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Navigation in 3D virtual environments: Effects of user experience and location-pointing navigation aids

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Abstract

In this paper, we describe the results of an experimental study whose objective was twofold: (1) comparing three navigation aids that help users perform wayfinding tasks in desktop virtual environments (VEs) by pointing out the location of objects or places; (2) evaluating the effects of user experience with 3D desktop VEs on their effectiveness with the considered navigation aids. In particular, we compared navigation performance (in terms of total time to complete an informed search task) of 48 users divided into two groups: subjects in one group had experience in navigating 3D VEs while subjects in the other group did not. The experiment comprised four conditions that differed for the navigation aid that was employed. The first and the second condition, respectively, exploited 3D and 2D arrows to point towards objects that users had to reach; in the third condition, a radar metaphor was employed to show the location of objects in the VE; the fourth condition was a control condition with no location-pointing navigation aid available. The search task was performed both in a VE representing an outdoor geographic area and in an abstract VE that did not resemble any familiar environment. For each VE, users were also asked to order the four conditions according to their preference. Results show that the navigation aid based on 3D arrows outperformed (both in terms of user performance and user preference) the others, except in the case when it was used by experienced users in the geographic VE. In that case, it was as effective as the others. Finally, in the geographic VE, experienced users took significantly less time than inexperienced users to perform the informed search, while in the abstract VE the difference was significant only in the control and the radar conditions. From a more general perspective, our study highlights the need to take into specific consideration user experience in navigating VEs when designing navigation aids and evaluating their effectiveness.

Keywords: Virtual environments; Navigation aids; Evaluation

1. Introduction

Three-dimensional virtual environments (VEs) are used in fields as diverse as manufacturing (Mujber et al., 2004; Dangelmaier et al., 2005), medicine (Tendick et al., 2000; John, 2006), construction (Thabet et al., 2002; Setareh et al., 2005; Westerdahl et al., 2006), psychotherapy (Riva et al., 2004), design (Maher et al., 2005), and education (Chittaro and Ranon, 2007; Pan et al., 2006). They also play an important role in the investigation of spatial processes, such as examining directional knowledge (Waller et al., 2004) or assessing spatial abilities (Waller, 2005), allowing researchers to design realistic experimental settings and flexibly record user behavior (Jansen-Osmann, 2002).

Although the diversity of VE applications makes it necessary to design VE interfaces that support domain-dependent needs (Chen and Bowman, 2006), some tasks, such as *navigation*, are common to all VE applications and are essential even when they are not the main objective of a user in a VE. Navigation can be defined as the process whereby people determine where they are, where everything else is and how to get to particular objects or places (Jul and Furnas, 1997). Navigation is the aggregate task of

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wayfinding and motion. Wayfinding is the cognitive element of navigation. It does not involve movement of any kind but only the tactical and strategic parts that guide movement (Darken and Peterson, 2001). Navigation behavior of users in VEs has been investigated to a large degree (Darken and Sibert, 1996; Gillner and Mallot, 1998; Ruddle et al., 1999). To navigate successfully, people must plan their movements using spatial knowledge they have gained about the environment and which they store as a mental map. However, accurate spatial knowledge of VEs typically develops very slowly after long periods of navigation or study, and users may not always be willing to spend this time (Ruddle et al., 1997). Thus, if the navigation support provided by user interfaces of VEs is insufficient, people become disoriented and get lost. Navigation problems are even more serious in large-scale VEs, where there is no vantage point from which the entire world can be seen in detail, and the amount of detail that can be seen (e.g., from a bird's eye view) is drastically reduced by occlusion. To learn the structure of an environment, users are thus forced to navigate extensively and to integrate information derived from different points of view. In desktop VEs, where mouse and keyboard are usually the main input devices and the virtual world is experienced through a computer screen, navigation is further complicated by the absence of many sensorial stimuli (e.g., vestibular and proprioceptive feedback) that are commonly exploited by users in the physical world.

A large body of work focuses on how to face navigation issues in VEs. In particular, a lot of effort has been aimed at developing *navigation aids* that help the user to explore and learn the environment around her, preventing disorientation and simplifying navigation. However, only limited attention has been devoted to compare different navigation aids, and relations between the effectiveness of navigation aids and different levels of user experience in navigating VEs have been left largely unexplored.

Our study has two main goals. First, we want to compare navigation aids that help users perform wayfinding tasks in desktop VEs by providing only essential information to point out the location of the specific targets (objects or places). Two of the considered navigation aids, respectively, exploit 3D and 2D arrows to point at target locations; the third employs a radar metaphor to indicate target locations. Second, we want to test a possible relation between user experience with desktop VEs and the effectiveness of the considered location-pointing navigation aids. In particular, we wanted to compare users who had experience in navigating VEs with users who did not. To the best of our knowledge, little has been reported about the effect of experience with VEs on navigation performance with navigation aids. In many domains, solutions that might be inappropriate for novice users may instead benefit experienced users. For example, it is well-known that WIMP (Windows, Icons, Menus, and Pointers) interfaces are suitable for novices but experienced users may prefer quicker alternatives such as keyboard shortcuts or even command line interfaces. Similarly, navigation aids that are appropriate for experienced users may not provide a suitable level of support for inexperienced users and solutions that may improve the navigation performance of inexperienced users may not benefit experienced users beyond a certain degree. In a recent study on the effect of age on the use of VEs, Sjölinder et al. (2005) took into consideration the impact of computer experience, Internet experience, and 3D-application experience in tasks where users were asked to search for specific objects in a 3D store, with or without an overview map of the VE. The study showed that, when the overview map was used, previous Internet experience did matter with respect to time spent to perform the tasks, but not with respect to number of interaction steps to move around in the VE. The experience in using VEs, instead, was not found to have an effect on performance.

In our study, users performed wayfinding tasks both in a geographic desktop VE representing an outdoor area and in an abstract desktop VE that did not resemble any familiar environment. In the geographic VE, users employed a walk navigation mode, which is commonly used in many VEs and videogames, that is user positions were restricted to the 2D plane of the terrain and included only translations and rotations along their main axis (yaw rotation). In the abstract VE, users employed a fly navigation mode, being able to move and turn in any direction. Because of the differences between these two navigation modes, examining user performance in both VEs may provide a more thorough test of the effectiveness of the three navigation aids and may contribute to better understand the effect of experience on navigation performance. For example, Vidal et al. (2004) showed that exploring a VE in a walk condition allowed better spatial learning of the environment with respect to a fly condition, particularly for complex 3D VEs. Nevertheless, with practice, performance in the fly condition improved whereas performance in the walk condition remained at its initial maximum.

Our study could benefit all those domains where it is important to provide simple yet effective indications to support user navigation in a VE, regardless of its scale, while limiting visual obstruction and keeping as much as possible the feeling of immersion which is typical of VEs. Examples include training, videogames (where the aids we studied are commonly employed) but also new car or pedestrian navigation systems based on 3D environments. For example, 3D arrows have been recently employed in an augmented reality environment to inform drivers about dangerous situations around their cars (Tonnis et al., 2005). At the same time, studying experienced versus inexperienced users makes it possible to determine the most appropriate solution for different situations, e.g. allowing navigation support to adapt as user navigation skills improve.

2. Related work

2.1. Spatial navigation

To effectively navigate an environment, users resort to three distinct types of spatial knowledge: *landmark knowledge*, *route knowledge*, and *survey knowledge* (Siegel and White, 1975; Cousins et al., 1983). In unfamiliar environments, people first learn about landmarks, which are distinctive environmental features (such as specific buildings, city squares, etc.) functioning as reference points during navigation (Siegel and White, 1975; Golledge, 1991). Landmarks act as visual anchors that identify different regions of space (Couclelis et al., 1987) or provide an organizational structure that facilitates the location of points that are nearby (Sadalla et al., 1980). Route knowledge is usually developed from a first person perspective and makes it possible to connect different landmarks in a sequence, creating paths between locations in the environment (Siegel and White, 1975; Hintzman et al., 1981; Golledge, 1991). It allows a user to travel to destinations through known routes, but does not allow the user to take alternate unfamiliar routes. Finally, survey knowledge is developed from a third person perspective (e.g., through maps) or by extensive traveling in an environment and describes relationships among locations allowing users to assess where certain objects are located with respect to others in the environment and to recognize alternate routes (Siegel and White, 1975; Hintzman et al., 1981).

It is now generally accepted that people simultaneously develop landmark, route and survey knowledge (Peponis et al., 1990; Montello, 1998), and form mental images of places, known as *cognitive maps*. Research also suggests that vestibular and proprioceptive cues are important in developing spatial knowledge (Presson and Montello, 1994), although some researchers found little effect of proprioceptive information on spatial learning of environments (Ruddle and Péruch, 2004). This contributes to the difficulties in navigating VEs, as they are often limited to the motor-environment interaction afforded by conventional keyboards and/or joysticks.

2.2. Navigation support in virtual environments

Navigation difficulties in VEs originate from different factors. Obvious sources of navigational problems are represented by not knowing the structure and layout of a particular VE as well as a lack of familiarity with VEs in general (Ruddle et al., 1998). Lack of intuitiveness of traditional navigation methods, such as navigating by mouse movement, joystick or keyboard causes additional difficulties (Waller et al., 1998; Witmer and Kline, 1998). Additional factors such as lack of support for speed control, navigation mode (e.g., walking vs. flying), lack of landmarks and restricted field of view create navigation problems (Sayers, 2004).

In general, there are two main ways to provide navigation support in VEs: building VEs that follow navigability guidelines and providing navigation aids to help the user.

2.2.1. Designing VEs for navigability

Approaches based on structuring a VE to facilitate navigation often derive from other fields which have already faced the problem in the physical world, e.g., Lynch's work on the classification of navigational contents of cities (Lynch, 1960). Some authors (Charitos and Rutherford, 1996) derive requirements for spatial design in VEs from architectural theories, while others (Darken and Peterson, 2001) discuss methods to organize the space for navigability, inspired by previous research in fields such as urban planning. Extensive work is available on the design and placement of landmarks (Ruddle et al., 1997; Vinson, 1999). The important role played by landmarks when acquiring route knowledge in a network of paths is investigated by Jansen-Osmann (2002), who found that landmarks do indeed aid orientation in wayfinding, and a route with landmarks is learned faster than one without landmarks.

2.2.2. Navigation aids

Several authors focus on providing navigation aids that actively help in the task of navigation, augmenting user capabilities to explore and learn.

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 the user with an electronic overview map of the environment (Darken and Sibert, 1993). Electronic maps can be powerful tools for navigation thanks to the rich information they supply and the rate at which some people can absorb it. They can be enhanced by providing features that are unavailable in paper maps, such as self-orientation and real-time indication of user position and orientation. Maps provide survey knowledge, which would be otherwise acquired only through extensive navigation of a VE. Several studies investigated the influence of electronic maps on navigation performance in VEs. Darken and Sibert (1996) as well as Ruddle et al. (1999) found that the use of an overview map improved the performance of users performing wayfinding tasks in a VE. Parush and Berman (2004) found that, while initial navigation with a map appeared to be harder than with a route list (i.e., a list of instructions to reach a target object from the point at which the user was located), longer exposure to navigation made this difference insignificant. Moreover, performance degradation upon removal of the navigation aids was smaller for users who navigated with a map compared to those who navigated with a route list. Sjölinder et al. (2005) found that an overview map helps both younger and older users in terms of supporting a better and more precise understanding of the layout of an information space, but places higher cognitive demands on users, thus slowing them down. The authors state that employing a map is useful when it is important for users to learn the layout of the space, while it is detrimental when users are not supposed to visit again a VE or be able to find their way back. Other studies have shown that the repeated switches of perspective needed to use a map (from the egocentric perspective of the user to the exocentric perspective provided by the map and vice versa) negatively affect performance (Rossano and Warren, 1989; Aretz and Wickens, 1992; Darken and Cevik, 1999). It is also to be noted that a single map cannot simultaneously provide the level of detail needed for local navigation and a global view of the entire environment for large-scale VEs. Moreover, the simultaneous use of a global and a local map, albeit effective, requires higher mental effort to be used (Ruddle et al., 1999).

3D maps are an interesting, more recent type of map-based navigation aids. Seminal work on 3D maps has been carried out by Stoakley et al. (1995). They proposed the well-known Worlds in Miniature (WIM) technique, based on embedding a 3D interactive miniature of a VE inside the VE itself. This small-scale model can be manipulated to give the user another point of view from which to examine the world. Recently, the I3BAM (Chittaro et al., 2005) extended the WIM by adding new functionalities to support multi-floor 3D buildings. Instead of embedding a WIM within a VE, Elvins et al. (1998) propose a technique based on the use of Worldlets, 3D interactive miniature representations of VE landmarks which are displayed outside the VE. Worldlets can be explored and manipulated, enabling a user to gain first-person experience of different destinations in a VE. In a pilot study, the authors found that Worldlets significantly reduced the overall travel time and distance in a wayfinding task when compared to text and image landmark representations.

Some projects have focused on proposing aids that guide or constrain user motion in a VE. Considering guided navigation, we can distinguish between *active* and *passive* approaches. In active approaches, users are required to actively (and autonomously) follow a guiding object, e.g. an animated humanoid (Chittaro et al., 2003). In passive approaches, users are automatically guided along a tour, e.g. by means of vehicles (Galyean, 1995). Constrained approaches are based on restricting the access to specific areas of a VE while users autonomously navigate. For example, Hanson and Wernert (1997) describe a solution employing hidden surfaces that constrain user motion. 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.

Finally, some solutions to help users gain navigational knowledge of a VE are based on providing them with special powers, such as seeing through occluding surfaces (Chittaro and Scagnetto, 2001) or traveling through them (Bowman et al., 1999).

3. The considered navigation aids

We designed three navigation aids that are widely employed to support user navigation in current 3D applications (e.g., videogames) and are based on providing users with information to reach specific places and objects in a *desktop* VE.

The first two aids exploit respectively 3D arrows (Fig. 1) and 2D arrows (Fig. 2) that point towards objects and

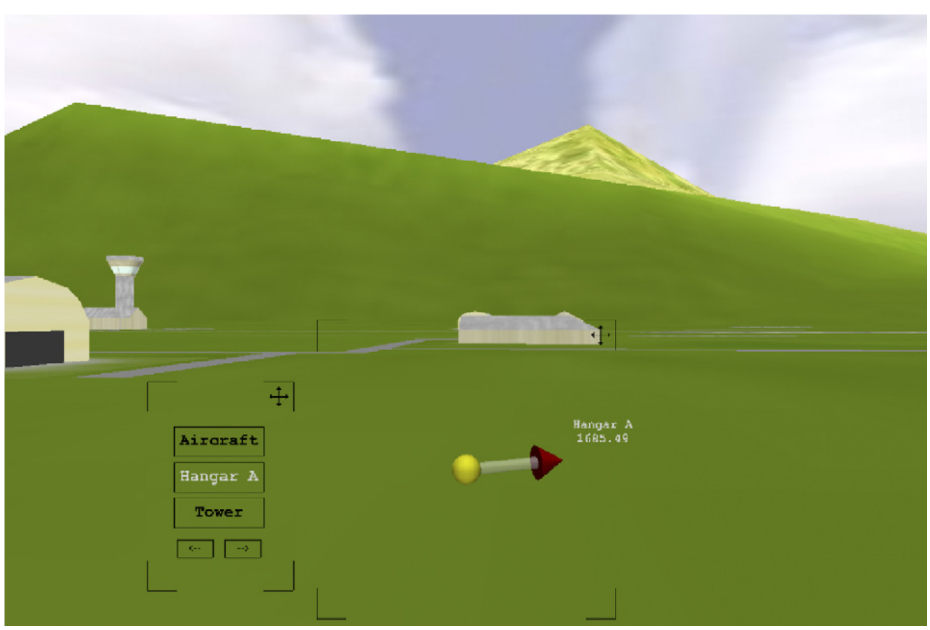


Fig. 1. The "3D arrows" navigation aid: 3D arrows are used to point towards target objects or places and associated text is used to provide information about target name and distance from the user.

Fig. 2. The "2D arrows" navigation aid: 2D arrows are used to point towards target objects or places and associated text is used to provide information about target name and distance from the user.

places the user has to reach, thus providing absolute bearings to target locations. In particular, our 3D arrows aid was inspired by people that point with their hands at destinations in 3D space, while the 2D arrows aid was inspired by road signs that are found before reaching crossroads. 2D and 3D arrows are also typically used for navigational purposes in commercial software, e.g. to provide directions to the driver of racing cars in videogames (Rockstar Games, 2003), or in car navigators and mobile tourist guides (Baus et al., 2005).

The information about distance and name of the target object is provided with text, coupled with the corresponding arrow. Users have also the possibility to automatically align their point of view with the direction indicated by 3D arrows by clicking with the mouse on the tip of an arrow. A smooth animated transition between the initial (actual point of view of the user) and final (target-aligned) point of view is then generated to prevent possible disorientation effects (van Ballegooij and Eliéns, 2001).

The third navigation aid is based on a radar metaphor (Fig. 3). The position of the user is in the center, and the position of targets is indicated by means of colored points in the radar area. Text is used to display object names and the distance from the user can be roughly derived from the radar scale. In the experimental study we carried out, the scale of the radar was set so that no target was ever out of radar range.

Both 2D arrows and 2D radar display indications with respect to the user plane. The user plane is based on the user viewing coordinates, so it changes if the user changes her orientation. Therefore, in the geographic VE, a 2D arrow pointing to the right or a point on the right of the radar center indicate a target that is located on the right of the user. In the abstract VE, the same arrow or radar point indicates a target which is on the right of the user, but at an undefined height (i.e., it indicates the projection of the location of the target on the user plane).

The information provided by all proposed aids is dynamic: it is updated in real-time as the user (or the selected targets) move. This behavior allows the user to be constantly aware of her position with respect to the selected targets. Besides, dynamic positional information can be especially interesting when VEs contain moving targets, since the user can track their positions even if she is not looking at them.

The interface of each navigation aid includes a menu that allows users to select targets. The menu is visualized as a head-up display and contains a list of objects/places identified by their names (see the left lower part of Figs. 1–3). Users can scroll the list by means of the two buttons at the bottom of the menu. After choosing a menu item by clicking it with the mouse, the navigation aid indicates where the corresponding target is, and the item changes color to indicate that it is selected.

A fundamental feature of the three considered navigation aids is that they support user navigation without taking control away from the user. Users are thus free to explore a VE, obtain navigation support when needed, keep their own pace while approaching a target and be able to take a different path if they change their mind or find something else worth looking at. This feature is important in applications where user personal exploration of the VE is part of the intended experience, such as in virtual tourism, racing games or training. Unlike solutions such as WIM or Worldlets, the three aids are also characterized by a limited level of visual obstruction that makes it possible

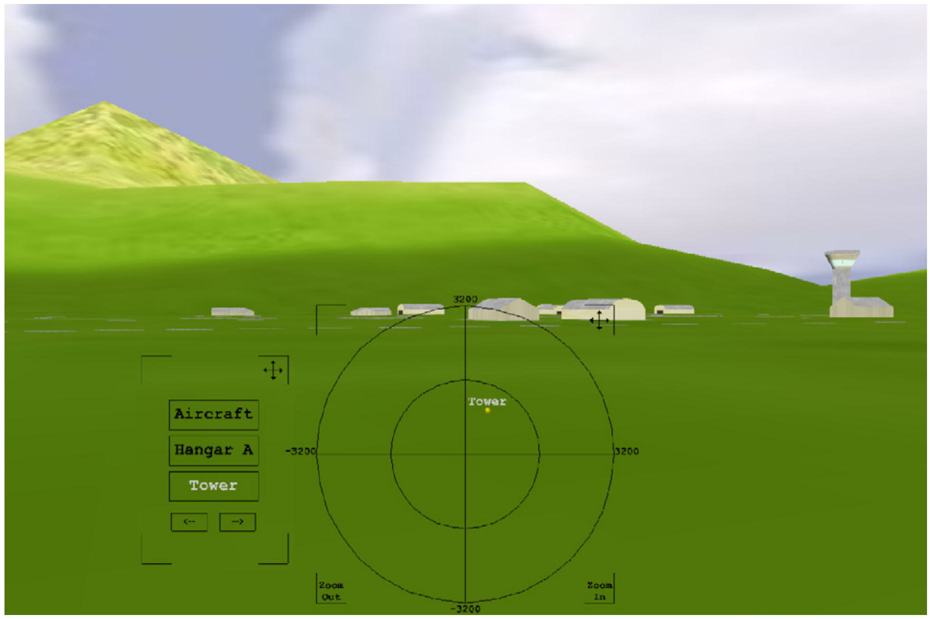


Fig. 3. The "2D radar" navigation aid: a 2D radar is used to provide information about the relative position of target objects or places with respect to the user position, text is used to display target names and the distance from the user can be qualitatively derived from the radar scale.

to preserve an adequate visual access to the VE as well as the feeling of immersion which is typical of VE navigation. Finally, unlike maps, which can be difficult to extend to large-scale VEs (Ruddle et al., 1999), the three aids are easy to integrate in any VE.

4. Experimental evaluation

4.1. Hypotheses

Our hypotheses in the present study are the following:

- Since navigation is a complex activity when no support is provided to users, all tested navigation aids should improve user performance in searching for specific objects when compared to a condition without aids, regardless of the considered VE.
- Previous experience in navigating VEs should have an effect on user performance, allowing experienced users to perform better than inexperienced users with all the tested navigation aids in both VEs.
- Since all three navigation aids provide similar information to support user navigation in the geographic VE, there should be no performance differences among the three aided conditions within each of the two user groups.
- In the abstract VE, both experienced and inexperienced users should perform better with 3D arrows than with the other navigation aids because 3D indications should provide users with more accurate information to reach specific objects in fly mode.

4.2. Participants

Forty-eight subjects participated in the study. Twenty-four of them (16 male and eight female) were recruited among students in Web Technologies and Multimedia who had attended a mandatory course on VRML.[1] Their age ranged from 20 to 30, averaging at 24. During their VRML course attendance, all these users had multiple navigation sessions in VEs and had to design a complex VE as part of their final examination. The other 24 subjects (17 male and seven female) were recruited among university students and people from other occupations who had basic experience in using computers but no experience at all in navigating VEs (or using any 3D software environment such as 3D games or 3D editing programs). Their age ranged from 21 to 55, averaging at 32. We consider the difference of a few years in the average age of the two groups to be acceptable because experimental evaluations focused at studying possible effects of age differences in VEs typically concern very large differences, e.g., 40 years (Sjölinder et al., 2005) or 20 years (Moffat and Resnick, 2002).

4.3. Materials

4.3.1. Virtual environments

To test the navigation aids both in walk and fly navigation modes, we developed two different desktop VEs. The first one (see Fig. 4) consists of a large-scale ($13\,km^2$ in size) geographic VE that includes an air base

[1] Virtual Reality Modeling Language: a standard language to create VEs (Web3D Consortium, 1997).

Fig. 4. The geographic VE used for the walk navigation mode.

(including runways, roads, hangars, and a control tower), surrounded by urban areas consisting of roads and many buildings, some of which designed to be landmarks.

The second VE is an abstract VE consisting of an empty sphere (with a 1 km diameter), where the user can freely move by flying. 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 (see Fig. 5 for a detail of the inside of the VE).

4.3.2. Targets

In the experiment, users had to search for different targets in each of the two VEs. The targets used in the geographic VE were distinctive buildings or objects (see Fig. 6, left). They differed from each other and with respect to the other buildings contained in the VE, and thus were landmarks. The targets used in the abstract VE were common objects (see Fig. 6, right) with different shapes and colors to be easily distinguishable.

4.4. Procedure

The experiment compared user navigation performance in four possible conditions (control condition with no navigation aids, 2D arrows, radar, 3D arrows). Performance was measured in terms of the total time to carry out an informed search for five targets, a metric that has been systematically used in previous studies to compare navigation aids in VEs. A standard VRML browser (Parallelgraphics Cortona) was used to view and navigate the VEs. Following a within-subjects design, every subject was presented with every experimental condition, thus performing eight tests, four for each of the two VEs. Subjects were initially asked to fill a questionnaire containing demographic questions (age, sex, computer experience, VE navigation experience, etc.) and were verbally instructed about the task to be performed. Before starting the actual tests, subjects went through a training phase where they were allowed to spend unlimited time in each VE until they felt familiar with the controls (based on mouse), the navigation aid interface and the shapes of targets (since the task was an informed search). In the geographic VE, users navigated in a way that is typical of desktop VEs, i.e. by positioning the mouse pointer anywhere in the VE and moving the mouse while holding down its left button (by moving it forward or backward, users navigated forward or backward in the VE, while by moving it right or left, they turned in the corresponding direction). In the abstract VE, users controlled their movement by using the mouse as in the geographic VE and they controlled their orientation by pressing a specific key on the keyboard (SPACE) and moving the mouse while keeping the key pressed (e.g., users can rotate their view up/down by moving the mouse forward or backward).

Positions of targets during the training phase and in each of the actual tests were varied, to prevent learning effects. In the training phase as well as during the tests, users were provided with a color printed sheet showing all targets and their names, as depicted in Fig. 6, to avoid possible misunderstandings and ambiguities in target recognition that could be caused by giving only names. During the training phase only, users were also allowed to look at a printed map showing the global structure of the geographic VE. This helped users to acquire limited survey knowledge of the VE to reduce the length of the training phase and limit the initial disorientation during the tests in any of the four conditions.

After the training phase, users performed the tests, searching for specific targets inside each VE. The order in which users had to find targets was specified through a

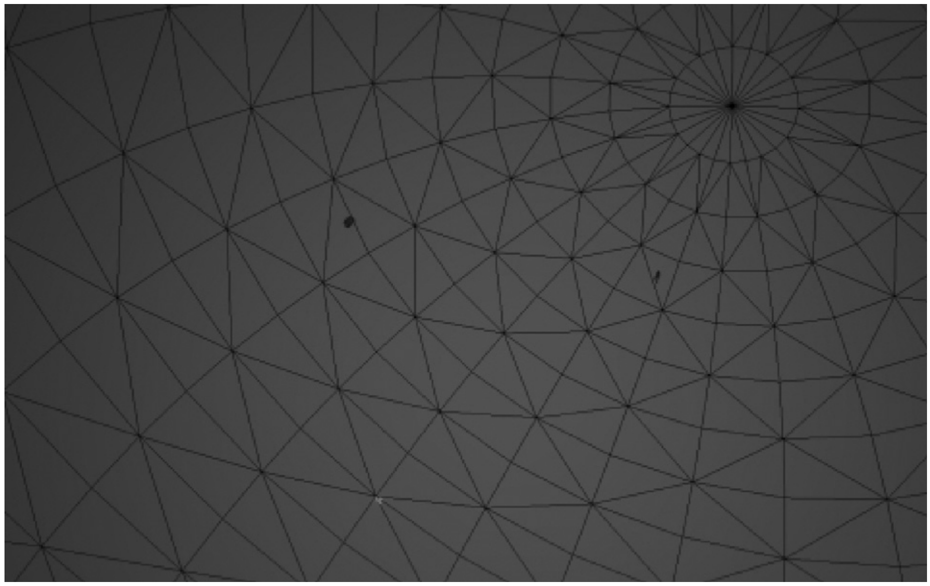


Fig. 5. The abstract VE used for the fly navigation mode.

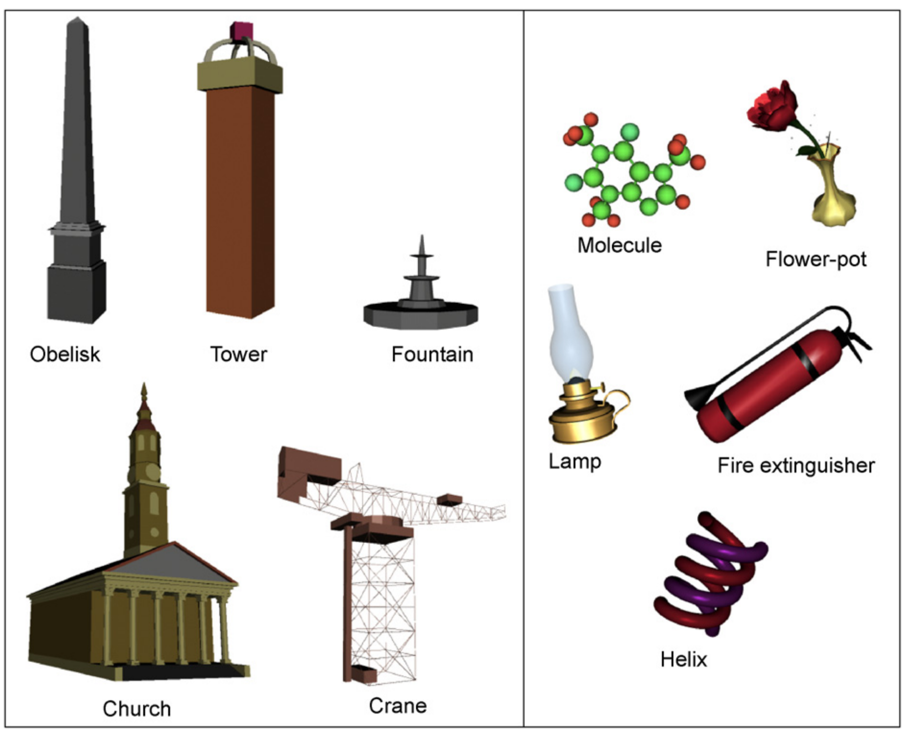


Fig. 6. Targets used in the geographic VE (left) and in the abstract VE (right).

panel in the upper part of the screen. At the beginning of a test, the panel displayed the word ''Start'' and users had to click it to make the first target name appear (see Fig. 7). The target name disappeared after 5 seconds and re-appeared when users reached the correct target. After reaching a target, users clicked on the panel to get the next target name. After getting a target, users selected its name in the selection menu and followed the directions provided by the navigation aid currently employed, except in the control condition where no navigation aid was available and users needed to blindly search for targets. Targets in the selection menu were displayed in the same order of targets to be searched for.

All possible care was taken to counterbalance learning effects due to repetitive testing:

- The order of the worlds was balanced, i.e. half users in each of the two groups carried out the tasks in the geographic VE first, while the other half carried out the tasks in the abstract VE first.

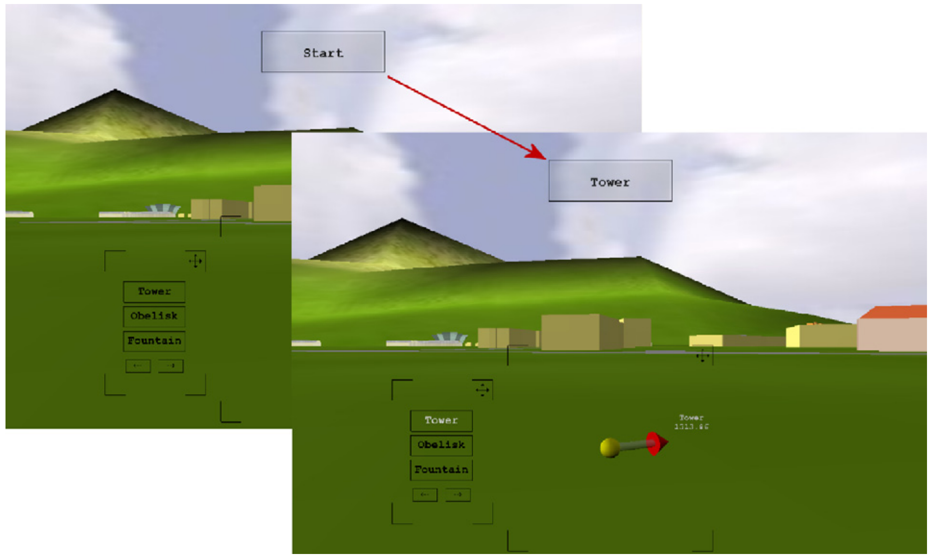


Fig. 7. The panel showing the name of the target to be reached.

- Every user in each of the two groups was presented with a different order of the experimental conditions.
- Five different configurations of targets were produced for each VE, one for the training phase and four for the tests. Total distance the user had to travel to carry out the search task was kept constant. Considering total angular distance needed to align with the targets, there were very small differences among target configurations and their influence, with respect to the total time needed to complete a test session, was negligible.
- There was no fixed association between 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 possible effects of the slightly different angular distance that we previously mentioned.

In each condition, the time spent by the user to find the five targets was recorded by logging code. After the conclusion of the tests, for each of the two VEs, users were asked to express their preference by ordering the four navigation conditions from the best to the worst one with respect to their ease of use and with respect to the usefulness of the provided information.

5. Results

5.1. Navigation performance

A two-way mixed-design analysis of variance (ANOVA) has been performed on the recorded times, for each of the two considered VEs. The within-subjects variable was the availability of navigation aids with four levels: no aids (CTRL), 2D arrows (2DARR), radar (2DRAD), 3D arrows (3DARR). The between-subjects variable was the type of user with two levels: experienced users and inexperienced users. The dependent variable was the time required to complete the task.

5.1.1. Geographic VE

For the geographic VE, the ANOVA revealed a significant main effect for both navigation aid ($F(3,138) = 288.57, p<0.0001$) and type of user ($F(1,46) = 127.69$, $p<0.0001$). There was also a significant interaction effect between the two factors ($F(3,138) = 12.95, p<0.0001$). Therefore, we employed the Bonferroni post-hoc test for comparison among cell means.

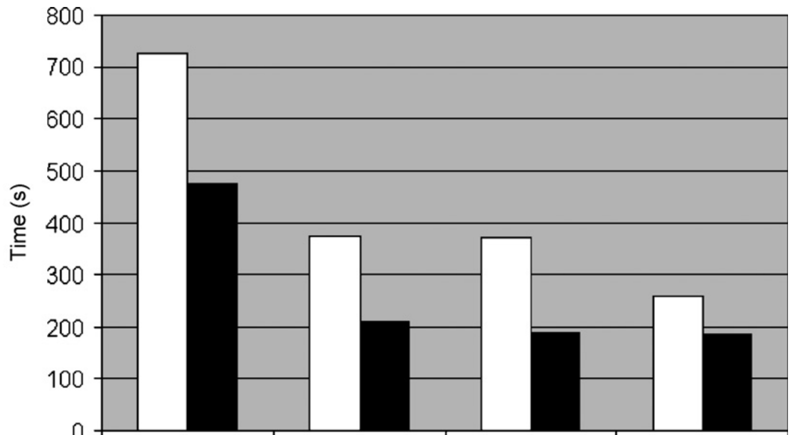
Mean search times for inexperienced users are shown in Fig. 8. Users spent significantly more time to search for targets in the CTRL condition than they did in the 2DARR ($t = 17.53, p<0.001$), 2DRAD ($t = 17.58, p<0.001$), and 3DARR ($t = 23.18, p<0.001$) conditions, and search time in the 3DARR condition was significantly lower than search time in the 2DARR ($t = 5.66, p<0.001$) and 2DRAD ($t = 5.60, p<0.001$) conditions.

Mean search times for experienced users are shown in Fig. 8. Search time in the CTRL condition was significantly higher than search time in the 2DARR ($t = 13.23$, $p<0.001$), 2DRAD ($t = 14.31, p<0.001$), and 3DARR ($t = 14.47, p<0.001$) conditions, while there was no statistically significant difference among the three navigation aids.

Moreover, experienced users took significantly less time than inexperienced users to complete the search task in the CTRL ($t = 10.92, p<0.001$), 2DARR ($t = 7.15, p<0.001$), 2DRAD ($t = 8.05, p<0.001$), and 3DARR ($t = 3.27$, $p<0.01$) conditions.

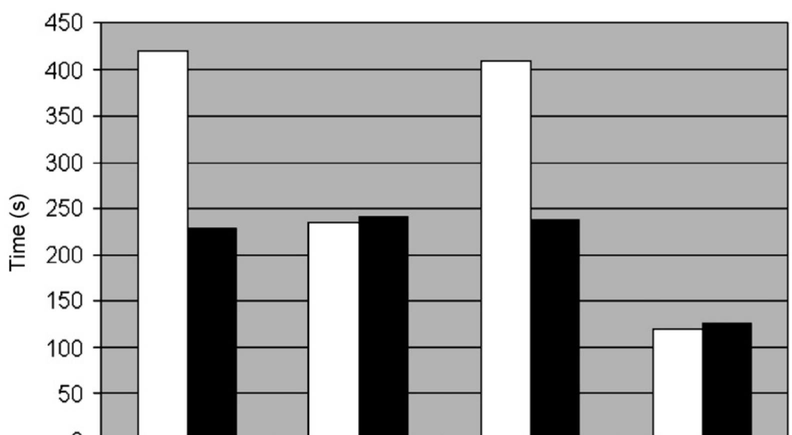
5.1.2. Abstract VE

For the abstract VE, the ANOVA revealed a significant main effect for both navigation aid ($F(3,138) = 48.47$,



	CTRL	2DARR	2DRAD	3DARR
□ Inexperienced users	728	374	373	260
■ Experienced users	477	210	188	185

Fig. 8. Comparison between mean search time for experienced and inexperienced users in the geographic VE, grouped by navigation aid.



	CTRL	2DARR	2DRAD	3DARR
□ Inexperienced users	420	236	410	121
■ Experienced users	230	242	238	127

Fig. 9. Comparison between mean search time for experienced and inexperienced users in the abstract VE, grouped by navigation aid.

$p < 0.0001$) and type of user ($F(1, 46) = 13.80, p < 0.0001$). There was also a significant interaction effect between the two factors ($F(3, 138) = 15.90, p < 0.0001$).

Mean search times for inexperienced users are shown in Fig. 9. Using the Bonferroni post-hoc test for comparison among cell means we found that search time in the 3DARR condition was significantly lower than search time in the CTRL ($t = 23.12, p < 0.001$), 2DARR ($t = 8.90, p < 0.001$), and 2DRAD ($t = 22.36, p < 0.001$) conditions, and search time in the 2DARR condition was significantly lower than search time in the CTRL ($t = 14.22, p < 0.001$) and 2DRAD ($t = 13.46, p < 0.001$) conditions.

Mean search times for experienced users are shown in Fig. 9. Users spent significantly less time searching for targets in the 3DARR condition than they did in the CTRL ($t = 7.96, p < 0.001$), 2DARR ($t = 8.92, p < 0.001$), and 2DRAD ($t = 8.50, p < 0.001$) conditions, while there were no statistically significant differences among other pairs of conditions.

Moreover, experienced users search time was significantly lower than inexperienced users search time in the CTRL ($t = 11.69, p < 0.001$) and 2DRAD ($t = 10.65, p < 0.001$) conditions, while it was not significantly different in the 2DARR and 3DARR conditions.

5.2. Subjective preference

To analyze the data on subjective preference, we employed Friedman's test separately for experienced and inexperienced users. Since users were asked to rate the four navigation conditions from the best to the worst, we assigned a score of 4, 3, 2, 1, respectively, to the first, second, third, and fourth condition.

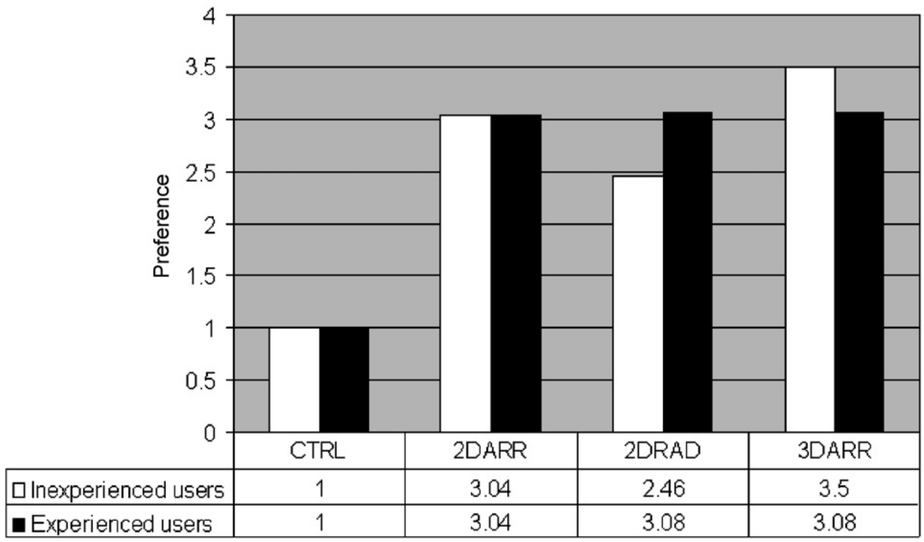


Fig. 10. Comparison between mean preference for experienced and inexperienced users in the geographic VE, grouped by navigation aid.

5.2.1. Geographic VE

For inexperienced users in the geographic VE, Friedman's test ($t = 51.05, p<0.001$) pointed out a significant effect for navigation aid. Mean preference is shown in Fig. 10. We employed the Dunn test for post-hoc analysis among total ranks. There was a statistically significant difference between the 3DARR and 2DRAD conditions ($p<0.05$), with users preferring the first one, and users preference for the CTRL condition was significantly lower than their preference for every navigation aid condition ($p<0.001$).

For experienced users in the geographic VE, Friedman's test ($t = 43.80, p<0.001$) pointed out a significant effect for navigation aid. Mean preference is shown in Fig. 10. There was no statistically significant difference among the three navigation aids in terms of user preference while preference for the CTRL condition was significantly lower than preference for every navigation aid condition ($p<0.001$).

No statistically significant difference was found between experienced and inexperienced users preferences in each condition.

5.2.2. Abstract VE

For inexperienced users in the abstract VE, Friedman's test ($t = 46.80, p<0.001$) pointed out a significant effect of navigation aid. Mean preference is shown in Fig. 11. Dunn's post-hoc analysis showed that user preference for the 3DARR condition was significantly higher than preference for the CTRL and 2DRAD conditions ($p<0.001$) while there was no statistically significant difference with respect to the 2DARR condition. Moreover, preference for the 2DARR condition was significantly higher than preference for the CTRL ($p<0.001$) and 2DRAD ($p<0.05$) conditions.

For experienced users in the abstract VE, Friedman's test ($t = 44.15, p<0.001$) pointed out a significant effect for navigation aid. Mean preference is shown in Fig. 11. Dunn's post-hoc analysis showed that user preference for the 3DARR condition was significantly higher than preference for the other conditions ($p<0.001$) while there was no statistically significant difference among other pairs of conditions.

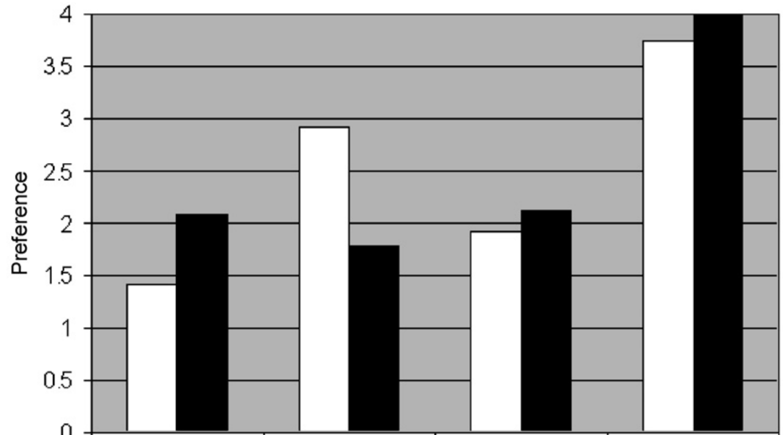
A statistically significant difference was found between experienced and inexperienced users preference for the 2DARR condition ($p<0.05$).

6. Discussion

The results of our study show that there are significant differences in how much inexperienced users benefit from the considered navigation aids compared to experienced users, and that these differences are strongly influenced by the VE where navigation takes place.

In the geographic VE, all navigation aids were effective in supporting both experienced and inexperienced user navigation when compared to the CTRL condition. This was expected because, without aids, users needed to blindly explore the VE to find targets, thus taking much more time to complete their tasks. It is also unsurprising that experienced users performed significantly better than inexperienced users in all conditions, because of their familiarity with navigation in 3D spaces. Analyzing the effectiveness of navigation aids for each of the two groups of users, we found that 3D arrows allowed inexperienced users to obtain better results than the other aids, while they were as effective as 2D arrows and radar for experienced users. The difference may be due to a higher difficulty for inexperienced users to map the information provided by 2D arrows and radar from the view plane to the walk plane, a process that is not needed for 3D arrows and that experienced users seem to be able to perform more quickly.

In the abstract VE, the total lack of effectiveness (with no difference from the CTRL condition) of navigation aids in the 2DARR and 2DRAD conditions for experienced



	CTRL	2DARR	2DRAD	3DARR
□ Inexperienced users	1.42	2.92	1.92	3.75
■ Experienced users	2.08	1.79	2.13	4

Fig. 11. Comparison between mean preference for experienced and inexperienced users in the abstract VE, grouped by navigation aid.

users was unexpected: by discussing with users, we found that many of them had trouble understanding how to interpret the information provided by these navigation aids while performing 3D rotations in the VE. Surprisingly, we did not obtain a similar result for inexperienced users, since there is a significant difference in user performance between the CTRL and 2DARR conditions while there is no difference between the CTRL and 2DRAD conditions. A possible explanation is that inexperienced users, having more difficulties navigating a VE, benefit more than experienced users from the information provided by navigation aids that exploit known metaphors (such as the arrows) while they do not benefit from information provided by less common metaphors (such as the radar). Both experienced and inexperienced users obtained the best performance in the 3DARR condition. While in the geographic VE users did not employ the automatic alignment feature provided by 3D arrows (probably because it required more time than manually aligning with the target), in the abstract VE all users employed it, even if it generally required an amount of time that was comparable to manual alignment. The result we obtained is thus likely due to the accuracy of the direction indication provided by the 3D arrows and by the automatic alignment feature, opposed to the difficulty for users to determine the correct direction of targets positioned in 3D space in the other conditions. Another interesting result is that in the 3DARR condition there is no significant difference between experienced and inexperienced users performance, which makes it the best condition for fly navigation mode, regardless of the type of user. Moreover, experienced users performed significantly better than inexperienced users in the CTRL and 2DRAD conditions, but there was no significant difference in the 2DARR condition. These two last results suggest that, in VEs where rotations in any possible direction are needed, navigation aids using known metaphors similarly help users with different levels of experience, while the navigation abilities of experienced users are fundamental when no navigation aids or navigation aids employing uncommon metaphors are used.

The analysis of experienced user preferences shows that the subjective perception of these users is consistent with their performance results in both the geographic and abstract VEs: statistically significant differences in mean search times corresponded to statistically significant differences in mean preference between the same pair of conditions. Subjective preference of inexperienced users was consistent with their performance results as well.

In the end, the fourth hypothesis we made was confirmed, since 3D arrows turned out to be the best navigation aid in the abstract VE. The first hypothesis, which stated that all navigation aids should improve user performance when compared to a condition without aids, was verified in the geographic VE but not in the abstract VE. This stresses the need for navigation aids to take into specific consideration the peculiarities of the VE where they will be used. Since the 2D radar and 2D arrows were not adapted to navigation in an environment where users have free orientation, they turned out to be completely ineffective. The second hypothesis, which stated that experienced users would perform better than inexperienced users, was confirmed in the geographic VE but was not confirmed in the abstract VE. When rotations in any possible direction are possible, user experience seems to play an important role only in the most difficult conditions, such as when there is no navigation aid or when a navigation aid exploits metaphors that are not very common. The third hypothesis, which stated that in the geographic VE there should be no performance differences among the aided conditions within each of the two user groups, was confirmed for experienced users but was not confirmed for inexperienced users, who seem to benefit more from navigation aids that provide direct information to guide their navigation (such as the 3D arrows), rather than information that must undergo some form of mental translation to be used for navigation, such as for the other two navigation aids.

Considering the specific navigation aids and task (informed search) we studied, our results show that some form of 3D indication is an appropriate solution both for traditional desktop VEs where users walk in a 2D plane and only perform translations and rotations along their main axis, and for desktop VEs where users need to translate and turn in any direction. However, to possibly generalize this result, we need to extend our investigation to other types of navigation aids and VEs. For example, it would be interesting to take the complexity of the environment into explicit consideration as a factor. However, we think that in environments such as mazes, absolute indications such as those provided by the aids we studied would not perform well. In this case, employing arrows that guide users along the shortest path to reach a target may provide more appropriate indications.

Overall, our study highlights the need to take into specific consideration the experience of users in navigating desktop VEs when designing navigation aids and studying their effectiveness. Unfortunately, most of the experimental studies available in the literature on navigation aids do not distinguish between experienced and inexperienced users. As a result, the conclusions they reach often risk being overgeneralized. Navigation aids that are appropriate for experienced users may actually not provide a suitable level of support for inexperienced users and solutions that may improve the navigation performance of inexperienced users may not benefit experienced users beyond a certain degree.

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