3D Location-pointing as a Navigation Aid in Virtual Environments

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ABSTRACT

The navigation support provided by user interfaces of Virtual Environments (VEs) is often inadequate and tends to be overly complex, especially in the case of large-scale VEs. In this paper, we propose a novel navigation aid that aims at allowing users to easily locate objects and places inside large-scale VEs. The aid exploits 3D arrows to point towards the objects and places the user is interested in. We illustrate and discuss the experimental evaluation we carried out to assess the usefulness of the proposed solution, contrasting it with more traditional 2D navigation aids. In particular, we compared subjects' performance in 4 conditions which differ for the type of provided navigation aid: three conditions employed respectively the proposed "3D arrows" aid, an aid based on 2D arrows, and a 2D aid based on a radar metaphor; the fourth condition was a control condition with no navigation aids available.

Author Keywords

Virtual environments, navigation aids, evaluation.

ACM Classification Keywords

H.5.1 [**Information interfaces and presentation**]: Multimedia Information Systems – *Artificial, augmented, and virtual realities*. H.5.2 [**Information interfaces and presentation**]: User Interfaces – *Interaction styles, evaluation*. I.3.6 [**Computer graphics**]: Methodology and techniques – *Interaction techniques*.

INTRODUCTION

A crucial aspect of interacting with a Virtual Environment (VE) is represented by navigation that can be informally defined as the process whereby people determine where they are, where everything else is, and how to get to particular objects or places [12]. Insufficient navigation support provided by user interfaces of VEs causes people to become disoriented and get lost.

Navigation problems become even more critical in large-scale VEs [20]. In this case, users cannot learn the structure of the environment from a single point of view but they are forced to navigate extensively and to integrate information deriving from different points of view. This task can be very complex since perception in VEs is different from perception in the physical world, due to the absence of many sensorial stimuli.

The aim of navigation aids research is to prevent disorientation problems as much as possible and to keep navigation (which is rarely the primary goal when interacting with a VE but is typically necessary to achieve that goal) as simple as possible, while preserving the elements of exploration and discovery.

In this paper, we propose and describe a navigation aid that provides users with information they can exploit to reach different places/objects in a VE. To preserve the feeling of immersion, which is a desirable feature in the interaction with a VE, the interface of the navigation aid has been designed to be less obstructive as possible and to provide users with information only when they request it. We then present and discuss the experimental evaluation we carried out to compare this navigation aid with typical alternative solutions that aim at providing the same kind of information.

NAVIGATION SUPPORT IN VIRTUAL ENVIRONMENTS

There are two main lines of research concerning navigation support in VEs. The first one is devoted to find guidelines for designing more navigable environments. These guidelines are often derived from other fields which have already faced the problem in the physical world. For example, some authors (e.g. [3],[4]) present a series of requirements for spatial design in VEs, deriving them from architectural theories, while others (e.g. [8]) discuss some methods to organize the space for navigability, inspired by previous research in fields such as urban planning. Extensive work exists on the design and placement of landmarks, which are distinctive environmental features functioning as reference points during navigation. An attempt to summarize the available knowledge on landmarks in the form of guidelines is provided by [19].

The second line of research concerning navigation support focuses on providing users with electronic navigation aids to augment their capabilities to explore and learn. Since the aid we propose belongs to this category, in the following subsection we summarize the different approaches that can be found in the literature.

Navigation aids

The first navigation aids to be proposed have been electronic analogues of the tools commonly used by people to navigate unfamiliar real world environments. From this perspective, the most common choice has been to provide an overview (in the form of an electronic map) of the environment to the user.

Electronic maps are powerful tools for navigation because of the richness of information they supply and the rate at which people can absorb this information. Maps provide *survey knowledge*, i.e. knowledge that describes the relationships among locations and can be usually acquired only through extensive navigation of the VE. At the same time, the use of maps requires repeated switches from the egocentric perspective of the user to the exocentric perspective provided by the map and vice versa. This often requires a mental rotation which is difficult to perform and affects performance as shown by [1], [7], [15]. Electronic maps may be enhanced by providing features that are unavailable in paper maps, such as the real-time indication of the position and orientation of the user or the capability of self-orientation (e.g. the upper part of the map always shows what is in front of the user). However, as previously stated, maps require some mental effort to be effectively used and are not always an easily viable solution. Indeed, when applied to large-scale VEs, a single map cannot simultaneously provide the level of detail needed for local navigation and a global view of the entire environment. To solve this problem, Ruddle et al. [16] propose the simultaneous use of a global and a local map. This solution has been shown to be effective, but it requires higher mental effort to be used.

3D maps are an interesting development of map-based navigation aids. An example of this kind of solution is given by Worlds in Miniature (WIM) [17]. A WIM is a three-dimensional small scale version of the VE, standing in front of the user, as if it were in his virtual hand. The user can directly manipulate both the WIM and the environment (changing something in one of the two directly affects the other and vice versa). The main disadvantage of WIM is that it overlaps the environment reducing user's visual access. Moreover, WIM cannot be easily applied to large-scale VEs unless a very low-detail version is used.

Recognition-based navigation aids provide users with visual information they can use to determine their current location. One such solution is given by the Worldlets approach [9]. Worldlets are 3D interactive thumbnails which are displayed outside the VE, so as not to overlap it, and can be explored and manipulated. They have been shown to be more effective than text and images for building a guidebook of landmarks to aid navigation in a VE. Their main drawback is the need for the user to suspend navigation in the VE to examine the information provided by the guidebook. Spaceboard [13] is another recognition-based navigation aid. It tries to reduce the cost of navigation by providing users with snapshots of interesting elements of the environment. Some of these snapshots are automatically created by the system while the user navigates through important areas of the VE, e.g. entry or exit points such as doors between different rooms. However, users are free to capture their own snapshots when they desire it. This way, the system stores a part of the mental representation of the environment (or cognitive map [18]) and allows users to inspect it.

Another approach to navigation aids is represented by *guided navigation*. For example, a humanoid animated character can lead the user on a guided tour of the VE [5]. While this solution requires to actively follow the guide, other authors propose passive tours, e.g. based on vehicles [10].

Closely related to guided navigation is *constrained navigation*. While in guided navigation the user still has the option to freely navigate the environment, constrained approaches restrict user's freedom. Indeed, the freedom to move arbitrarily can be at times detrimental to orientation and wayfinding. Placing constraints on user's motion allows for a simplification of the effort needed to navigate the VE. Hanson and Wernert [11] describe a solution employing hidden surfaces that constrain users' motion. Besides, each point of the constrained surface has an associated viewpoint, dynamically generated in such a way that users do not miss important objects while navigating near them.

Another way to help users gain navigation knowledge of the VE is to provide them with *empowerments*. In [6], for example, users can see through occluding surfaces with the aim of improving their navigation abilities and awareness of the VE structure.

Finally, some solutions provide *navigational search engines.* As an example, Navigation by query [2] augments the user interface of a VE by providing a simple search engine that allows users to navigate by querying the contents of the VE. This technique makes it easier for users to learn what a specific world has to offer without spending considerable time exploring that world.

THE PROPOSED APPROACH

The approach we propose belongs to *guided navigation* and aims at been especially useful for navigation in large-scale VEs. Most of the discussed solutions are instead more suitable to and have been tested mainly on smaller VEs. In

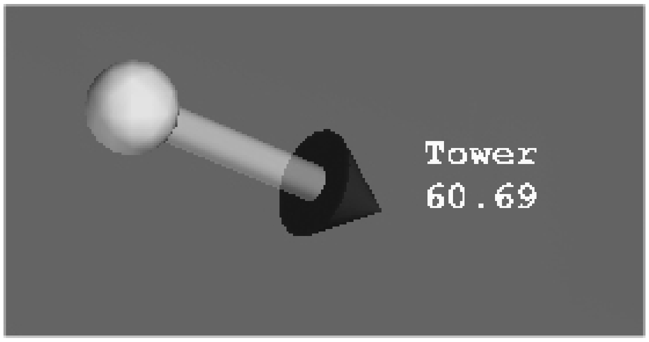

Figure 1 - A 3D arrow pointing towards an object with text indication of the object name and the distance (in meters) from the user

designing our navigation aid we have been careful to: i) provide users with information that requires a low mental effort to be understood; ii) simplify interaction, allowing users to easily obtain the needed information; iii) integrate the navigation aid with the VE to maintain the feeling of immersion, that is an important feature for VEs; iv) limit the caused visual obstruction to preserve an adequate user's visual access to the VE; v) allow users to request information only when they need it.

The specific information provided by the navigation aid concerns the direction in which users can find specific places and objects of a VE and the distance from them.

In the physical world, such kind of information is usually provided by means such as road signs or people giving navigation instructions by typically using their hands to point towards objects or places. This last method seemed to us promising, because it is familiar to users, very easy to understand and, at the same time, very useful to provide direction information. Initially, we explored both 3D models of human hands and 3D arrows to display the direction towards the destination. This pointed out that it is sometimes difficult to understand the direction pointed by 3D human hands (especially when part of the hand occludes the pointing finger), and we preferred to use 3D arrows (that were not affected by those perception problems). It is interesting to note that simple forms of 3D arrows that provide directions to the driver of racing cars have recently appeared in videogames [14]. The results presented in this paper can thus be useful also in that domain since no experimental studies are available in the literature. Location pointing may also be relevant for the Mobile HCI research community. Indeed, some navigators and touristic guides developed for mobile devices are beginning to explore the use of this metaphor to provide navigation information to the user. The kind of arrows we used in our navigation aid is depicted in Figure 1; note that the arrow body is semi-transparent to reduce visual obstruction. The information about distance and name of the pointed object is provided with text, coupled with the 3D arrow.

Users can select targets of interest by means of a menu

Figure 2 - The target selection menu

integrated with the VE. The menu is visualized in head-up display (HUD) fashion and contains a list of objects/places identified by their names (see Figure 2). Users can scroll the list by means of the two buttons at the bottom of the menu and they can type a letter on the keyboard to reach the set of items that begin with that letter. After choosing a menu item by clicking it with the mouse, a directional arrow pointing towards the corresponding element in 3D space appears together with distance information. At the same time, the selected item on the menu changes color to highlight its selected state. Users have the possibility to simultaneously display information about different targets by selecting all of them on the menu (e.g., there are two selected targets in Figures 3 and 6). This functionality can be especially useful to assess relations among elements of the VE and better understand its spatial structure.

The information provided by the proposed aid is dynamic: it is updated in real-time as the user or the selected targets move. This behavior allows users to be constantly aware of their position with respect to the selected targets and allows them to easily reach the desired destinations. Besides, dynamic positional information can be especially interesting when VEs contain moving targets, since users can track their positions even if they are not looking at them. To the best of our knowledge, none of the navigation aids in the literature has a similar functionality, since they mostly deal with static objects. Although one could think of integrating positional information about moving objects in 2D maps, our navigation aid has the advantage of easily providing information about the altitude of targets (while maps can only show a projection of the motion on the plane of the VE).

We indeed designed our navigation aid to be generally useful in different kinds of VEs and applications: this includes the case of three-dimensional navigation where users can move in every direction and are not limited to walking on a plane or other constrained surfaces. Finally, a specific functionality of the navigation aid was introduced

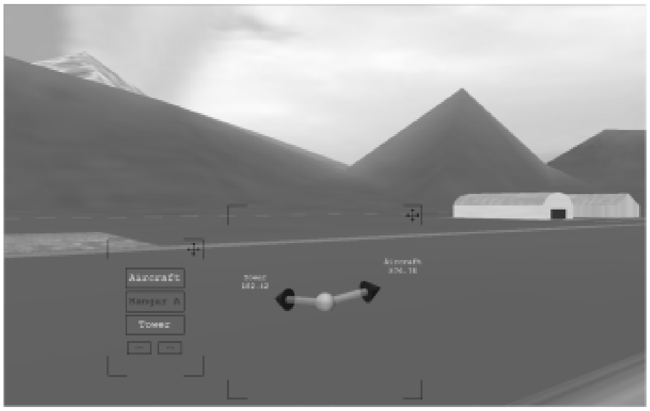

Figure 3 - The proposed navigation aid in a VE

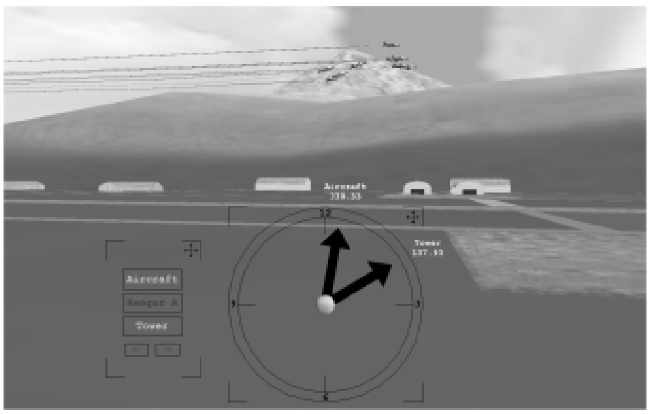

Figure 4 - "2D arrows" navigation aid in a VE

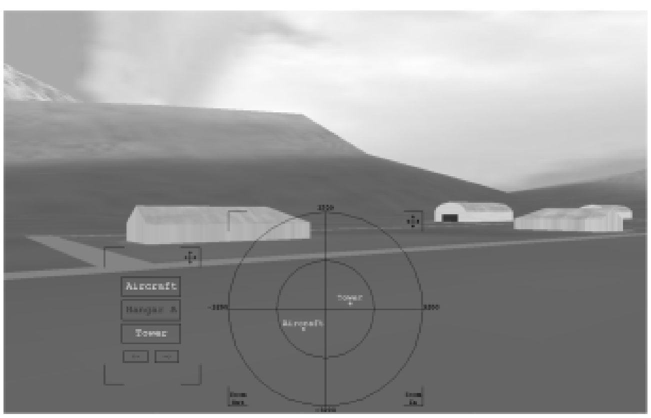

Figure 5 - "Radar" navigation aid in a VE

to prevent the difficulties users encounter when trying to align themselves with a given direction in 3D space (such as the one provided by the arrows). To solve this problem we provided users with the possibility to automatically align their point of view with the direction indicated by any of the 3D arrows. This functionality is activated by clicking with the mouse on the tip of an arrow. We implemented this functionality by generating intermediate points of view between the initial (actual point of view of the user) and final (target-aligned) point of view to obtain a smooth

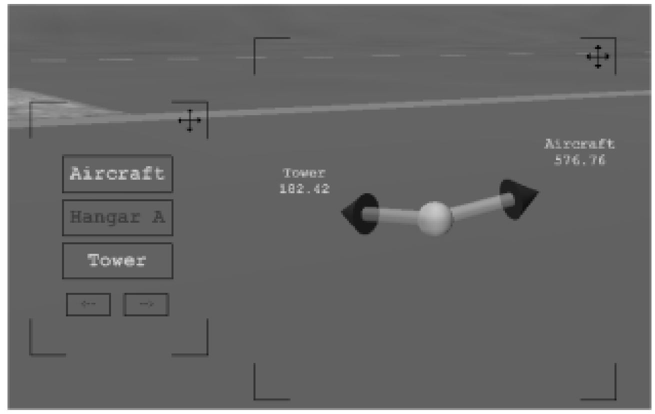

Figure 6 - Close-up view of the proposed navigation aid

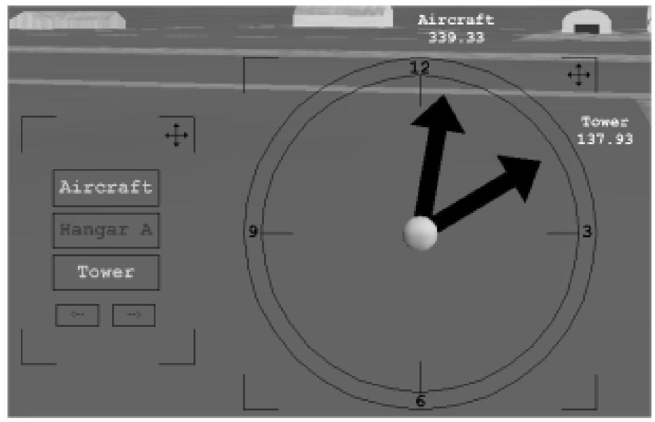

Figure 7 - Close-up view of the "2D arrows" navigation aid

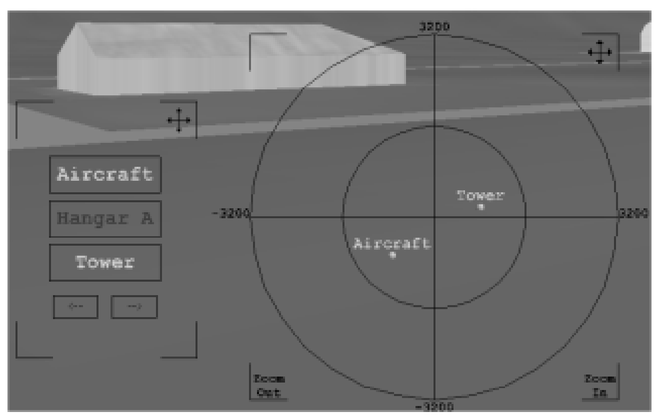

Figure 8 - Close-up view of the "radar" navigation aid

animated transition between the two, preventing possible disorientation effects.

THE EXPERIMENTAL STUDY

To evaluate the proposed approach, we carried out an experimental study comparing the proposed "3D arrows" navigation aid with two more traditional navigation aids based on 2D techniques, that aim at providing information about the position of objects with respect to user's position. We also considered a control condition where no navigation aid was available. The 2D navigation aids were integrated with the same target selection menu employed for the proposed navigation aid. One of the 2D navigation aids (see Figures 4 and 7) is based on 2D arrows providing users with direction information in the same way as some road signs do. The other 2D navigation aid (see Figures 5 and 8) is based on a radar metaphor: user's position is the center of the radar, and the relative position of targets is shown by means of colored points in the radar area. In the experimental study we carried out, the scale of the radar was set so that no target was ever out of radar range.

The goal of the experiment was to test the aids both in “walk” and “fly” navigation modes. In the former, users move by walking on the ground in a VE as in the physical world; in the latter, users can fly through the VE without being restricted to the ground. To test the navigation aids in both modes, we developed two different VEs, one more suitable for the walk mode and the other for the fly mode. The first one (see Figure 9) consists of a large-scale (13 square kilometers in size) urban environment that includes an air base, made up of runways, roads, hangars and a control tower, surrounded by civil areas consisting of roads and many buildings, some of which designed to be landmarks. The second VE is an abstract environment and consists of a void sphere of 1 km in diameter, where the user can freely move by flying (see Figure 10 for a detail of the inside of the VE). A distinctive wireframe pattern has been applied to the internal face of the sphere to ease the perception of motion and distance and to better highlight the boundary.

The experiment compared users' performance in the four possible conditions (3D arrows, 2D arrows, radar, no navigation aids) in a search task where subjects had to find five targets in a specified order. We repeated the experiment in the two described VEs with different sets of targets. The targets used in the urban environment were distinctive monuments or objects. They were different among each other and with respect to the other buildings contained in the VE, representing landmarks according to the definition of [19]. The targets used in the abstract environment were common objects (e.g. a lamp, a pot, ...) with different shapes and colors so as to be easily distinguishable.

Experimental design and procedure

Subjects were recruited among students in Computer Science. Fourteen of them were regular users of 3D computer games. The age of subjects ranged from 20 to 30, averaging at 24. We recruited a total of 24 subjects, 16 male and 8 female. The experiment was successfully completed by all subjects.

Following a within-subjects design, every subject was tested in every experimental condition, so there were 8 tests for each subject, 4 for each one of the employed VEs. Before every test, subjects were allowed to spend unlimited time in the environment until they felt familiar with the controls (the mouse was the only input device in the experiment), the navigation aid interface and the shapes of the targets (since it was an informed search). Positions of targets during this familiarization phase were different from positions of targets in the actual tests. To make it easier for the users to recognize the targets, they were provided with a color printed paper with the images of the targets, both in the familiarization phase and in the testing phase. During the familiarization phase, users were also allowed to look at a printed map showing the global structure of the urban environment. The effects of using a paper map in this phase are well-known and desired: it helps users in acquiring limited survey knowledge of the environment, thus reducing the length of the familiarization phase and limiting their initial disorientation during the tests in any of the four conditions.

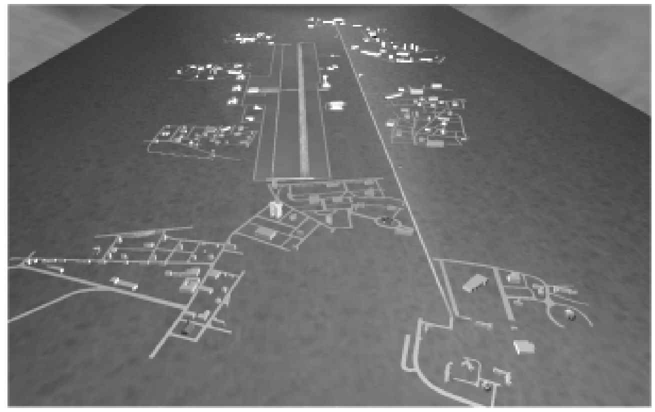

Figure 9 - Overview of the urban environment

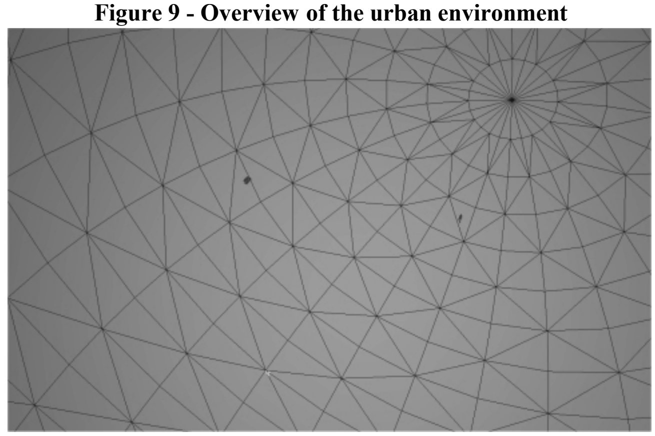

Figure 10 - Inside the abstract environment

After every familiarization phase, there was a testing phase in which users had to carry out the informed search. The order in which they had to find the targets was specified through an head-up display integrated with the VE.

All possible care was taken to counterbalance learning effects due to repetitive testing in the same environment:

1. Every user was presented with a different order of the experimental conditions.

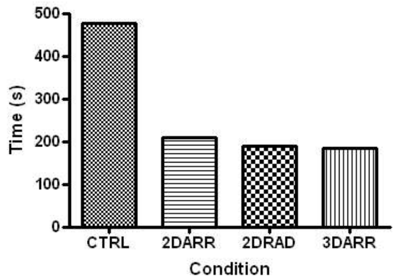

Figure 11 - Mean search times for the urban environment

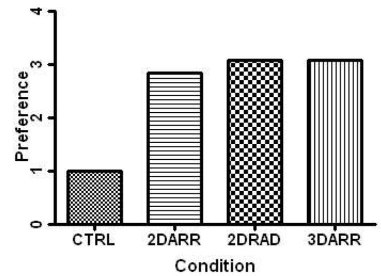

Figure 13 - Means of users' preference (urban environment)

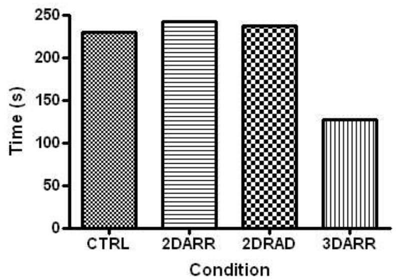

Figure 12 - Mean search times for the abstract environment

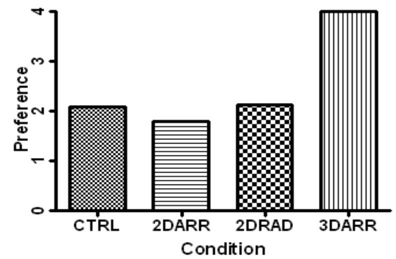

Figure 14 - Means of users' preference (abstract environment)

2. During testing, targets positions were different for each test condition. Five configurations of targets were produced for every VE, one for the familiarization phase and four for the testing phase. Total distance the user had to travel to carry out the test was kept constant. Total angular distance needed to align with the targets was not taken into consideration: there were small differences in the magnitude of this parameter between target configurations but their influence, with respect to the total time needed to complete a test session, was minimal.
3. There was no fixed association between test condition and target configuration. This way, a condition could not benefit by possibly unaccounted factors that might make a target configuration easier to complete than others. This solution counterbalances, for example, the effects of the slightly different angular distance between target configurations.
4. Users could not select more than one target at the same time in the selection menu. This solution was adopted to force a given interaction style with the selection menu (select one target, reach the target in the VE, deselect the target, select the next target and so on). For the same reason, the order in which users had to search for targets was identical to the order of the list of targets in the selection menu.

In every test phase, the time spent by the user to find the five targets was recorded.

After the conclusion of the four test phases, for each of the two VEs, users were asked to express their preferences by ordering the four navigation conditions from the best one to the worst one according to their ease of use and the usefulness of the provided information.

Analysis and results

A one-way analysis of variance (ANOVA) has been performed on the recorded time data. The within-subjects variable was the availability of navigation aids with four levels: no aids (CTRL), 3D arrows (3DARR), 2D arrows (2DARR), radar (2DRAD). The dependent variable was the time required to complete the task. For the urban environment, the ANOVA ($F(3,69)=120.65$, $p<0.0001$) pointed out that the effect was significant. We thus employed the Tukey test for post-hoc comparison among means. The values of means for the urban environment are graphically illustrated in Figure 11, while results of the post-hoc analysis are given in Table 1. It turns out that user performance in the control condition is significantly worse than performance in the other conditions, while there is no statistically significant difference among performances with the three navigation aids. Considering the abstract environment, the ANOVA ($F(3,69)=152.4$, $p<0.0001$) pointed out that the effect was significant. The values of means are graphically illustrated in Figure 12, while results of post-hoc analysis are given in Table 2. In this environment, results in the 3D condition are significantly better than each of the other three conditions, while there are no statistically significant differences among the control condition and 2D navigation aids. This result is likely due to two facts: (i) the direction indication provided by the 3D arrows is more accurate than the indication provided by 2D navigation aids, and (ii) the automatic alignment of the user's point of view towards the targets simplifies the interaction with the VE interface. It is interesting to note that all subjects used the automatic alignment functionality

Conditions	Difference among means	p value
CTRL vs 2DARR	267.00	p < 0.001
CTRL vs 2DRAD	288.60	p < 0.001
CTRL vs 3DARR	291.80	p < 0.001
2DARR vs 2DRAD	21.60	p > 0.05
2DARR vs 3DARR	24.80	p > 0.05
2DRAD vs 3DARR	3.30	p > 0.05

Table 1 - Tukey's post-hoc analysis for the urban environment

Conditions	Difference among means	p value
CTRL vs 2DARR	-12.50	p > 0.05
CTRL vs 2DRAD	-6.90	p > 0.05
CTRL vs 3DARR	103.00	p < 0.001
2DARR vs 2DRAD	5.60	p > 0.05
2DARR vs 3DARR	115.50	p < 0.001
2DRAD vs 3DARR	109.90	p < 0.001

Table 2 - Tukey's post-hoc analysis for the abstract environment

in the abstract environment while less than half of them used it in the urban environment. In the urban VE, indeed, all targets laid in the same plane as the user and more time was needed to interact with the arrow rather than directly rotating the point of view. The total lack of effectiveness of 2D navigation aids in the abstract environment was surprising, with no difference among the control and the aided conditions: by discussing with users, we found that many of them had trouble understanding how to interpret the information provided by 2D navigation aids while performing rotations in the VE.

To analyze the data on subjective preferences we employed Friedman's test. Four points were assigned to the best navigation condition and 1 to the worst. No draw was allowed. For the urban environment, Friedman's test ($T=43.8$, $p<0.001$) pointed out that the effect was significant. We thus employed the Dunn test for post-hoc analysis among total ranks (the total rank of a condition is the sum, among all users, of the weights assigned to that condition). The means of users' preference for the urban environment are graphically illustrated in Figure 13, while results of the post-hoc analysis are given in Table 3. There was no statistically significant difference among the three navigation aids in terms of users' preference while each of them was significantly preferred to the control condition. Considering the abstract environment, Friedman's test ($T=44.15$, $p<0.001$) pointed out that the effect was significant. Means of users' preference are graphically illustrated in Figure 14, while results of post-hoc analysis are given in Table 4. In this environment, the 3D condition was significantly preferred to the other conditions while

Conditions	Difference among total ranks	p value
CTRL vs 2DARR	-44.00	p < 0.001
CTRL vs 2DRAD	-50.00	p < 0.001
CTRL vs 3DARR	-50.00	p < 0.001
2DARR vs 2DRAD	-6.00	p > 0.05
2DARR vs 3DARR	-6.00	p > 0.05
2DRAD vs 3DARR	0.00	p > 0.05

Table 3 - Dunn's post-hoc analysis for the urban environment

Conditions	Difference among total ranks	p value
CTRL vs 2DARR	7.00	p > 0.05
CTRL vs 2DRAD	-1.00	p > 0.05
CTRL vs 3DARR	-46.00	p < 0.001
2DARR vs 2DRAD	-8.00	p > 0.05
2DARR vs 3DARR	-53.00	p < 0.001
2DRAD vs 3DARR	-45.00	p < 0.001

Table 4 - Dunn's post-hoc analysis for the abstract environment

there was no statistically significant difference among the other conditions.

Users' preferences analysis shows that the subjective perception of users is consistent with performance results: users' like/dislike of the navigation condition coincides with best/worst performance results.

DISCUSSION AND CONCLUSIONS

The results of the experiment showed that the proposed 3D navigation aid is at least as effective as 2D navigation aids in helping users during “walk” mode navigation, while it outperforms them in “fly” mode. Part of this last result can be attributed to the possibility of automatic alignment of the user's point of view towards the targets, since all users in the abstract environment used this feature. It has to be noted here that our experiment compares a new navigation aid, 3D location-pointing with the possibility of automatic alignment, against more traditional 2D navigation aids commonly lacking this functionality. This suggests further investigations. The first concerns the addition of automatic alignment to the 2D navigation aids. While this is easy for the 2D arrows, it could be difficult to operate in the case of the 2D radar, where the targets are displayed as dots and may be difficult to select, especially if they are moving. The second investigation concerns a more precise assessment of the influence of automatic alignment, comparing users' performance with and without it. Even if the addition of this functionality to the 2D navigation aids could help users, it cannot solve the other important problem that emerged from users' comments, that is the difficulty to understand the information provided by 2D navigation aids in “fly” mode. In this case, it seems that some form of 3D indication is anyway a better solution.

Other features of the proposed navigation aid, such as the possibility to simultaneously display many directional arrows and the possibility to track moving objects were not tested in the described experiment and further experimental studies are needed to assess their usefulness. Moreover, although the three navigation aids we tested performed equally in the urban environment, it is likely that when the targets are not located on the same plane (such as the case of flying objects or irregular ground) our solution could provide more precise indications.

Our navigation aid could be easily modified to guide users towards the objects of interest by following a path that avoids all obstacles, instead of providing absolute direction indication. This way, the navigation aid could be used when it is more important for the user to acquire procedural knowledge about how to reach an object instead of knowing where it is located with respect to the user's current position.

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