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Author

Smith, Shamus P, Hart, Jonathan

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Evaluating distributed cognitive resources for wayfinding in a desktop virtual environment

Shamus P. Smith* Jonathan Hart†

Department of Computer Science, Durham University
Durham DH1 3LE, United Kingdom

ABSTRACT

As 3D interfaces, and in particular virtual environments, become increasingly realistic there is a need to investigate the location and configuration of information resources, as distributed in the human-computer system, to support any required activities. It is important for the designer of 3D interfaces to be aware of information resource availability and distribution when considering issues such as cognitive load on the user.

This paper explores how a model of distributed resources can support the design of alternative aids to virtual environment wayfinding with varying levels of cognitive load. The wayfinding aids have been implemented and evaluated in a desktop virtual environment.

CR Categories: I.3.7 [Computing Methodologies]: Computer Graphics—Three-Dimensional Graphics and Realism;

H.1.2 [Information Systems]: Models and Principles—User/Machine Systems

Keywords: Wayfinding, navigation, distributed cognition, resource allocation, virtual environment, cognitive load, cooperative evaluation.

1 INTRODUCTION

Virtual environments are typically systems that are far removed from traditional computer systems. In traditional computer systems, users interact with the computer-based environment from outside the environment itself. However, virtual environments provide a situation where the user can be immersed, physically and possibly mentally [17], within the environment. Although some elements of the environment may be well-defined, for example physical layout, other aspects are more troublesome, for example the organisation and presentation of interaction cues and capabilities. The location of information, either represented externally in a computer system or internally by the user, may have wide-ranging effects on a systems usability [16, 25].

The view of information as being either external or internal to the user is extremely important for virtual environment design. As typical environments are a blend of the user's senses, the virtual environment and the enabling technology, the location of information resources between the user and the system is blurred. Virtual environments commonly aim to provide an environment where the user's interaction with this environment is done transparently to any technology-based devices [20]. The user is not interacting "through the interface" [1] but is part of the interface. Hence, there is a direct need to consider where the responsibility, the user or the system, lies to manage particular information resources in a virtual environment.

The identification of this responsibility management is a key element in the design of successful virtual environments. This paper investigates the location of information resources distributed in the human-computer cognitive system for the commonest virtual environment interaction, namely navigation. The *distributed information resources* model (or resources model for short) [25] is considered as a starting point for the cognitive analysis of virtual environment navigation. Several configurations of navigational aids based on the resources model are demonstrated and evaluated for cognitive load.

The remainder of this paper is organised as follows. Section 2 considers related work on navigation aids while section 3 examines background material on (i) the general distributed cognition approach, (ii) a specific resource-based framework and (iii) the implications for design. Section 4 describes the interaction area of interest, namely navigation and how it can be represented as distributed resources. Several wayfinding aids have been developed (section 5) and an initial user study has been completed (section 6). In section 7 the results of the user study are presented and discussed in section 8. The conclusions are presented in section 9.

2 RELATED WORK

Navigation in virtual environments can be supported by the inclusion of explicit aid mechanisms, as demonstrated in this paper, or by changing the nature of the environment itself. An example of the later can be seen in [21]. Design guidelines for environment definition, based on cinematography conventions, were developed to reduce user disorientation when navigating in a virtual environment. The environment is augmented with features to increase the user's awareness of off-screen space. User studies demonstrated how the use of the design guidelines reduced disorientation when navigating [21].

Navigation aids can be designed to support or simplify plans for future action, i.e. wayfinding, and the execution of these plans, i.e. travel. Paelke [13] describes a systematic approach to the development of new navigation aids. Scenarios and the definition of a proposed actor metaphor are used to communicate and define a specification for new navigation aids. The approach is demonstrated in the development of animated pets that provide navigation support at key locations in a virtual city. The approach focuses on producing an accurate first-prototype to guide further refinement and evaluation. Similar to the aids discussed in this paper, the pet guides are reusable across a number of environments.

Darken and Peterson [4] present an overview of navigation in virtual environments. They consider how understanding how people navigate can affect the design of virtual environment applications. A number of navigation tools are discussed including maps, landmarks, trails and direction finding mechanisms. Several design principles for the design of navigable virtual environments are described that focus on providing the user with enough spatial information so that users can execute navigation tasks as demanded

*e-mail: shamus.smith@durham.ac.uk

†e-mail: jhartuk@gmail.com

by the application without overconstraining the interface [4]. The use of the resources model in this paper provides a framework to evaluate where in the interface this source of spatial information is and where it might be re-allocated in order to support particular navigation tasks.

Whether multiple external navigational aids provide better support for users is an issue considered in [15]. A number of navigational tools were evaluated in order to determine if the visual presentation of navigational aids improves navigation performance, in terms of the time to complete a searching task. A user study confirmed the positive effects of navigational aids and that the presence of a number of visual tools improves performance more significantly than any individual tool. However, their study did not strongly differentiate between the usefulness of individual navigational aids, discussed here in section 8.

An example of combining internal navigation aids is described in [14]. Combinations of trails and landmarks were evaluated with a searching task in first-time and subsequent navigation. Overall, participants searched more efficiently when a trail was provided. However, there were issues with *trail pollution*, the visual clutter produced by a number of trails being laid over time, which made it difficult for users to determine a primary trail. This is similar the experiences with concurrent path representation described in this paper.

3 Background

3.1 Distributed cognition

Distributed cognition (DC) is a hybrid approach to studying all aspects of cognition, from a cognitive, social and organisational perspective [25]. The DC position is that the appropriate unit of analysis is not an individual but rather a distributed cognitive system of people and artifacts. The means by which this distributed system is studied is by analysis of the way in which distributed representations are co-ordinated, propagated and transformed. By analysing this process of representation and re-representation it is possible to account for how tasks of humans in the system are transformed and made more or less difficult [19].

For modelling human-computer interaction, the DC paradigm has some obvious attractions. It might be used to understand how properties of objects on the screen can serve as external representations and reduce cognitive effort [16]. The deliberate softening of the boundary between the user and system inherent in the distributed cognition view also brings into focus the design question of the information requirements for interaction. For example, what information is required in order to carry out some task and where should it be located? Should it be as an interface object or as something that is mentally represented by the user? In support of the DC approach is that it provides a framework and analytic methodology for examining the interactions between people and artifacts which is not possible with traditional approaches to cognitive analyses [25].

3.2 Distributed cognition for design

Distributed cognition, as an approach, makes a valuable contribution to design because it leads us to re-examine the relations between actors, artifacts and the settings in which interaction occurs. By identifying information structures or representations flowing through functional systems as objects of analysis, it becomes possible to reason, not only about design artifacts, but also cognitive artifacts, within a single framework [25].

Scaife and Rogers [16] use cognition theory to inform the design process and aid the selection of appropriate graphical representations. They analyse graphical representations as forms of *external cognition* and emphasise the importance of considering how the properties of such representations can affect thinking and reasoning. However they do not provide an account of action or interaction [25].

Cockayne, Wright and Fields [3] note that "the distributed cognition literature [8, 9, 16, 27] has demonstrated how differences in the externalisation of resources for action [22] can materially affect ease of use and ease of learning. At times it has been harder to see how to relate these findings to design decisions."

A problem with the DC approach is that it is not a methodology that one can readily pick off the shelf and apply to a design problem [25]. This is especially problematic as the design of virtual environments is traditionally seen as a highly implementation based process [18]. For example, developments typically focus on the use of rapid prototyping and system refinement. However, recent virtual environment research is moving towards alternative approaches to virtual environment development, i.e. more structured pre-implementation design [10, 23, 24].

An alternative to the general theory provided by DC is to consider an approach based on similar concepts but more applicable to virtual environment design. One such alternative is the resources model [25]. One of the main features of the resources model is in its focus on interaction between entities within a cognitive system. As complex, and/or realistic, interaction is one of the defining aspects of many virtual environments, this is a promising start to cognitive modelling for virtual environments.

3.3 The resources model

The resources model is comprised of two components; *abstract information structures* and *interaction strategies*. Wright, Fields and Harrison [8, 25] identify six abstract information structures that can be used to classify the types of information that inform interaction; *plans*, specifying actions to be performed; *goals* and sub-goals to be achieved; the *current state* of the world or interactive system; historical information or *interaction history* about previous actions and what properties held of the state in the past; an *action-effect model* of the effect actions have on the system; and the set of *affordances* that the system currently supports. These structures can be grouped to make up a *resource configuration*. A resource configuration is a collection of information structures that can be defined for each step in an interaction and which can be used to inform action [25].

These resources can either be external in an interface or represented in the head of the user. When action is taken in an environment there is a change in the resource configuration. For example, the current state and the history structures may change. An interaction sequence can thus be seen as a number of steps between changing resource configurations.

The second part of the resources model is the interaction strategies. Interaction strategies are the linkages between resource configurations that can be used to make decisions about what action to take. Wright, Fields and Harrison [25] define four strategies; *plan following, plan construction, goal matching* and *history-based selection/elimination*. Plan following involves the user in coordinating a pre-computed plan with the history of action so far undertaken. In its simplest form the plan is followed by determining the next action on the list until the list is exhausted. Plan construction requires the user to compare the current state of the world with some goal and to select from possible next actions those that reduce the difference between the two states. This process may need to be done iteratively on future states and affordances. The output of this process is a plan. A goal matching strategy is when affordances visible in an environment are used to control a search for the next action that matches, or moves closer to, a goal. History-based selection and elimination is similar to goal matching, only that the interaction history, not the action effect, is used for the selection of the next action.

Strategy	Resources required
plan following	plan, history and current state
plan construction	goal, affordances, action-effect and current state
goal matching	goal, affordances and action-effects
history-based choice	goal, affordances and history

Table 1: Strategies and the resources they require.

Interaction strategies presuppose certain configurations of resources to make them effective and conversely, how a configuration of resources can make a particular interaction strategy possible [25]. This is summarised in Table 1. By making the organisation of information explicit, the model facilitates reasoning, analysis and comparison.

3.4 Resources model for virtual environment design

In general, an abstract information resource can be represented or implemented by any of the human or machine agents in a cognitive system [8]. The benefits of this type of model is that it allows a designer to allocate information resources to the system and helps an analyst discover problematic points in a design by identifying how task-critical information structures are distributed around a system, and how the user is able to gain access to them [25].

The resources model has proved useful in framing analysis of interaction in terms of distributed cognition [25]. Firstly, as a means of comparing different interface designs, secondly, as a means of analysing interaction and thirdly, as a way of generating design alternatives and analysing their effects on user performance. Smith, Duke and Wright [19] describe the use of a distributive cognition approach using the resources model to help analyse information resources in virtual environment design. They presented four examples of how the resources model can be used in the virtual environment design process.

1. Designing interaction episodes can help identify where the scarcity of externalised resources places heavy demands on the user's knowledge.

2. Device classification allows a better match between physical devices and logical devices and allows designers to identify missing device functionality early in the design process.

3. By matching the veracity of tasks to the available resources, the final implementation can provide the level of interaction required for the current task.

4. The externalisation of plans in virtual environments can aid in reducing the users cognitive load, for example when navigating in a virtual environment.

This paper revisits the externalisation of plans in virtual environments and investigates several aids to support a wayfinding task.

4 Navigation, wayfinding and a virtual tourist

At this stage, we should clarify some terms. We consider the process of moving through an environment as *motion*, or *travel* [2, pg 183]. This is a combination of orientation and translation movements by the user. The act of *navigation* is the meaningful travel through an environment typically as the operation of a targeted search, e.g. the user has a destination in mind. Bowman et. al. [2, pg 227] describe *wayfinding* as the cognitive process of defining a path through an environment, using and acquiring spatial knowledge aided by both natural and artificial cues. Darken and Peterson [4] observe that navigation is an aggregate task of wayfinding and motion and must have both a cognitive element (wayfinding) and a motoric element (motion).

The problem domain used in this paper is the difficulty involved in a virtual tourist navigating for the first time in a virtual environment while searching for a set of landmarks. Navigation in such virtual environments is difficult, especially in large virtual worlds [5]. Contributing factors to this are the lack of veracity in the presentation and utilisation of navigation metaphors, problems with interaction hardware and cognitive load that is placed on the user. Also travellers visiting large virtual environments for the first time are easily disoriented, may have difficulty identifying a place upon arrival and may not be able to find their way back to a place just visited [7]. When navigating, unless the user has a good knowledge of the environment, they are unlikely to build complex plans before starting navigation. Virtual environment navigators may wander aimlessly when attempting to find a place for the first time [5].

4.1 Navigation and the resources model

Typically navigation is based on locally obtained information, for example the current state of the environment, externalised in the visual representation, and the goal of the navigation and knowledge of the navigation technique, both internalised in the mind of the user. The user then continues with a mixture of goal matching and history-based choice interaction strategies. In goal matching the user decides what to do in a localised way by matching the effects of an action to the current goal and checking if the current system state satisfies the goal [25]. For example, setting local sub-goals, e.g. "I should move forward", to see if this gets them closer to the overall goal. With history-based choice, the interaction history is used, with the current possible actions, to determine the next course of action. For example, if the user has navigated forward into a wall, the history, i.e. "move forward", can be used to eliminate another "move forward" action and select an alternative action.

Both these strategies, when applied to navigation, only provide localised decision-making and may require the user to extensively explore a virtual environment, building their own mental spatial model, before either reaching their goal, through trial and error, or building internalised plans to reach currently unexplored areas. The additional cognitive processing required for perception of the virtual environment and the navigation actions can tie up cognitive processing resources, reducing the effective deployment of higher level cognitive processing functions [12]. Depending on the spatial abilities of the user, and the veracity of the environment, users can easily become lost, disoriented and unmotivated.

An alternative to localised action selection is to apply a plan following strategy. Plan following is an interaction strategy that involves the user co-ordinating a pre-computed plan with the history of action so far taken, and, optionally, with the current goal [25]. However, a pre-computed plan is central to the plan following strategy.

Figure 1 shows an overview for navigation in a virtual environment where a user follows a generated route/plan from a current position to a destination. Before the user starts to navigate, the following is the current resource configuration.

- Goal: Destination (user).

- Current State: Current environment (system), spatial knowledge (user).

- Affordances : Navigation method (environment).

- Action-effect: Result of navigation method (user).

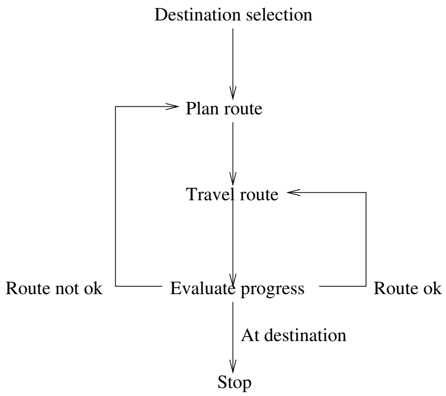

Figure 1: Navigation overview.

There is an assumption that the user has mastery over the interaction technique that is being used to enable navigation, e.g. *travel route* of Figure 1. This includes the possible actions that are available in terms of this interaction, i.e. the affordances, and the effect that this interaction will have on the current state and history resources, i.e. via the action-effects. This is in terms of the direct interaction only. The user does not have access to knowledge about the action-effect in terms of changing their location in regard to their position in the environment i.e. extending their spatial knowledge of the environment. For the task domain in this paper, the user is intending to do a *naive search* [5]. This is any searching task in which the navigator has no priori knowledge of the whereabouts of the target in question. A naive search implies that an exhaustive search must be performed [5].

The process described in Figure 1 blocks when the user tries to plan a route. Without access to spatial or survey knowledge, configurational or topological knowledge [5], of the environment, the user does not have the affordance/action-effect information resources needed to plan a route. Therefore the resource configuration of the environment needs to be changed or altered to allow the user to be able to plan a route to the target destination. However, artificial aids in virtual environments can do more than help the user plan routes, they can shift some of the cognitive processing that plan construction and plan following involves away from the user. Five wayfinding aids based on the resources model have been developed and evaluated.

5 Wayfinding aids

Wayfinding is something humans do, and take for granted, on a day to day basis. However, techniques used in the real world often translate poorly when navigating in virtual environments. Such environments commonly lack cues used in reality, for example distance travelled can be estimated by noting fatigue over time or travel speed can be determined by whether a person is walking or running. In addition, in new environments searching for specific locations can be difficult and slow and in complex environments users may become disorientated or lost.

In real world navigation and searching tasks, the use of wayfinding aids is common, for example the use of maps, compasses and sign posts to act as artificial landmarks. Such aids have also been utilised to aid virtual environment wayfinding and navigation (see for example [2, 4, 13, 14, 15]). However, many of these examples are attempting to benefit from the users previous knowledge of such aids [20]. What is less clear is the cognitive benefit that such aids provide. These aids change the resource configuration of the human-computer system and may in fact increase the cognitive load on the user.

In the next sections five resource-based wayfinding aids are described and predictions on how they will alter the cognitive load when used to aid navigation are generated. This is not an exhaustive set of wayfinding aids. The aids will be described in context of searching for a set of landmarks in a desktop virtual environment. All but one of the aids have been implemented as a 2D interface external to the 3D environment that is being navigated.

5.1 Distance only

The user is simply given the distance to a selected landmark as an integer (see Figure 2). It is predicted that this aid will place a large cognitive load on the user as they will have to interpret the direction they need to travel in as the distance to the landmark increases or decreases requiring coordination of the interaction history resource. The user will be required to remember their movement history implicitly in order to benefit from the distance information. The *distance only* aid fulfils the *goal*, displayed in the interface, and *action-effect*, as the indicated distance changes, of the resources model.

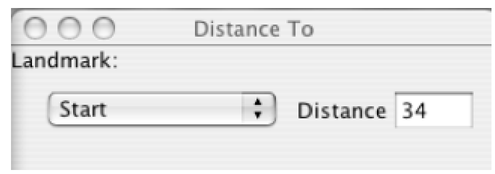

Figure 2: Distance only interface.

5.2 Graphical compass

The graphical compass is a standard compass interface that has four concurrent pointers; red pointing north, and blue, green, yellow pointers being user allocated to environment landmarks (see Figure 3). The cognitive load on the user should be low as the compass explicitly displays the direction to each landmarks but, as Bowman et al. [2, pg 247] observe, most users of 3D user interfaces will not be familiar with effective methods for using compass information, thus a medium cognitive load level is predicted. The *graphical compass* fulfils the *goal*, displayed in the interface, the *affordance*, with the compass points indicating directions to travel and *action-effect*, as the direction pointers dynamically change, of the resources model.

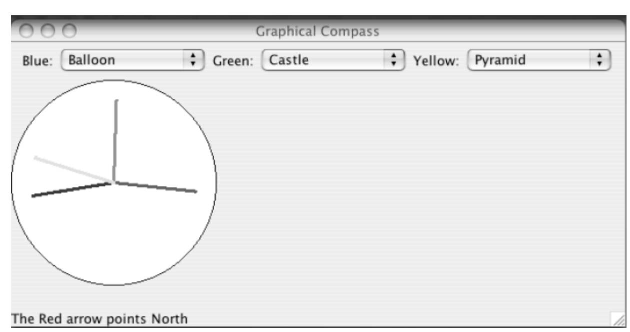

Figure 3: Graphical compass interface.

5.3 Dead reckoning

This method uses a simple text message to indicate the required movement to the highlighted landmark, for example one of four descriptions ; *ahead*, *left*, *right* and *behind* (see Figure 4). The text message is generated from the users current facing to a selected landmark (see Figure 5). The user will also be given the distance to the selected landmark. This method aims to have a low cognitive load on the user as it gives a rough indication of the next travel requirement. The *dead reckoning* aid fulfils the *goal*, displayed in the interface, *action-effect*, as the dead reckoning text is updated as the user moves and the distance changes, and the *affordance* by indicating the direction to travel.

Figure 4: Dead reckoning interface.

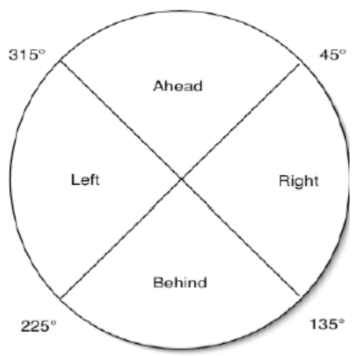

Figure 5: Angles for dead reckoning allocation.

5.4 Map-based route planning

This wayfinding aid requires the user to select the landmarks they wish to visit from an onscreen map before exploring the virtual environment. The user examines a 2D map of the environment and places markers, or waypoints, that they wish to visit (see left side of Figure 6). Once all the waypoints have been set, the user enters the 3D virtual environment and is guided along the route by a single point direction compass and distance measure (see right side of Figure 6). With the pre-planning stage of this aid, it is hoped that user will internalise some of the spatial information for their route that will be reinforced, once in the environment, by the 2D interface. Therefore it is predicted that it will significantly aid the user and reduce their cognitive load. The *map-based route planning* fulfils the *goal*, displayed in the interface, *plan*, presented in the saved landmark route, and *action-effect*, as the direction pointer dynamically changes, of the resources model.

5.5 Graphical plan following

This wayfinding aid inserts a *path* into the virtual environment, which the user can follow from landmark to landmark. The paths are semi-transparent tubes which stretch between landmarks above ground level and above head height (see Figure 7 with a path leading to a pyramid landmark). The paths can be considered as *trails* [2, pg 249] that provide direction information. This should have a low cognitive load on the user as they just have to follow the path between landmarks. The *graphical plan following* fulfils

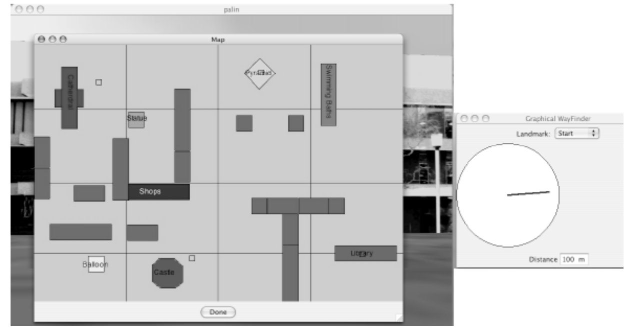

Figure 6: Map-based route planning interface.

the *plan* resource as the pre-calculated path, encapsulating the resources from plan construction (see Table 1).

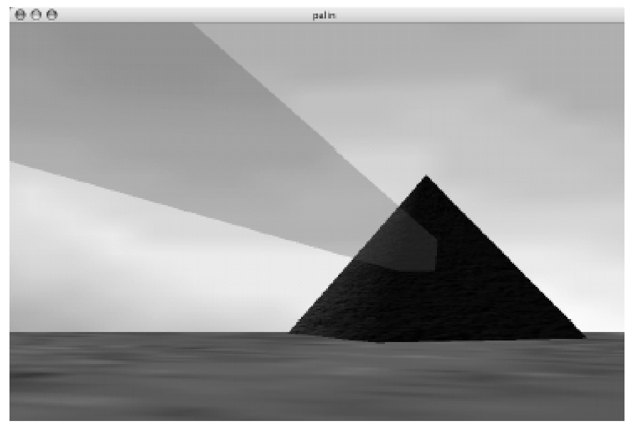

Figure 7: Graphical plan following example.

6 Study outline

A user study with six users was conducted to evaluate the wayfinding aids. The study group was required to take on the role of a virtual tourist and were asked to visit five landmarks in a desktop virtual environment. There was no set order in which the users must visit the landmarks and the virtual environment was developed so that the users would have no prior knowledge of the particular task environment. This ensured that their navigation was dependent on the currently provided wayfinding aid.

The experiment was run on a Macintosh iBook laptop running Mac OS X. The virtual environment was a basic 3D world developed in Java3D (see Figures 7 and 8). Embodiment in the world was via a first-person perspective and travel in the environment was enabled by using the arrow keys on a standard keyboard. Test subjects were located in an isolated room with one instructor/observer and an audio recorder to capture any verbalisations.

Before starting the main task, the users were shown the controls used to travel in the virtual environment and were allowed to explore an example environment so they could become familiar with the travel controls and the task of finding landmarks. Two map configurations were used and each wayfinding aid was tested twice, each time by a different user on a different map. Each map was designed with approximately the same (i) area, (ii) density of buildings and (iii) landmarks (see Figure 9 for a plan view of one of the maps).

Figure 8: Durham cathedral landmark in the virtual environment.

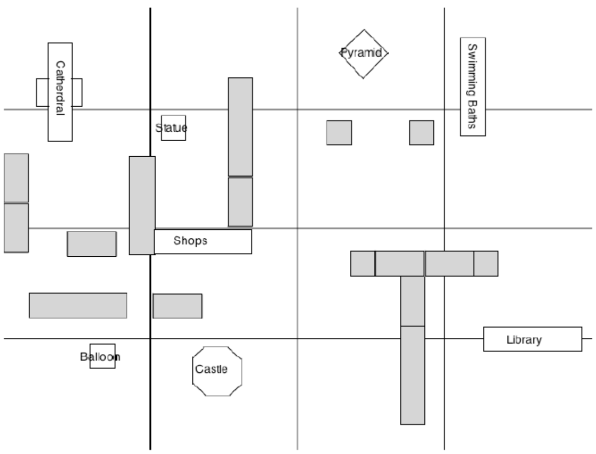

Figure 9: Example environment plan view.

The cooperative evaluation technique was used to encourage users to detail their experience while completing the landmark searching task.

6.1 Cooperative evaluation

The cognitive load placed on a user whilst navigating is subjective and is therefore difficult to measure directly or quantify. Traditional information gathering methods such as post-session interviews and questionnaires can lead to biased results if subjects misremember their experiences. This has been a recurrent issue when measuring subjective experiences such as immersion and presence in virtual environments [17]. One alternative is to invite subjects to verbalise their experience as they have it, i.e. using a *think aloud* protocol [6, pg 343], during the session. The verbalisations can then be captured on audio recordings. This evaluation mechanism is not without its problems because the user may (i) forget to verbalise their actions, (ii) feel self conscious verbalising or (iii) miss reporting features that the evaluator is particularly interested in.

Wright and Monk [26] proposed an augmented form of the think aloud protocol called *cooperative evaluation*. This is a concurrent think aloud verbal protocol where users are encouraged to treat the evaluation as a shared experience with the evaluator and may ask questions at any time. Also subjects may be prompted to explain actions as the session progresses. Similar to an in-session interview, it can provide qualitative feedback on the motivations for the users current behaviour. Marsh and Wright [11] describe how the qualitative data from a cooperative evaluation session can be quantified. The think aloud verbalisations can be assessed according to their quantity and quality. Quantity can be determined by counting all the verbalisations. Quality is attained by judging the value of each verbalisation.

Low quality problems are judged to be of low importance or impact to the environment or task under analysis and are more likely to be overcome with more usage and time in the environment. *High quality* problems are judged to be of high importance to the designers, and something that is not likely to be reduced by prolonged use, i.e. something that may shock or startle a user, for example moving through or colliding with objects. In this paper, high value will be associated with usability problems that are judged to be associated with the wayfinding aid under evaluation.

Cooperative evaluation has been successfully used for the evaluation of usability issues in virtual environments [11, 21]. One drawback of this technique is that prompting the user to talk may interrupt their train of thought and be distracting. However, Marsh and Wright [11] found that users encountered no significant addition to the time taken to complete their task whist thinking aloud as when not.

In this study, quantifying the in-session usability problems will provide a measure of the cognitive load that is placed on the user by the different wayfinding aids.

7 Results

After the sessions, the evaluator's notes and the audio recordings were used to classify any verbalisations by the users into nine indicators of cognitive load, namely, (i) collisions with buildings in the environment, (ii) attempts to leave the environment bounds, (iii) being disorientation, (iv) confusion with the travel controls, (v) confusion with using the wayfinding controls, (vi) confusion with the wayfinding aid directions, (vii) being lost in the environment, (viii) problems with the task and (ix) any other questions. In total the users provided 38 verbalisations related to the indicators during the sessions and of these verbalisations, 12 (32%) were exteriorised following evaluator questions.

A summary of the results can be seen in Table 2. Down the left hand column are the nine indicators of cognitive load. Along the top of Table 2 are the five wayfinding aids. From Table 2 the number of verbalisations can be quantified (i) per indicator and (ii) per wayfinding aid. Indicated in each table cell is a judgement, by the authors, of whether the verbalisation was of low (L) or high (H) value in comparing the wayfinding aids. An "E" indicates that the verbalisation was exteriorised following a question from the evaluator to the user.

The cooperative evaluation provides data in terms of quantity of verbalisations and a classification of quality, indicated as high or low ratings by the evaluator. In order to highlight the impact value of high quality verbalisations the totals in Table 2 have been augmented with weights where high quality verbalisations are twice as important as low quality verbalisations.

In terms of the indicators of cognitive load, the greatest number of verbalisations involved confusion over the directions provided by the wayfinding aids (11 weighted verbalisations). This was followed by verbalisations about collisions with objects, i.e. buildings, in the 3D environment, and confusion with the wayfinding controls. No users had problems with the environment travel controls and only minor issues with getting lost in the environment or other, unspecific, issues.

Of the wayfinding techniques, the graphical compass and the graphical plan following prompted the most verbalisations, while the dead reckoning aid prompted the least.

Usability problem / Wayfinding aid	Distance only	Graphical compass	Dead reckoning	Map-based route planning	Graphical plan following	Number of times verbalised	With weights $(L*1+H*2)$
Collision with environment	L, L	L, L	L, L	H, L	L	9 (8L,1H)	10
Attempts to leave map bounds	0	L, L	0	0	L	3 (3L)	3
Disorientation	L	L	0	LE	L	4 (3L,1LE)	4
Confusion with travel controls	0	0	0	0	0	0	0
Confusion with using wayfinding controls	L,LE, LE	0	0	LE,HE	LE, HE	7 (4LE, 2HE, 1L)	9
Confusion with wayfinding directions	0	H,HE	0	L,LE	L,HE, HE	7 (3HE,2L 1H, 1LE)	11
Lost	L	0	0	0	0	1 (1L)	1
Other question	0	LE	0	0	0	1 (1LE)	1
Problem with task	0	H,L	L,L	L	L	6 (5L,1H)	7
Total	7 (2LE,5L)	10 (6L,2H, 1HE,1LE)	4 (4L)	8 (3LE,3L, 1HE,1H)	9 (5L,3HE, 1LE)	38 (23L,7LE, 5HE,3H)	-
With weights $(L*1+H*2)$	7	13	4	10	12	-	-

Table 2: Reduction of think-aloud usability verbalisations to cognitive load indicators (L = low quality, H = high quality, E = exteriorised following evaluators question).

8 Discussion

The user study evaluated how the different wayfinding aids reduced or increased the cognitive load, measured as usability problems, on the user while they navigated around an environment searching for landmarks. To generate a general cognitive load classification, e.g. *low*, *medium* or *high*, for each wayfinding aid the weighted results were examined. This classification was compared with the predicted load for each wayfinding aid (see Section 5). A summary of the predicted and evaluated cognitive loads can be see in Table 3.

Wayfinding method	**Expected cognitive load**	**Evaluated cognitive load**
Distance only	High	Medium
Graphical compass	Medium	High
Dead reckoning	Low	Low
Map-based route planning	Low	High
Graphical plan following	Low	High

Table 3: Expected versus evaluated cognitive loads of each wayfinding aid.

The distance only aid was well received by the users. Its use was quickly determined by the users. Collisions with the environment happened as the aid only provided direct distances and required users to navigate around other buildings in the environment to reach each landmark. The expected high load on the users in integrating distances to interaction history did not manifest itself with the main issues being with the wayfinding aid controls i.e. the pull-down menus for landmark selection.

The graphical compass confused users and they required further direction on its use. At each new travel movement every compass point moved, indicating the direction to the assigned landmark. The constantly changing points caused the users to have difficultly in coordinating the next travel movement to a particular landmark. It may have been helpful if the compass needles of landmarks already visited were removed, hence reducing the concurrent goal resources in previous and future landmark searches.

The dead reckoning aid provided support as predicted and users found the general guiding provided adequate. The only verbalisations were about collisions with buildings in the environment and how to complete the task. Both would be reduced with further practice in the environment and are not explicitly related to the wayfinding aid.

The majority of the problems with map-based route planning involved its use in the searching task. Users had few problems setting waypoints on the 2D map. However, once in the 3D environment, there were issues with coordinating the pre-planned path and how this was supported by the wayfinding interface. Users were required to manually select the next waypoint in the interface from a pull-down menu. This broke their attention with the wayfinding task as they were forced at each step to re-coordinate the current goal and the distance and direction, action-effect resources, provided by the wayfinding aid. Thus the pre-session and in-session components of the aid increased the user's cognitive load.

For the graphical plan following it was predicted that the users would have few problems coordinating the plan provided by the path with their landmark goals. However, the users indicated three main problems. Firstly the paths would disappear through buildings. It was not clear to some users of whether these buildings were the landmark in question or the path continued on the other side. Thus they were required to navigate to the other side of the building to reorientate themselves. Secondly, all the paths were displayed concurrently and thus at path crossroads it was difficult to distinguish paths between different landmarks. This is similar to the *trail pollution* observed by Ruddle [14]. In this situation the plan resource and the internalised affordances, represented by the paths, was poorly coordinated with the landmark goals. Finally, the paths gave no indication of the distance to the landmark or in which direction to travel along the path (also noted in [4]). This was evident in the results by high quality verbalisations in reference to the wayfinding direction provided by the aid.

Four factors have been identified that may have contributed to the mismatch between the predicted results and those found in the user study. Firstly the predicated impact of the resource allocation to cognitive load may have been optimistic. This was influenced by a desire reduce the users cognitive load by moving resources to the artifact, in this case the wayfinding aids. In many cases the need for the user to coordinate resources explicitly represented in the wayfinding aid caused confusion, for example the multiple compass points in the graphical compass.

Secondly the implementation of the wayfinding aids may require more fine tuning. For the graphical path following, externalising the plan resource as the multiple paths overwhelmed the plan following strategy of the user. Representing the paths as distinct plans, e.g.

in different colours or styles, may help the user coordinate their current goal with the plan offered by the environment.

Thirdly, the study presented in this paper was exploratory in nature and the number of participants was limited. Although care was taken in the distribution of users to maps and wayfinding aids, it is likely that a larger user population would generate data to make stronger claims on the predictive qualities of a resource model based analysis in general and of the wayfinding aids in particular.

Finally, usability problems, as identified in the cooperative evaluation, were used as indicators of cognitive load. This provided one measure for comparing the wayfinding aids. Darken and Peterson [4] observe that other measures for wayfinding performance are (i) the time taken to complete a wayfinding task and (ii) the spatial knowledge of the environment by the user. These measures are complementary and the data could be collected in-session, for example with a background process collecting timing information while a cooperative evaluation is carried out, and post-session with a spatial awareness test. In a follow-up study all three measures could provide alternative dimensions to comparing the wayfinding aids.

9 Conclusions

As virtual environments become increasingly realistic it is important to identify the location and configuration of information resources, as distributed in the human-computer system, to support any required activities. An awareness of information resource availability and distribution can aid decision making when 3D interface developers are considering issues such as the cognitive load on the user.

The use of the resources model provides a framework to identify and communicate how information resources in an environment are allocated and how alternative allocations may support tasks such as navigation. Several wayfinding aids have been developed and evaluated in reference to the resource model. Cooperative evaluation has been used to identify usability problems as a measure of cognitive load on the users of a desktop virtual environment.

The results of the user study are promising. Issues with resource allocation, interface development and the wayfinding aids were highlighted. However, only a small number of wayfinding aids were examined with a limited number of participants. A follow-on study is planned to examine more resource model based wayfinding aids, with more users and several complementary measures to determine the cognitive load on users. These measures include timing information for searching tasks, usability verbalisations from a cooperative evaluation and a post-session spatial awareness test.

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