may have resulted in the loss of spatial-updating abilities and path integration which affected performance [17, 20]. Spatial updating is the dynamic process of adjustment of a cognitive map based on movements within an environment. It seems therefore that a successful method of motion control must support spatial updating and spatial awareness in general for effective navigation to take place.

B. Motion Control Methods

Locomotion in VR can be implemented by making physical movements, by adopting a steering metaphor using a hand-held device which simulates walking, or by a combination of these methods [5]. Ref [21, 22] compared several different methods with respect to spatial awareness. They reported that some ad-hoc methods, such as the target specification method which involves teleportation (moving instantaneously to different locations), resulted in participants becoming disorientated after the transition. They reported that walking or steering using a motion control metaphor allowed the user to progress smoothly through an environment, allowing for spatial updating to take place.

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 [23] 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 [24] in a comparison between different immersive travel methods designed for children. More recently there have been developments in omnidirectional treadmills which allow actual walking e.g., [25, 26]. These are used mainly in conjunction with HMDs and allow the user to walk normally on the treadmill and their movement is used to update the view of the virtual world.

The importance of real walking in spatial cognition was highlighted by a series of experiments by [18, 27] 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 real walking with HMD was performance comparable to the same task conducted in the real world. The other two methods produced more errors. 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 condition provided both rotational and translation body information.

These results support the use of physical walking interfaces in VR navigation. However, walking devices have limited scope and applicability as they are expensive, difficult to install and to move around, and can lead to fatigue. Addressing these issues [19] performed the same experiment as in [18, 27] but requiring participants to wear a HMD in all conditions. 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 having no body-based information at all. This suggests that allowing a user to perform physical rotations in a virtual environment is more beneficial than providing physical translation.

The results of [19] 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 [5]. Two steering methods commonly used are the gaze-directed method and the pointing method [28]. Ref [5] 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 been subjected to comparative evaluations to find which is preferred by users. Asking users to walk along a line to a target object [21] found that the gaze-directed method produced slightly better performance in terms of speed and accuracy. 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. 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. 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.

In other studies of steering [29] compared real walking with gaze-directed and pointing motion control tasks using a HMD. They found a trend for better performance with real walking but no difference between the other two methods. Additionally, [24] reported a study in which child participants had to navigate to fixed targets displayed in a CAVE. They compared travel using (1) a pointing method with (2) a gesture-based interface using a pair of data gloves and (3) a body-centered interface utilizing a dance platform for simulated walking. They found that conditions (1) and (2) produced the fastest results and that (1) also yielded the lowest error-rate.

III. Experiment

These latter findings suggest that performance with gaze-directed and pointing methods may be dependent on the type of display used. All the studies above used a HMD with limited field of view except for [24] which took place in a CAVE. Theoretically, the display device may have an influence on navigation in that devices with limited field of view may force different strategies for wayfinding. We were therefore interested in making a direct comparison between pointing and gaze-directed control using a wide field of view display and in a realistic wayfinding task. Our experiment would therefore differ from previous comparisons in the following respects:

Fig. 1. Screenshot of the virtual environment and picture of a participant in the CAVE.

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

The virtual setting was a village populated with distinctive buildings serving different social functions such as a school and a bakery (see Fig. 1). Signs clearly marked the function or name of each building. We envisaged a task involving users being shown a map of their start location in the village and the location of a building that was their wayfinding target. Performance measures would include whether they could reach the target, the time required to reach target and the ability to maintain control of their motion and stay on paths connecting the buildings. The motion control method which is more intuitive and easy to learn would yield the least impedance to the cognitive task at hand and would therefore lead to higher success rates and faster route traversals.

Because this is a high-level task and different users may vary widely in their wayfinding abilities, a within-subjects design was considered preferable. A fair comparison would have participants travel exactly the same route using the two travel methods and comparisons made in performance. However, in this scenario there would be an effect of learning as much of the cognitive effort in translating from the map to the environment would be achieved on the first trial. We therefore considered an alternative method of using the same environment but to exchange the start and end points for each route traversal. Thus, the same route would be traversed for each mode of travel. However, depending on the method of wayfinding used there might still be an advantage of learning as the same map layout is used in both cases. To disrupt this even further we considered rotating the maps 180 degrees between conditions. This

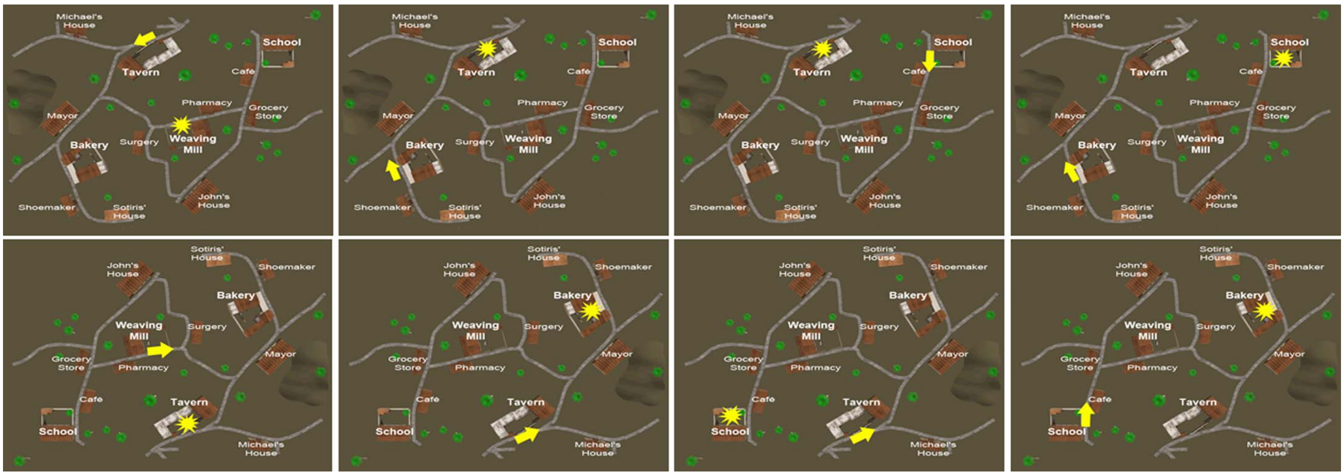

Fig. 2. Maps used to prime participants as to their start location and heading (arrow) and the location of the target (star). Participants completed 4 routes for each travel mode. The second row of maps are equivalent to the corresponding maps in the first row but the map layout has been rotated 180 degrees.

procedure would be especially effective if the route information derived from maps is ego-centric and procedural in nature. We were able to confirm this in pre-tests trials using eye-tracking. These showed that when people are asked to memorize their route between two points on a map they subjectively report storing the sequence of movements involved (turn left, turn right etc.) and their fixations on the maps are concentrated predominantly on the junctions in between.

A. Navigation Test

In the main experiment subjects had to proceed from one of four predetermined start locations to a target building indicated on a map shown on the front projection screen at the start of each trial (see Fig. 2). There was only one distinct route connecting the start and destination. To counter learning effects the start and end points were switched between conditions and the layout rotated (compare Fig. 2, top and bottom rows). The eye-tracking studies indicated that participants were most likely to use procedural encoding and as such the two routes would require a new encoding for wayfinding for each condition. It should be noted that in some cases the implied user start position in relation to the map violates the forward-up equivalence principle [13] (e.g. see Fig. 2, column 1). Counterbalancing of the maps used for each condition reduced the possibility that this was reflected in the results.

B. Participants

We used advertisements for recruitment and 10 males and 6 females volunteered. There was no financial reward. The mean age was 26 years (SD=6.3, range=24. A pre-test questionnaire was also administered to obtain background information about computer use. This showed that most participants had some exposure to computer games but most were unfamiliar with virtual reality.

C. Setup

Experiments took place in a CAVE-like display consisting of four projection screens surrounding the participant. Each screen was controlled by a separate workstation forming a cluster. The projection area of each screen was 2.44mx1.83m, with 1600x1200 pixels resolution. The refresh rate of 120Hz allowed active stereoscopy with the use of CrystalEyes 3 shutter glasses. The left and right eye views were alternately displayed at a frequency of 60Hz.

The CAVE was equipped with a Vicon tracking system that allowed position and orientation tracking. Head tracking was facilitated by highly reflective spherical markers on the shutter glasses. An Xbox 360 controller was used for user input. This controller also had sphere markers attached and its position and orientation were tracked. The participant's position and orientation within the CAVE were used to update their view of the scene. The position and orientation of the wand was used to update the position and orientation of a virtual beam of approximate length 60cm emanating from the front of the wand. This informed users of their intended direction when pressing the joystick in the pointing condition.

D. Design

Participants had to traverse the same path using both gaze-directed and pointing methods. This was repeated four times for four different start-target pairs chosen in advance. This resulted in two conditions each with two levels and four trials (routes) for each condition. Participants alternately started with gaze-directed or pointing as their initial condition.

The dependent variables were the number of successful trials, the duration of each trial (time required to reach the destination) and the deviation from the path (participants were instructed to stay close to the center of the paths). A trial was considered successful if the participant reached within a fixed distance of the entrance to the destination building. At this point trial time recording ceased and results were recorded.

Each trial was limited to 80 seconds; after which time it was considered unsuccessful. It was reasoned that this would induce a speed-accuracy trade-off. The more intuitive of the two travel modes would result in fewer errors under time pressure and would enable an assessment of its ease of use and ease of learning.

E. Procedure

Each participant was briefed on the experiment and signed an informed consent agreement. They were then given written instructions summarized as follows: (1) From the start-point proceed to the 'Target' location as quickly as possible. (2) Keep as close to the center of the shortest path as possible. (3) When you arrive at the location you will be notified. (4) After 80 seconds the trial will finish.

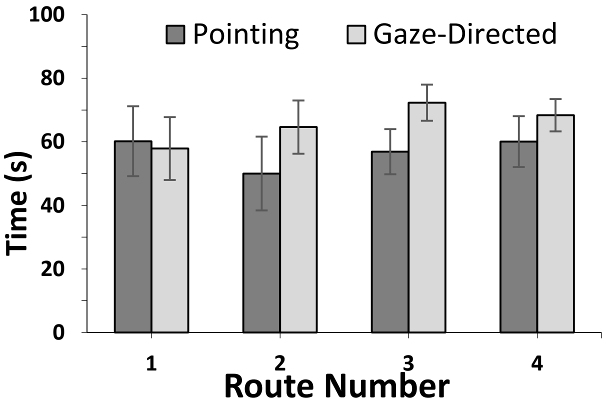

Fig. 3. Time taken to complete each trial as a function of travel mode. Data includes all trials whether successful or unsuccessful. Vertical bars denote 0.95 confidence intervals.

Fig. 4. Shows the routes followed by participants for each trial. Data is colour coded: Red for the Pointing, and blue for the Gaze-Directed motion control. Inset picture shows all data including when participants got lost or used 'illegal' shortcuts.

They were then fitted with the stereo glasses and received instructions on the operation of the current travel mode. They practiced their movements along an unrelated path for a short time until confident they had mastered the controls. .

IV. Results

Fig. 3 shows the mean trial times as a function of route for each of the two conditions. Results show that in most cases the pointing method was faster. The time data for both successful and unsuccessful trials was subjected to a within-subjects repeated-measures analysis of variance (ANOVA) with two factors: the mode of travel (2 levels) and the route traversed (4 levels). The time taken to reach each target was significantly different [$F(2.90, 40.61)=3.14$, $p< 0.05$] as expected because the paths were of different lengths and travel speed was held constant. More importantly the mode of travel was also significant [$F(1, 14)=22.08$, $p < 0.005$]. The interaction between mode and route was not significant [$F(1.42, 19.93)=1.0$]. Note that the assumption of sphericity was violated for the route traversal times and interaction and therefore the Greenhouse-Gheissler correction was applied.

The mean number of successful trials for all participants were 2.94 (SD = 0.77) and 2.31 (SD = 1.07) for the pointing and gaze-directed modes respectively. A within-subjects ANOVA with travel mode as repeated-measures factor showed that the pointing method resulted in significantly higher success rates compared to the gaze-directed method [$F(1,15)=5.95$, $p<0.05$]. The number of times participants ran out of time during their wayfinding can also be derived from our data. This shows that for the pointing method participants ran out of time 18 times (relative frequency=0.28) in total, whereas for the gaze-directed condition they ran out of time 26 times (relative frequency=0.41).

Participants were also asked to navigate to their goal by keeping to the shortest route. In order to assess how well each travel mode facilitated this we stored participant's position in model space from the beginning to the end of their journey. Fig. 4 shows the routes taken by participants in the gaze-directed condition (blue dots) and the pointing condition (red dots). It can be noted that in a number of cases participants got lost and veered dramatically from their route to the target (see Fig. 4 inset). However, both modes of travel resulted in reasonably accurate path following on most trials. To assess the data quantitatively the 2D points were filtered to remove points which overlapped (which could occur when participants were standing still) and to remove points that were widely off-track based on a threshold of 15 world units. We calculated the mean square deviation (Euclidean distance) of each data point from the corresponding ideal route situated exactly in the middle of each path. The data in terms of mean square deviations as a function of path suggest a benefit for the pointing method for most of the routes. A within-subjects repeated measures ANOVA with travel mode as repeated-measures factor showed that the difference between the two travel modes was significant [$F (1, 45) = 1.35$, $p<0.005$].

V. Summary & Discussion

Participants initially found the wayfinding task quite challenging. Subjective verbal reports indicated that they preferred the pointing method for control of movement. Objective data in terms of success rates, timing and control show a benefit of using the pointing method. The results show that uncoupling the direction of travel from the orientation of the head results in faster travel times, more successful traversals to the destination and greater accuracy in keeping to the center of the paths.

These results extend the findings of previous experiments that have compared these travel methods [21, 29]. In [21] they found no significant difference between them except in tasks that initially favored the use of one method over the other. However, they used a sparse virtual environment consisting of concentric lines with no landmarks and little visual detail. Our tests were carried out in a large-scale environment where buildings obscured the target locations from view. Participants therefore had to maintain route directions in memory while constantly updating their mental map of their position by looking around. It is conceivable that this was facilitated by being able to freely look around while moving.

Previous experiments were also carried out using limited field of view HMDs which perhaps limited some of the benefits of the pointing method. Traditional HMD field of view was limited to around 60°, in comparison to 110° for CAVE. The CAVE also provides a user with peripheral vision allowing them to make small rotations of the head and still have an awareness of travel direction. Head-movements appeared to be very important in our task as the participants had to maintain awareness of their position on the path while assessing the scene to look for up-coming junctions. Peripheral vision is also used to detect collisions with objects. In real environments such collisions are detected through peripheral vision. This is lacking in a HMD with limited field of view and so users in previous studies were perhaps forced to adopt a more gaze-directed approach. The benefits of larger field of view has been demonstrated in the development of cognitive maps [30] as well as in the control of locomotion [31] and path integration [32].

In conclusion, our results suggest that uncoupling the gaze direction from the direction of travel in a CAVE improves navigation performance. We propose that this has to do with increased peripheral vision provided by the CAVE. This would limit the applicability of our findings somewhat as CAVEs are not commonly available because they are expensive to install. However, recent developments in HMDs utilizing wide-screen AMOLED displays and therefore large field of views makes our results more pertinent for improving immersive simulations.

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