Transfer of Spatial Knowledge from Virtual to Real Environments

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Abstract. The transfer of spatial knowledge from virtual to real environments is one important issue in spatial cognition research. Up to now, studies in this domain have revealed that the properties of spatial representations are globally the same in virtual and real environments, and in most cases transfer of spatial information from one kind of environment to the other occurs. Although these results suggest that virtual environments contain much of the spatial information used in real environments, it seems difficult or even impossible to draw any clear conclusion about the spatial information which is transferred and about the conditions of transfer. Being able to quantitatively and/or qualitatively predict and observe such a transfer would broaden the possibilities of training and our knowledge of the cognitive processes involved in spatial behavior. In a first step, arguments in this sense are developed on the basis of a review of some recent studies concerned with the transfer of spatial knowledge between virtual and real environments. In a second step, empirical data are reported, that illustrate the interest and limits of such studies.

1 Introduction: Spatial Cognition and Spatial Knowledge

In large spaces people are frequently required to move towards unseen goals, and therefore they must plan their movements. To do so, spatial knowledge about the environment is required, which may be in the form of a physical map or a mental (cognitive) map. Many studies have documented the processes involved in the mental representation of realworld environments (see Golledge, 1987, for a review), and have shown that different levels of spatial knowledge, from "route" to "survey" (Siegel & White, 1975) are elaborated and required according to the task to be performed. Reproducing a familiar route is possible with only a route-type mental representation, while taking a shortcut or selecting a new route is supposed to require a survey-type mental representation. Several alternative models have been proposed recently. For instance, Montello (1998) argues for a quantitative rather than qualitative evolution in the acquisition of spatial knowledge, and Thinus-Blanc and Gaunet (1999) suggest that spatial representations are necessary not only for planning spatial behavior, but they also control the organization of the spontaneous acquisition of information. The features of cognitive maps have been extensively investigated in different situations

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and in various populations. Among others, a strong aspect of cognitive maps is their inaccuracy: it is well known that mental representations are deformed, distorted (e.g., Tversky, 1981). Such features are for instance expressed in errors made on direction and/or distance estimates between places or landmarks. Also, studies on experts are particularly interesting since they may give us a general idea of what could be an optimal situation. One well-known example is reported in Pailhous (1970)[1], who distinguished primary (or basic) and secondary networks in mental representations of Parisian taxi-drivers. The primary network, mainly composed of large streets (about 10%), roughly corresponds to the skeleton of the mental representation. One of the studies reported in this chapter (Section 4, Study 1) is based on this idea.

Humans acquire spatial knowledge both while traveling through environments and through the use of maps, photographs, videotapes, verbal (oral or written) descriptions, and, most recently, virtual environments. The literature provides abundant evidence that the nature of the cognitive map formed depends to some degree on the information available during knowledge acquisition (e.g., Thorndyke & Hayes-Roth, 1982). For instance, Presson and Hazelrigg (1984) make the distinction between primary (or direct, such as navigation) and secondary (or symbolic) learning. Learning from a map results in a mental spatial representation which has a specific orientation, while learning from navigation results in a more flexible mental representation.

2 Virtual Environment Technology (VET)

In their Preface of a Special Section of the Journal "Humans Factors" devoted to Virtual Environments (1998), Barfield and Williges define Virtual Environment (VE) and Virtual Environment Technology (VET). "The term VE represents a family of computer-generated virtual representations of human visual, proprioceptive, haptic, auditory, and olfactory displays". ..."Under the general rubric of VET, there is all the technology related to virtual reality, augmented reality, visualization, head-mounted displays, desktop computer displays, wall/room projections, perspective displays, computer walk-throughs, stereoscopic displays, wearable computers, computer-based simulations, and so forth".

2.1 VET Systems

Two main categories of systems are currently used: desk-top systems (which display the virtual environment on a fixed computer screen) and immersive-display systems (e.g., the environment is displayed on two small screens of a head-mounted display).

[1] Pailhous, J. (1970). La représentation de l'espace urbain: L'exemple du chauffeur de taxi. Paris: Presses Universitaires de France. For an English summary of Pailhous's work see (1984) The representation of urban space: its development and its role in the organisation of journeys. In R. Farr & S. Moscovici (Eds.), Social Representations. Cambridge: Cambridge University Press. See also Golledge (1987).

In desk-top systems the direction of gaze is altered by translations and rotations from an input device (e.g., joystick or mouse), while in immersive-display systems the direction of gaze is linked to head-movements. Moreover, vestibular information is available from immersive-display systems only. Finally, due to head-movements the scene occupies a wider angle in immersive-display systems than in desk-top systems, though image quality is generally poorer. In summary, both systems have specific advantages and limitations, and their use is tightly related to the nature of questions under study (see for example Arthur, Hancock, & Chrysler, 1997; Pausch, Shackelford, & Proffitt, 1993; Ruddle, Payne, & Jones, 1999). The same line of reasoning can be applied to the output interfaces that produce the movements, that is, keyboard, joystick, treadmill, etc.

2.2 VET and Spatial Cognition

Among others, one increasing application of VET is spatial cognition studies. The potential advantages and drawbacks of this technology have been reported by several authors (see Darken, Allard, & Achille, 1998; Loomis, Blascovitch, & Beall, 1999; Mallot, Gillner, van Veen, & Buelthoff, 1998; Péruch & Gaunet, 1998; Péruch, Gaunet, Thinus-Blanc, & Loomis, 2000; Wilson, 1997). The main advantages of VET is the possibility it gives to create environments of varying complexity, to make on-line measurements during (interactive) navigation, to control many spatial learning parameters, such as the amount of exposure to the environment and the number, position, and nature of landmarks. However, the present state-of-art of this technology has several drawbacks: lack of realistic environmental modelling, slow image generation and rendering, narrow field of view, optical distortions, poor spatial resolution, etc. In spite of these, the relevance of VET for spatial cognition studies becomes more and more evident.

Although VET is relatively recent, cognitive mapping studies using it have already investigated several different issues. In brief, as is often the case when a new technology first comes into existence, investigators have first tried to replicate (or/and extend) some basic experiments dealing with cognitive mapping. An example is the study by Ruddle, Payne, and Jones (1997), in which most of the findings obtained by Thorndyke and Hayes-Roth (1982) in real settings were confirmed within virtual environments: participants were found to be equally good at performing direction and relative distance estimates. Such research confirms that the same processes operate in virtual (in general, purely visual) conditions and, at the same time, provides further validation of using VET for research in spatial cognition.

Since VET permits the isolation of sensory modalities, other studies are concerned with the respective role of external (for instance visual) vs internal (for instance proprioceptive or vestibular) information in spatial learning (see for instance Chance, Gaunet, Beall, & Loomis, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

Some other studies have investigated the properties of the cognitive maps that are elaborated in virtual environments, through navigation and way-finding tasks (for a discussion see also Darken et al., 1998). With natural environments, navigation results in a representation that does not depend on a particular orientation while the use of maps is tightly related to the orientation in which they have been presented (see for instance Presson & Hazelrigg, 1984). Results supporting this hypothesis have been found with navigation in virtual environments though other data are more or less divergent (see for instance Tlauka & Wilson, 1996) or more or less contradictory (see for instance May, Péruch, & Savoyant, 1995; Péruch & Lapin, 1993; Rossano & Moak, 1998; Richardson, Montello, & Hegarty, 1999).

Another important issue in spatial cognition is the status and role of landmarks. The following questions have been investigated: "What is a landmark? How is it used? Why is a cue, among so many others, selected and used as a landmark?". Using VET, Tlauka and Wilson (1994) have investigated to what extent landmarks are decisive in the acquisition of route knowledge in a virtual environment: performance was higher in the landmark group than in the non-landmark group. Steck and Mallot (1998) have addressed the question of the role of global and local landmarks in navigation, in situations in which landmark information was manipulated. Moreover, Jacobs, Thomas, Laurance, and Nadel (1998) have conducted experiments in a virtual arena. Human adult participants learned to find an invisible target that remained in a fixed location relative to distant landmarks. Removing these landmarks had no important effect, while merging them (changing their topographical relations) dramatically decreased performance.

Finally, some studies are concerned with the transfer between virtual and real environments (see for example Bliss, Tidwell, & Guest, 1997; Darken & Banker, 1998; Waller, Hunt, & Knapp, 1998; Witmer, Bailey, & Knerr, 1996). They demonstrate that virtual environments contain much of the essential spatial information that is utilised by people in real environments.

3 Transfer between Virtual and Real Environments

Transfer studies make a distinction between transfer of skill (for instance Regian, Shebilske, & Monk, 1992), and transfer of spatial knowledge. This last case can be considered either as the conservation of a type of spatial knowledge from a learning to a test situation (Witmer et al., 1996), or as the transfer of spatial information from one sensory modality to an other.

The need to develop a set of tasks to support research on training applications of VET (i.e., the Virtual Environment Performance Assessment Battery or VEPAB, see Lampton, Knerr, Goldberg, Bliss, Moshell, & Blau, 1994) reveals that the transfer of skill or/and of spatial knowledge is complex. For instance, Witmer et al. (1996) suggest that although studies about the training potential of VEs have shown how task performance improves with practice, they have not indicated how skills acquired in a VE affect real world performance. The authors invoke various reasons, some of them have been already cited in section 2.1 as drawbacks of VET: VEs have deficiencies that diminish the training transfer, the visual simulation may be imprecise, the mode of production of movement is more or less artificial, and people may be affected by simulator sickness.

Waller et al. (1998) report a general assumption found in the literature, according to which knowledge or skills acquired in a VE will transfer to the real world.

Referring to Witmer et al. (1996), the authors acknowledge that one key aspect of transfer is exposure to a VE, which can substitute for actual exploration of the real world. However, the authors stress the need to examine the variables that mediate the training effects of VEs: fidelity of the interface (the mapping between the VE and the mental environment of the trainee), environmental fidelity (the mapping between the real-world environment and the VE), and training time. Waller et al. (1998) define fidelity as the "extent to which the VE and interactions with it are indistinguishable from the participant's observations and of interactions with a real environment" (p. 130). Although information about a real-world environment is never preserved perfectly in either the training environment or the trainee's mental representation (e.g., Tversky, 1981), some structures are preserved in the mapping between the three domains: fidelity is concerned with the quality of these mappings. Finally, the authors underline that a slight increase in fidelity may be very expensive. Developers are usually confronted to the following compromise: which technological variables may be most easily sacrificed without degrading the trainee performance?

Rose, Attree, Brooks, Parslow, Penn, and Ambihaipahan (1998) confirm that transfer needs for further systematic investigation. At the present time, literature reveals various intended outcomes of the training process: simple sensorimotor performance, complex sensorimotor skills, spatial knowledge of an environment, vigilance, memory, and complex problem solving. In such conditions, comparisons are difficult about the extent and type of transfer. Moreover, Rose et al. (1998) indicate that only a few authors analyse transfer in terms of the well established literature on the transfer of training (for instance Cormier & Hagman, 1987), or of the more extensive literature on the psychology of learning. Some cognitive models (e.g., Parenté & Hermann, 1996) stress the importance of the similarity, between the real and virtual situations, of stimulus and response elements but also of the cognitive strategies. In their paper, Rose et al. (1998) attempt to systematically investigate the nature of the transfer in terms of the extent and robustness of what transfers.

In summary, an overview of some recent studies on transfer shows that transfer of skill and/or of spatial knowledge occurs largely (e.g., Bliss et al., 1997; Rose et al., 1998; Waller et al., 1998) or partially (e.g., Darken & Banker, 1998; Wilson, Foreman, & Tlauka, 1997; Witmer et al., 1996). However, due to the large variability of situations and tasks, it is difficult to known exactly what type of information is actually transferred and the nature of the underlying cognitive processes. According to what has been said before, the main observation is that in some conditions we observe that training improves performance. Additionally, although one can conclude to some equivalence of spatial information in real and VEs, performance (for instance in direction estimates) is generally better in real than in virtual environments.

4 Transfer Studies Conducted in Marseille

In line with the above remarks, in the present section we briefly report two studies conducted in Marseille laboratory. The first one was aimed at evaluating the effects of the amount and quality of information on the transfer of a spatial representation and on its transfer from a VE to the corresponding actual situation. The second one compared the accuracy of representations acquired either in a VE or in the actual environment.

Virtual models of the campus of the CNRS-Marseille were used. The campus covers about 300 x 200 m of floor space and comprises roads, parkings, buildings, lawns and trees. The VET device is a desk-top PC-based graphics workstation (Pentium 133 MHz in Study 1, Pentium II 450 MHz in Study 2). The environments (colored in Study 1 and textured in Study 2) have been modeled with 3D Studio (Study 1) and 3D Studio Max (Study 2), and the real-time rendering program uses RenderWare 2.1. The scenes (in an horizontal field of view of 45 degrees) are displayed on a 21" monitor with a resolution of 640 x 480 pixels in Study 1, and of 800 x 600 pixels in Study 2. The displays are controlled with a keyboard (Study 1) and a 3D SpaceMouse (Study 2) and, according to the complexity of the scene, the frame rate varies from 10 to 20 images per second.

4.1 Study 1: Varying the Amount and/or Quality of Available Information

This study aimed at examining if the increase of amount and/or quality of available information facilitates spatial learning, and how. Thirty adult participants (fifteen females and fifteen males), who did not know the campus, learned a virtual version of it before being tested in the real situation. During the learning phase participants freely explored the environment without time limit. They were encouraged to memorize 6 locations marked by objects and appearing on 6 pictures that were shown permanently. The participants were never shown a top-view of the environment. Three versions of the campus were compared, one for each group of ten participants (Fig. 1).

In all these versions, the buildings were represented by grey, not textured, volumes. Since only the geometry of the environment was maintained, the degree of realism was very weak. In the most detailed or Rich version (Fig. 1a) the buildings, the lawns, the hedges, and the main roads (linking the locations) were represented. The Medium version (Fig. 1b) comprised only some buildings and the main roads. Finally, the Poor version (Fig. 1c) comprised only a subset of the buildings. After learning (from 15 to 40 minutes) the participants were blindfolded and transported by car to the different locations. From each location, they had to indicate the direction, the travelled distance (using the shortest path), and the direct distance of the other locations. Each participant performed ninety tests (6 locations occupied x 5 locations tested x 3 measures).

The results (Table 1) show that direction and travelled distance errors were smaller in the Rich and Medium conditions than in the Poor condition; these results were confirmed by statistical analyses. No difference was observed between the conditions on the direct distance estimates. Performance was equivalent in the Medium and Rich conditions, revealing that there was no effect of the amount of available information. In brief, the best performance occured in the presence of roads linking the locations. Such roads may have played the role of primary grid (Pailhous, 1970), that is, may have structured the mental representation of the environment. In summary, these results show that some transfer of spatial knowledge from a virtual to a real environment is possible even in very schematic virtual conditions. The second study deals with the transfer of spatial knowledge using a more realistic model of the campus.

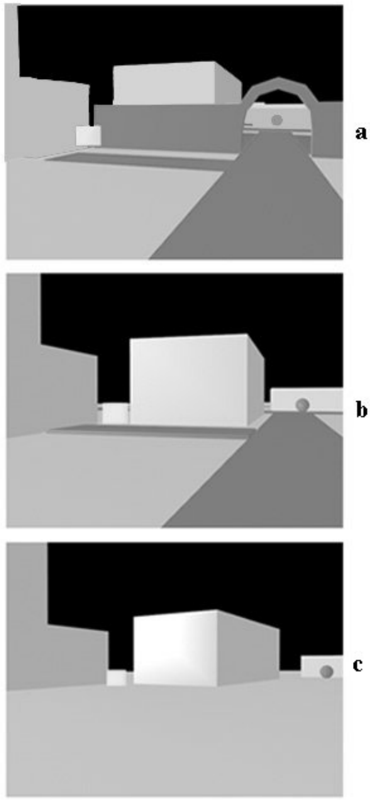

Fig. 1. Perspective views in the different models of the campus of the CNRS-Marseille, taken from the same place. The Rich (a), Medium (b), and Poor (c) views come from the models used in Study 1. Two of the objects marking locations (the white cube on the left and the grey sphere on the right) are visible on each of the views

Table 1. Average (and SE of the mean) performance values by condition in Study 1

	Absolute direction error (degrees)	Travelled distance error (normalized)	Direct distance error (normalized)
Rich	42.5 (10)	.21 (.10)	.20 (.09)
Medium	47.0 (11)	.19 (.09)	.18 (.08)
Poor	62.0 (13)	.26 (.18)	.22 (.12)

4.2 Study 2: Learning and Testing in Virtual vs Real Conditions

A central question investigated here was to evaluate to what extent virtual training (in desk-top mode) can be compared to real training (with all internal and external information). Moreover, to our knowledge no similar study has been conducted in an outside environment: investigations have been carried out only in buildings. Thus, this study aimed at examining the conditions of transfer of spatial information from an exterior virtual (but realistic) environment to a real one.

Fig. 2. Views of the campus of the CNRS-Marseille from Study 2. View (a) shows a part of the virtual environment, while views (b) and (c) correspond approximately to the same views of Study 1 in the virtual and in the real campus, respectively

Two groups of eight adult female and male participants who did not know the campus explored it freely for 20 minutes. The Virtual group explored the virtual campus (Fig. 2a and 2b) while the Real group explored the real campus (Fig. 2c). During the exploration, each participant was requested to search for 5 target locations, corresponding to 5 pictures that were shown permanently. The pictures had been taken in the virtual campus for the Virtual group and in the real campus for the Real group, but they corresponded to the same locations. As in Study 1, the participants were never shown a top-view of the environment. At the end of the exploration, both groups were tested in the virtual environment first and then in the real environment. In the Virtual tests the participants were dropped at each of the locations, while in the Real tests they were first requested to find each of the locations using the shortest path. From each location, the participants had to indicate the direction, direct distance, and travelled distance of all other locations. Each participant performed sixty tests (5 locations occupied x 4 locations tested x 3 measures).

The results (Table 2) show that the Real group performed better than the Virtual group, but the performance was significantly different on Virtual tests only; these results were confirmed by statistical analyses. The performance of the Real group was the same on both Virtual and Real tests, indicating that transfer from the real to the virtual environment globally occured. No improvement of performance was observed from the virtual to the real tests (except on direction error), suggesting that learning was optimal in the real world. By contrast, the performance of the Virtual group improved from the virtual to the real tests on all aspects of performance: the fact that all sensory information was available in the real world, on the one hand, and that participants had more experience of the environment because they walked to the real test conditions, on the other hand, has probably facilitated the transfer of spatial information from the virtual to the real environment.

Table 2. Average (and SE of the mean) performance values by condition in Study 2

Group	Test	Absolute error direction (degrees)	Absolute travelled distance error (meters)	Absolute direct distance error (meters)
Virtual	Virtual	66.8 (4.2)	101.5 (7.0)	72.0 (5.5)
	Real	30.8 (3.1)	72.5 (5.3)	51.0 (4.5)
Real	Virtual	27.8 (2.3)	58.0 (3.5)	40.5 (2.5)
	Real	19.7 (1.5)	56.5 (3.5)	41.5 (2.5)

4.3 Discussion

In summary, data from Study 1 show that the quality of available virtual information is more important than its amount to construct a spatial representation that has to be transferred to the actual environment. In addition, data from Study 2 suggest that although learning in the actual environment results in better quality representations than training in a VE, the transfer of spatial knowledge from a virtual to a real environment is possible to some extent. The experimental conditions in the two above studies were somewhat different, but performance can be compared (at least on direction estimates). In Study 2, direction estimates were better in the Real tests for the Virtual group (30.8 degrees) than those observed in the Rich condition of Study 1 (42.5 degrees). This means that an accurate mental representation is easier to acquire in a realistic virtual environment than in very schematic virtual conditions, although in this last case performance can be optimized by roads linking the locations.

These studies are probably among the first that evaluate the conditions of transfer of spatial knowledge between exterior, virtual and real environments. It appears that training in a pure visual mode (using a desk-top system) may be sufficient to acquire a coherent mental representation. Moreover, this representation is less well elaborated but may be as performant as the representation that may be acquired in the real environment. It is likely that a representation coming from a virtual experience may benefit from real-world experience. In other words, spatial knowledge acquired in a virtual environment (on a pure visual basis) could be used optimally in real conditions (that is, in situations more natural and rich with respect to the variety of available information). In such conditions, a good transfer of spatial knowledge would require several alternated experiences, both in virtual and real environments.

5 Conclusion: Future Work on Transfer

Studies concerned with the transfer of spatial knowledge from virtual to real environments demonstrate that the properties of spatial representations are not radically different in virtual environments than in real ones. These results suggest that virtual environments contain much of the spatial information used in real environments. However, drawing a clear conclusion about the spatial information which is transferred and about the conditions of transfer remains problematic. Being able to predict such a transfer would broaden the possibilities of training and enlarge our knowledge of the cognitive processes involved in spatial cognition.

In summary, VET has been only recently used in spatial cognition research, so transfer studies are just beginning. Gathering more experimental evidence would certainly strengthen the relevance of using VET in human spatial cognition studies. Other steps are of course necessary before strong conclusions can be drawn. Obviously, significant progress will be made only if researchers have a good knowledge of human spatial behavior. Among others, one goal for future research would be to try to define optimal conditions of transfer. It is likely that, among others, two kinds of improvements will play a decisive role here. First, more and more complex and realistic VEs will be available. Second, VET will be more and more combined with other techniques related to movement (whole-body interfaces) and/or to navigation (Geographical Positioning Systems).

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