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Active and passive spatial learning in a complex virtual environment: The effect of effcient exploration

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Abstract - In natural and virtual environments (VE) spatial learning depends on several factors including the spatial goal, environmental complexity and mode of learning. A factor influencing the *mode of learning* is the extent to which exploration is self-governed. The aim of this study was to investigate the effect of active (*self-governed*) vs. passive (*avatar-guided*) exploration on the organization of spatial knowledge of a large-scale VE in a wayfinding task. In particular, we wanted to test the hypothesis that *self-governed* exploration promotes the creation of a survey-type representation when participants are requested to *explore efficiently* (i.e. avoid repeatedly traversing the same paths).

Twenty male participants were randomized to a passive group or an active group; both groups performed a two-phase task. In the first phase (*learning phase*), they learned an unfamiliar large-scale closed VE on two floors with a cross shaped ground plan. The passive group learned by following an avatar; the active group explored at will. All were instructed to find, in the shortest possible time, target flags positioned through the VE. In the *test phase*, participants' spatial knowledge was assessed by three tasks: wayfinding (one session), pointing to the starting point of a traveled path (four sessions), and producing a sketch map of the VE. In the wayfinding task, 7 active participants found the way against 2 in the passive group. Among participants who found the way 5/7 in the active group have drawn a survey-type (hierarchically organized) map while none of the 2 in the passive group produced a map of this type.

As expected, the groups did not differ in performance of the pointing tasks. These findings support the hypothesis that self-governed explorations in a VR are favored if spatial knowledge is organized in survey mode.

Key words: spatial learning, virtual environments, active/passive learning, efficient exploration.

Introduction

Interest in virtual environments (VEs) as tools for exploring spatial knowledge is expanding (Péruch and Gaunet, 1998; Wilson, 1997). A VE is a three-dimensional computer-generated environment that users can explore and interact with in real-time. Several authors have shown that VEs have significant potential as

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instruments for promoting the acquisition of spatial knowledge and accumulating evidence indicates that the spatial knowledge acquired in VEs is substantially similar to that acquired in real environments (O'Neill, 1992; Regian, Shebilske and Monk, 1992; Ruddle, Payne and Jones, 1997; Stanton, Wilson and Foreman, 1996; Tlauka and Wilson, 1996).

A variety of factors affect spatial learning. These include the *nature of the activity* the spatial knowledge supports (e.g. searching for objects or finding the way to a target), the *type of environment* (e.g. closed or open, large or small, barren or rich in landmarks) and the *mode of learning* (e.g. driving a car or traveling as a passenger). VEs have great potential for creating experimental contexts in which these factors can be varied systematically and their importance explored. Environments can be created with virtually any desired characteristics and with numerous kinds of activities that the participant can engage in; they can incorporate simulated movements and actions that allow the user to experience the effects these have on the environment. This interactive presentation of the environment may endow the user's internal representations with the same qualities that result from the exploration of real space (Wilson, Foreman, Gillett and Stanton, 1997).

The current literature with regard to VEs is mainly concerned with two learning modes (Wilson, Foreman, Gillett and Stanton, 1997). In the first of these the participant can experience a dynamic three-dimensional simulation either *physically* passively (observing a pre-recorded tour in the VE) or *physically* actively (navigating within the VE using a joystick or keyboard). In the physically active condition the participant has control of his/her movements, observes the environment via active perception – a form of perception in which the visual stimuli depend on the participant's actions in a closed cycle (Gibson, 1979) – and has the freedom to choose from a variety of possible views in order to gain familiarity with the environment.

In the second mode, a participant can either explore an environment freely, or is constrained to follow certain routes; these two possibilities have been called *psychologically* active and *psychologically* passive, respectively, by Wilson, Foreman, Gillett and Stanton (1997) to distinguish them from *physically* active and passive.

In experimental learning situations involving VEs the physical and psychological active/passive conditions can be combined in various ways making it possible to create a series of fundamentally different spatial knowledge learning situations. Several recently published studies have investigated the effects of exploration conditions spanning the active/passive dichotomy on spatial learning – both from the physical and psychological point of view. In particular, Larish and Andersen (1995), Péruch, Vercher and Gauthier (1995) and Wilson, Foreman, Gillett and Stanton (1997) compared free movement in an environment with exposure to a continuous flow of scenes corresponding either to a recorded pre-determined exploration path, or to a series of static, slide-like pictures selected from the same recorded path. In other studies learning in physically active but psychologically passive conditions was compared to that in physically and psychologically passive conditions of different types (involving observations of continuous visual sequences or selected snapshot) (Gaunet, Vidal, Kemeny and Berthoz, 2001). In all these experimental situations, the cause of the performance differences could not be established unequivocally: physical interactivity, freedom of choice, or both? The results to date have been discordant and definitive conclusions not forthcoming.

In our view, the problem can be better faced if a theoretical position is assumed on the nature of spatial representations that learning induces. We accept the theoretical hypothesis that spatial knowledge of large-scale environments is organized into *route* or *survey* maps (Golledge, 1990, 1999; Kitchin and Freundschuh, 2000). The characterization of such maps is a matter of controversy, but it is generally agreed that in *route* maps the environment is represented in a viewer-centered frame of reference that reflects the person's navigational experiences, while in *survey* maps distant places are linked together to form a coherent global overview of the entire environment. Although the classic literature on the development of spatial representations has largely been described through the "landmark-route-survey" model (e.g. Siegel and White, 1975; Chown, Kaplan and Kortenkamp, 1995) that there is a systematic development towards survey maps is not universally accepted. In many situations survey maps are never constructed (Moeser, 1988) or take a long time (years of experience) to develop (Thorndike and Hayes-Roth, 1982); the reasons for this are either that the environment is too complex or that simpler representations are perfectly adequate for the needs of the individual concerned. Furthermore, it has been shown that survey maps are not necessarily created or derived from route maps in a rigid progression (Lindberg and Gärling, 1982).

We hypothesized in this study that psychologically active exploration facilitates the organization of spatial knowledge into a survey map, but *only* when one must or one wants to explore the environment in the most efficient way possible – traveling the same paths as least as possible (*efficient exploration*). In fact, in such a condition, the participant is free to choose his or her own routes but has to avoid getting lost and re-visiting the same places, he or she will therefore be forced to reason about the relative positions of landmarks – particularly distant ones – encountered during the exploration. This will facilitate the formation of tentative panoramic views of the environment which are revised during the exploration. Such views may occur in parallel with the formation of a route map. Furthermore, the routes chosen for exploration will probably be those the participant considers most likely to promote the formation or checking of hypotheses about the structure of the environment; this further encourages the formation of a survey map.

As noted, most spatial behavior does not require a survey-type representation. However survey representations render certain spatial tasks – in particular way-finding in a complex environment in which it is difficult to orient oneself – more effective. While moving in such an environment, it is necessary to continually check one's position and this is much easier if there is an integrated representation of the entire environment to refer to (Thorndyke and Goldin, 1983; Darken, 1995; Chen and Stanney, 1999). Moreover, one of the most important characteristics of survey representations is that they allow the planning in advance of new shortcuts connecting distant landmarks, i.e. landmarks not visible at the same time (Carassa and Geminiani, in press).

For other spatial tasks, such as *pointing* to an unseen target on the traveled path, the construction of a survey representation would not seem help performance.

We therefore devised an experiment to compare wayfinding performance within a complex environment under two learning conditions: an active condition, in which participants explored freely with the constraint that they explored efficiently (*self-governed*) and a passive condition, in which the exploration took place following the route prescribed by an avatar (*avatar-guided*). For the latter condition the participants had to follow the avatar but were permitted to move freely nearby. This allowed them to position themselves so as to gain additional perspectives of their environment and to direct their attention to aspects of it for as long as they wanted. Compared to the yoked pair experimental procedure (where an active participant explores freely and the "attached" passive participant can only observe the scenes brought to light by the former's exploration), the avatar-guided procedure provides certain features of exploration which, as emphasized by several authors, are important for the construction of spatial representations, for example the possibility of obtaining multiple views (see for example Christou and Bülthoff, 1999). We expected better performance in the wayfinding task when spatial knowledge was organized into survey-type in representations: that is in the group who were allowed *self-governed* exploration.

Methods

Materials

A relatively complex VE was created using the Superscape software version 5.6 (Bussolon and Varotto, 2000). It was a two-floor cross-plan building (see Figure 1), closely similar to a real building (a school) where previous wayfinding experiments had been conducted (Carassa, Aprigliano and Geminiani, 2000). The plan of the real building was scanned into a computer and used to create two distinct layers (one for each floor) on a 1:10,000 scale (1m in the real environment corresponding to 10,000 virtual units); the total area of the VE corresponded to 1,443.2 m^2. The VE was completely empty, there were no objects that could be used as landmarks. In order to prevent opened and closed doors serving as signs of previous exploration, all doors were timed to close one minute after being opened. Participants were allowed to enter in all rooms but were not allowed to open doors exiting the building or to navigate outside the building.

The VE was presented on an IBM computer with an Intel Pentium II 400 MHz processor, main RAM 196 Mb, and a Diamond Viper 770 AGP video card processor with 32 Mb of Video RAM. This hardware allowed a 25 fps providing a reasonably fluid impression of movement. The viewpoint was set at a height of 17,000 virtual units, corresponding to the eye position of a 1.70 m tall person.

Participants explored the VE, and interacted with objects within it, using a joystick. The joystick had been modified by placing two keys at the apex permitting the control forward and backward movements using the thumb only, and a frontal key to allow the opening and closing of doors using the index finger. For exploration, participants donned a head-mounted display (Virtual Research V8) with a 60° horizontal visual angle so that they were totally immersed within the environment.

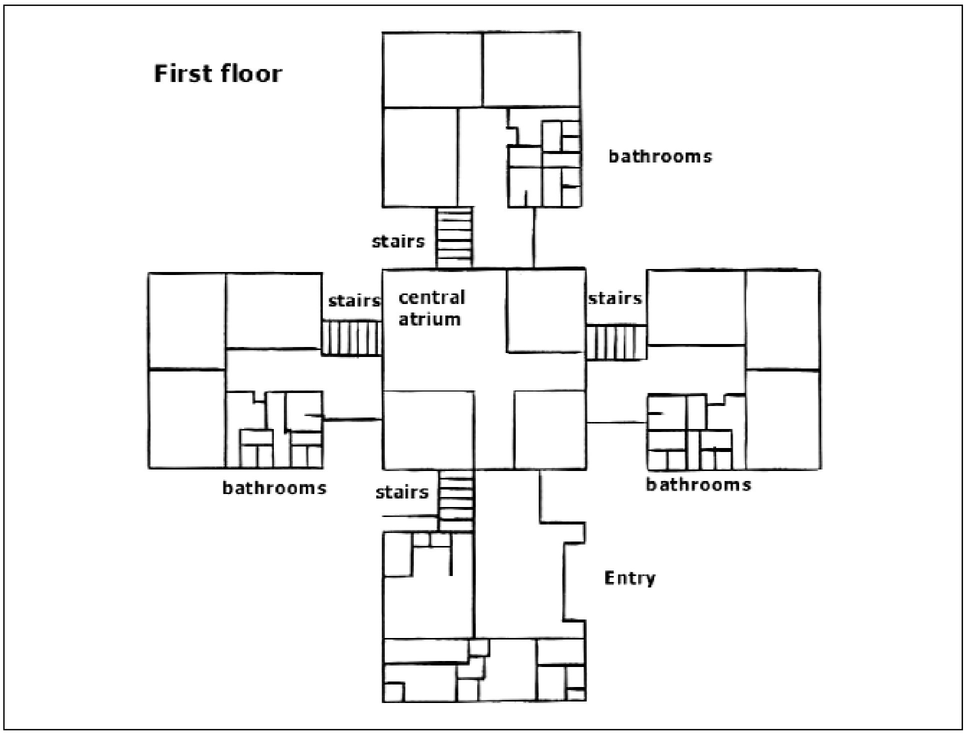

Fig. 1. Plan of the ground floor of the experimental virtual environment.

Participants could modify their view-direction movement rotating the head for 360° only in horizontal plane. When participant intended to change direction of exploration he had to rotate the head in that direction. It was not possible to move in one direction while looking in a different direction.

The display received a 640 × 480 pixel color image whose brightness could be adjusted with a control box. In addition, the head-mounted display was connected to a Inter Trax-Intersense gyroscopic sensor, which sent rotational and translational data to the PC via an RS232 port. Thus, the software was able to detect the participant's position within the environment. In particular head rotation on the vertical (y) axis was detected by the sensor (rotation on the x-axis was disabled), translation on the forward-backward direction (z-axis) was detected by the joystick, with consequent updating of the virtual scene on the display.

For the *avatar-guided* condition we created a virtual guide who walked about in the environment leading the participants to specific areas. The avatar was programmed using SCL (Superscape Control Language) code to follow pre-defined paths and to adjust its velocity on the participant's velocity.

A file containing the x, y, and z coordinates of a given participant every 500 ms within the VE was produced for each environmental exploration session. We created an application to read these files and provide a pictorial representation of the movements of the participant within a two-dimensional plan of the environment.

Participants

Twenty male students, age 20-26, from various faculties of the University of Padua, Italy, participated in the study as paid volunteers. They were randomized to two groups: the *self-governed* (active) exploration group and the *avatar-guided* (passive) exploration group. None of the participants had had previous experience of the VE used in the experiment, or of the real building used to a model the VE.

Procedure

After a 10 minute training session in a VE different from the experimental one, the participant embarked upon the two phase experimental procedure. In the first or *learning* phase the participant had to explore the VE searching for eight target rooms. Participants were informed previously that their spatial abilities would be tested in the subsequent test phase involving the performance of a way-finding task, four pointing tasks, and production of a sketch map.

1. *The learning phase*.

In the *self-governed* condition participants started their exploration at the entrance of the building. They had four sessions of 10 minutes to explore; each ten minute exploration was separated by a 10 minute rest. Each new exploration recommenced from the position reached at the end of the preceding session. These periods were chosen so as to minimize the risk of cyber-sickness with the least number of pauses. The total exploration time of 40 minutes was sufficient to explore the whole building. Participants were instructed to freely explore ("walk about") the environment with the constraint to efficiently explore (i.e. they were requested to search for the greatest number of target places in the total time).

In the *avatar-guided* condition participants were required to follow an avatar, but could move about freely nearby. The avatar was programmed to wait until the participant was ready to follow. There were eight sessions of five minutes, with a five-minute break between each. At each session the avatar conducted the participant from the building entrance to the entrance of each of the eight parts of the building in turn (four wings per floor). Having arrived at the wing entrance the avatar disappeared and the participant was free to explore at will that wing only. This arrangement allowed the participant to explore each wing and reduced the chance of him/her getting lost. Figure 2 shows the avatar-guided paths on the ground floor.

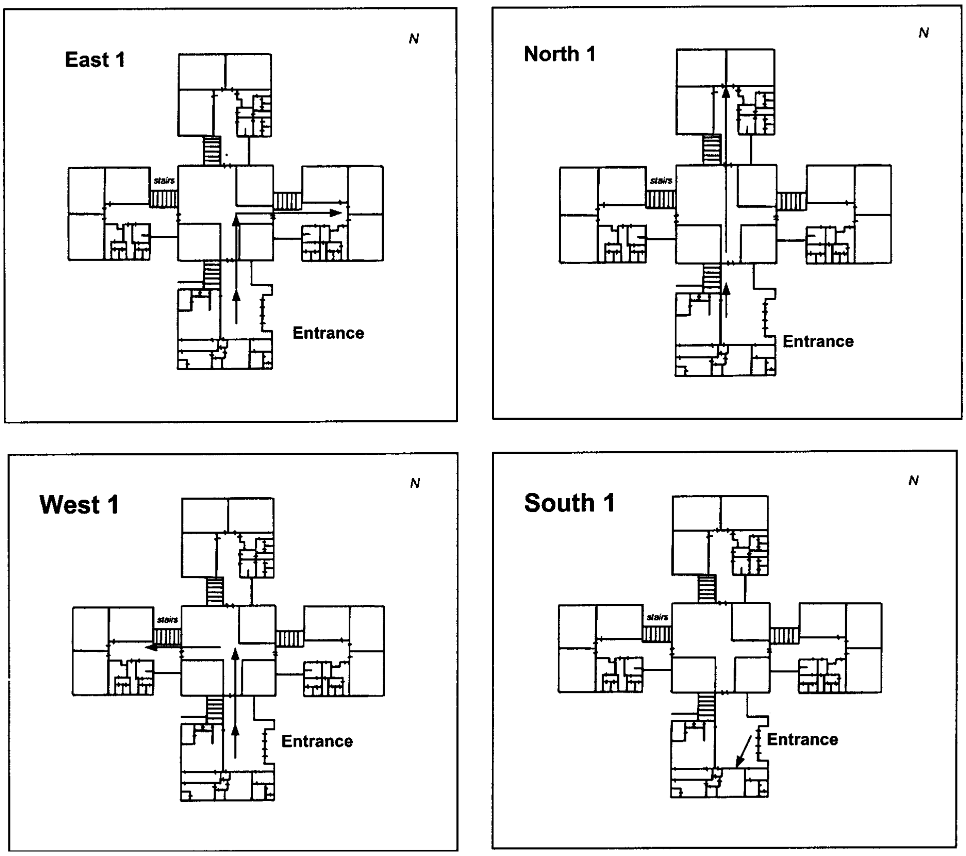

Fig. 2. Avatar-guided paths on ground floor.

2. *Test phase*.

In the *wayfinding* task, the participant was avatar guided along a complex path that started on the first floor, passed thorough the ground floor and ended at a place of the first floor different from the starting point (see Figure 3a). The task was to return to the starting point by the shortest route (see Figure 3b).

Each participant's path was recorded on the two-dimensional representation and a wayfinding optimization score calculated. In the calculation one point was awarded for each of the following:

1. Participant explored first floor only.
2. Participant reached and stopped exploring at the target corridor (participant did not go on to explore other corridors).
3. Participant went directly to the target corridor, and stopped exploring there, without previously exploring other corridors (implying participant had correctly identified the target corridor relative to the central atrium (Figure 1).

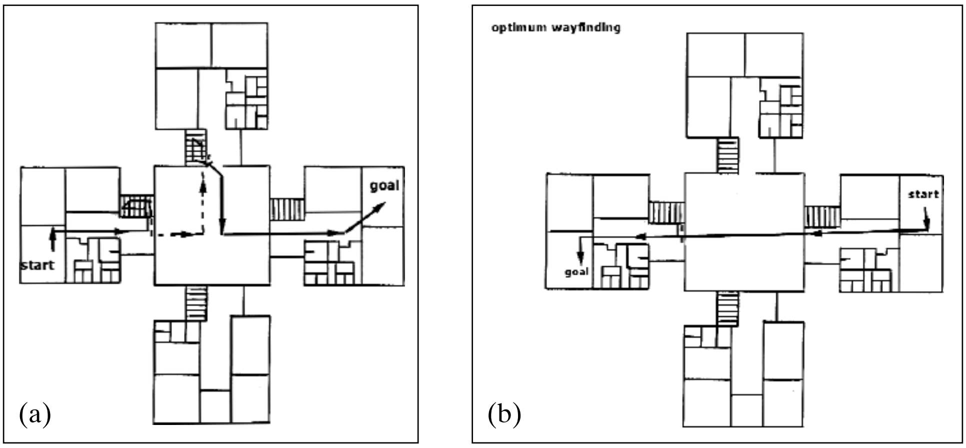

Fig. 3. (a) Avatar path in wayfinding task for both exploration conditions. (b) Optimum wayfinding path.

4. Participant reached target corridor and stopped exploring there without previously exploring rooms in other corridors (implying participant had recognized he/she had entered a non target corridor without needing to explore the rooms of that corridor to confirm this).
5. Participant reached target room and stopped exploring (participant recognizes target room).
6. Participant reached target room and stopped exploring without previously exploring other rooms in the target corridor (implying participant knew position of target room within target corridor).
7. Participant reached target room crossing the atrium once only (this is the one possible shortcut).

The possible score was therefore in the range 0-7, with higher score implying closer approach to optimum wayfinding.

The hypothesis was that self-governed participants would show better performances in the wayfinding task.

For the pointing task the participant was first avatar-guided along a route within the VE. At the end of the route the participant had to orient him/herself so as to be facing the direction of the point of origin of the route. There were four routes with four different endpoints, which varied in difficulty for the number of turns and whether or not there was a floor change (see Figure 4). Each route started from the entrance of the building on the ground floor of the south wing. The north1 and east1 routes included one and two turns respectively and did not include a floor change. The west2 and north2 routes had one and two turns respectively and both ended on the first floor. The angular difference between the facing (pointing) direction and the actual direction of landmark was noted for each participant.

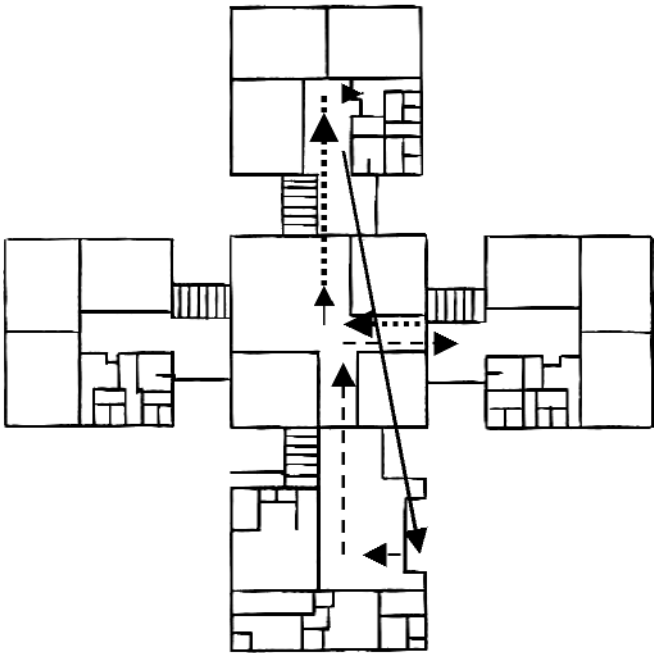

Fig. 4. Example of an avatar-guided path on the ground floor (----) and on the first floor (....) in the pointing task. The continuous arrow shows the correct pointing direction.

The hypothesis here was that the pointing can be performed successfully if the participant continually updates the estimate of his/her actual position relative to the position of the origin (Gaunet, Vidal, Kemeny and Berthoz, 2001). This may be done by continuously updating the vector between the explorer's position and the origin. As the participant follows the avatar and makes more turns he/she is participant to cumulative error in the updating so the angular error in pointing is expected to increase. According to this hypothesis, there should be no difference between the two groups in the performance of this pointing task.

The final task was to draw a sketch map of the virtual building, from which map local accuracy and presence of a survey-type organization were assessed. The map was considered locally accurate if at least one group of elements consisting of 3Í1 rooms, a staircase, a toilet block, and corridor was represented.

The map was considered to indicate survey-type organization if it contained a hierarchic organization of clusters of elements and if the spatial relations between them was also represented (wings of building arranged in a cross with central atrium). Our hypothesis was that the local accuracy of the map would be similar in the two groups, while the survey-type organization would be more frequent in the self-governed explorers.

Results

The individual test phase results are summarized in Tables 1 and 2. Seven of the 10 self-governed explorers and 2 of the 10 avatar-guided explorers successfully performed the wayfinding task (chi-square=5.05, Fisher exact probability = 0.03); 3 self-governed explorers and 2 avatar-guided explorers did so taking the shortcut. The wayfinding score was significantly higher in the self-governed group than avatar-guided group (Mann-Whitney adjusted z = -2.24, p=0.03). Table 3 shows the numbers of participants fulfilling the wayfinding criteria by group.

To analyze the pointing task results we used repeated measures ANOVA with one "between" factor (group) having two-levels (avatar-guided and self-governed), and two "within" factors, i.e. number of turns in path (two levels: one or two) and change in floor (two levels: change, no change). We found a significant effect only for the factor "number of turns in path" (F(1,18)=12.92, p=0.002): paths with two turns (east1 and north 2) were associated with greater angular error than one turn paths (north1 and west2) (Figure 5). The two groups did not differ significantly with regard to pointing performance, although the avatar-guided group had a lower mean error than the active group (see Figure 6).

Tables 1 and 2 also show the results of the sketch map evaluations. Six participants in each group produced a locally accurate map according to our pre-established criteria. A survey-type organization characterized the maps of 5 out of 10 self-governed participants and 3 out of 10 avatar-guided participants (chi-square=0.83; Fisher exact probability= n.s.); all 5 of these self-governed explorers had a good wayfinding score (>3), but none of the 3 avatar-guided explorers had a good wayfinding score (chi-square=8.00; Fisher exact probability=0.02).

Discussion

As expected, the self-governed explorer group was more successful than the passive group in completing the wayfinding task. In particular 7 of the former group found their way while only 2 of the avatar-guided group did so. Analysis of the paths on the two-dimensional plan showed that the self-governed explorers adopted more efficient strategies in searching for the target (compare the wayfinding optimization scores in each group in Table 3). In fact half the avatar-guided group but none of the self-governed group explored both floors during this task.

Péruch, Vercher and Gauthier (1995) also found better performance in a wayfinding task in the group that had explored the environment actively compared to those that explored it passively. However, individuals of the passive group explored the environment either by looking at a continuously changing scene correspondent to a pre-recorded path or by observing selected static slide-like scenes selected from the same path.

In both these conditions the exploration was both physically and psychologically passive, hence the findings do not shed light on the role of self-governed exploration in wayfinding.

In a paper published in 1997, Wilson, Foreman, Gillett and Stanton investiga-

Table 1. *Performance of active explorer group in test phase.*

Participant	Wayfinding score	Pointing error	Sketch map	
			Accurate	Survey-type organization
1	6	36.5	Yes	no
2	4	44.3	No	yes
3	4	16.0	No	no
4	1	70.3	No	no
5	3	33.5	No	no
6	1	32.2	Yes	no
7	7	34.7	Yes	yes
8	5	25.6	Yes	yes
9	7	11.0	Yes	yes
10	4	22.9	Yes	yes
Mean (SD)	5.6 (2.9)	32.7 (16.6)		

Table 2. *Performance in the test phase in the avatar-guided group.*

	wayfinding score	pointing error	Sketch map	
			accuracy	survey organization
1	1	35.5	no	no
2	1	8.4	no	no
3	0	6.8	yes	no
4	7	78.7	no	no
5	1	7.7	yes	no
6	0	12.3	no	yes
7	0	14.2	yes	no
8	0	17.8	yes	yes
9	0	49.8	yes	yes
10	7	50.6	yes	no
Mean (SD)	2.6 (3.4)	28.2 (24.5)		

Table 3. *Number of participants fulfilling each criterion of the wayfnding assessment.*

Criterion	**Active exploration**	**Avatar-guided exploration**
1. Participant explored first floor only	10	5
2. Participant reached and stopped exploring at the target corridor	8	2
3. Participant went directly to target corridor, and stopped exploring there, without first exploring	4	2
4. Participant reached target corridor and stopped exploring there without first exploring	7	2
5. Participant reached target room and stopped exploring	6	2
6. Participant reached target room and stopped exploring without previously exploring other	5	2
7. Participant reached target room crossing the atrium once only (optimum wayfinding)	2	2

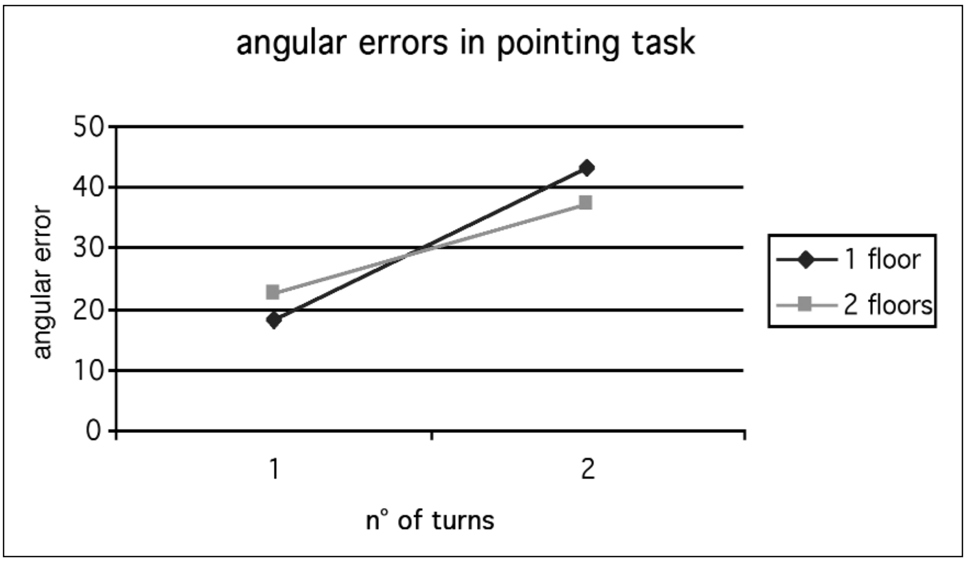

Fig. 5. Angular errors in pointing tasks: interaction between number of turns and number of floors in the path.

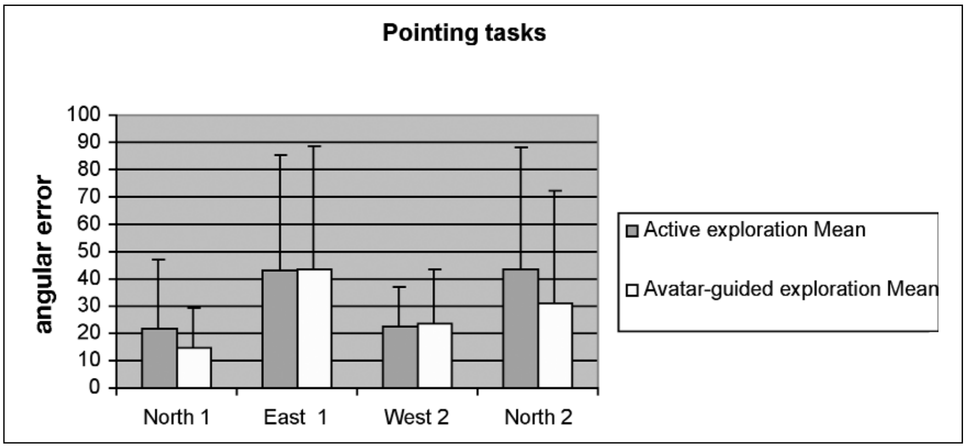

Fig. 6. Mean and standard deviation of angular error in pointing for each group.

ted the importance of an active role in the exploration of a desktop VE, controlling separately for the effect of interaction with the environment (active physical) and for freedom to decide the route (active psychological). Thus these authors had experimental groups in which these two factors were variously coupled; however they found no differences in performance between the groups. This could be because they did not require their participants to explore as efficiently as possible as in our self-governed condition.

As we expected, sketch map local accuracy was similar in both groups. This finding allows us to exclude the possibility that different exploration modes produced different attention to environmental features leading to different performance in local accuracy. The numbers of participants in each groups who produced survey-type maps did not differ significantly. It is possible that other factors could have influenced this performance, such as drawing ability and whether or not a person draws maps frequently (habitually externalized spatial knowledge) (Newcombe, 1985; Blades, 1990; Seibert and Anooshian, 1993; Billinghurst and Wegorst, 1995).

However, an interesting finding was that while all in the self-governed group who drew a map showing survey-type organization successfully completed the wayfinding task, none of those in the avatar-guided group who drew such a map, successfully completed this task. We hypothesized, given the regularity of the environment and absence of landmarks, that ability to successfully complete the wayfinding task depended not only on possession of a good spatial map, but also on ability to relate one's position in the environment to correct map coordinates. In our experimental design this latter ability was repeatedly exercised in the self-governed participants as they explored the environment. Thus the association between wayfinding performance and a survey-type sketch map suggests that self-governed exploration favors the creation of a survey-type organization of spatial knowledge.

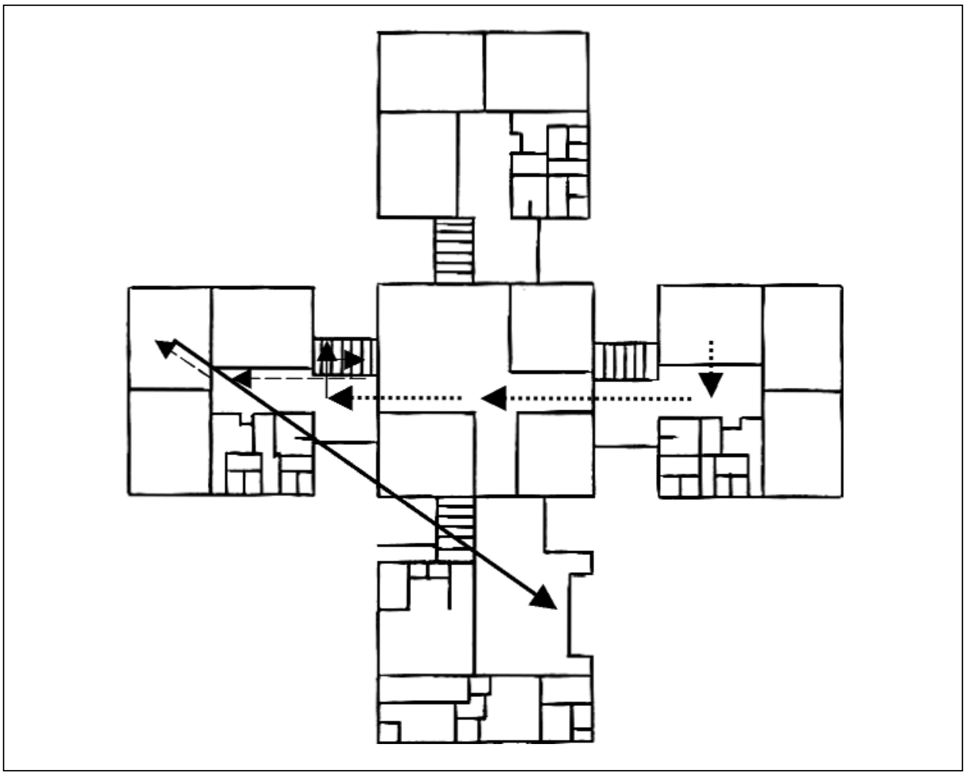

Fig. 7. External pointing task. The figure shows an avatar-guided path in the ground floor (....) and on the second floor (- -); the subject has to pint a landmark place (the entry) out of the path.

Our results did not reveal differences in pointing task performance between the two groups. As expected, however, the number of turns along the route (excluding those on the stairway) did affect performance, while changing floors did not. This suggests that the turns on the stairs were viewed separately in the local reorienting and were not integrated into the overall route. In our hypothesis there was switch to the vertical axis when negotiating the stairs, as occurs when ascending a winding staircase. Thus, to elucidate the role of spatial representations (route or survey) in a pointing task, it would be appropriate to ask participants to point to places not on the traveled path (Figure 7).

In addition to original choice of path having a role in determining the type of representation created in the active condition, we propose that the specific path chosen and traveled during the learning phase would also exert an influence. Analysis of the paths taken by the active participants during learning revealed that the exploration patterns tended to be fairly similar (see Figure 8), that differed markedly from the one take by avatar-guided participants (see Figure 2). A likely reason for this is that active participants had to traverse routes that facilita-

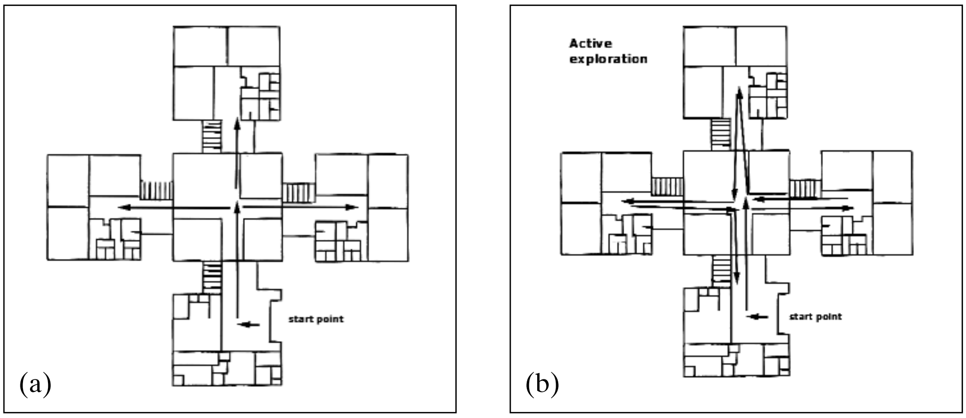

Fig. 8. (a) The avatar-guided paths on the ground floor. (b) The paths performed by an active explorer on the ground floor.

ted reasoning and the creation of an overview of the environment. We suggest that this pattern may not have had the same effect on passive participants if the avatar had used is as the guide route.

To conclude, the active explorers did not do better in all the tasks of this experiment but the differences we did find suggest that the two groups organized their spatial representations differently. We hypothesized that the constraint of efficient exploration would induce participants to create a survey representation while exploring in the learning phase that would allow them to locate themselves in the environment while learning by means of an integrated, though perhaps incomplete, overview, allowing them to avoid exploring the same area more than once. This hypothesis needs to be further explored by comparing active exploration performance with and without the constraint of efficient exploration. Unlike Rossano and Reardon (1999) we are not of the opinion that the best way to develop a survey representation is to explore freely without a specific goal; possibly constraints on *how* to explore the environment are more important than whether or not there is a final destination.

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