Computers in Human Behavior 64 (2016) 191–205

Contents lists available at ScienceDirect

Computers in Human Behavior

journal homepage: www.elsevier.com/locate/comphumbeh

Acquisition of spatial knowledge through self-directed interaction with a virtual model of a multi-level building: Effects of training and individual differences

Stefan Münzer*, Mahsa Vali Zadeh

Psychology of Education, School of Social Sciences, University of Mannheim, Germany

ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form
12 May 2016
Accepted 24 June 2016

Keywords:
Virtual spatial models
Spatial learning
Visualization
Interactive controls
Spatial ability
Training

ABSTRACT

Knowledge about complex spatial structures can be acquired through self-directed interaction with virtual models. In the present study, interactive controls enabled flexible exploration of desktop virtual multi-level building models from an allocentric perspective (providing zoom, rotation, and selection of building levels) as well as from the egocentric perspective (providing virtual movement). Short-time training for deliberate exploration were investigated with respect to spatial knowledge acquisition ($N = 115$, 59 females and 56 males). Four training conditions were included: (1) no training, (2) interaction with a training model with a basic exploration task, (3) cognitive prompts stimulating organisation of spatial information, (4) cognitive and meta-cognitive prompts stimulating planning and controlling the exploration activity. In addition, spatial abilities, real-world spatial strategies and computer game experience were considered as aptitudes. Aptitude variables explained up to 30% of the variance in spatial learning and mediated an effect of sex. Training explained up to 10% of the variance in spatial learning. Qualified training with prompts (conditions 3, 4) did not improve spatial learning compared with training with the basic task (condition 2). Training strongly diminished the role of aptitudes.

1. Introduction

In computer-based learning environments, learners are more and more presented with interactive visual-dynamic representations of spatial structures. Examples can be found in geographical information systems and in visualizations of physical, mechanical or biological systems. Virtually moving through virtual indoor and outdoor environments is an everyday experience in computer games. The popular use of interactive software for flexible visualizations of spatial structures based on virtual models suggests that those visualizations are considered supportive for spatial knowledge acquisition.

In the present study, users could utilize interactive controls when exploring a virtual three-dimensional (3D) desktop model of a complex, multi-level building. The controls provided flexible visual access to the modeled spatial structure from an external, allocentric viewpoint (with zoom, selection and rotation options) or from an internal, egocentric viewpoint (virtual movement through the model). Learners had to decide deliberately on the spatial perspective, selection of partial structures, use of zooms and rotation, and choice of routes during virtual movement. Exploring a virtual model with the goal of spatial knowledge acquisition can be characterized as self-directed learning.

In the present study, it was assumed that self-directed spatial knowledge acquisition during interaction with a virtual model would depend (1) on learner aptitudes (individual differences in spatial abilities, spatial strategies and computer game experience) and (2) on deliberate and effective exploration strategies. Elements of such strategies were stimulated through short-time training. The training conveyed cognitive and meta-cognitive aspects through prompts during extra training time with a training virtual building model.

1.1. Spatial learning about complex spatial structures

Spatial knowledge acquisition through interaction with a virtual model of a building requires particular spatial transformations. On

* Corresponding author. Lehrstuhl für Bildungspsychologie, Fakultät für Sozialwissenschaften, Universität Mannheim, A 5,6, 68131 Mannheim, Germany.
E-mail address: Stefan.muenzer@uni-mannheim.de (S. Münzer).

http://dx.doi.org/10.1016/j.chb.2016.06.047

the one hand, the visualization is presented on a desktop computer screen of limited size. The learner has an external view on that “small-scale” space (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). From this allocentric-external viewpoint, the learner might manipulate, rotate and zoom the virtual object as any other spatial structure that can be visualized as a virtual model. On the other hand, a “large-scale” space is represented through the virtual model, and the learner could imagine to be part of the space shown. Correspondingly, virtual movement through the virtual model is intended to resemble the impression of being part of a “large-scale” space and involves encoding of spatial relations with respect to the egocentric perspective. Effective understanding of the spatial structure would therefore require to relate the different spatial perspectives to each other involved in this particular scenario.

Spatial cognition research suggests that different types of spatial knowledge exist about large-scale environments. Route knowledge can be conceived of associative memory of a sequence of landmarks together with turning actions. This kind of knowledge is anchored in the egocentric reference frame, i.e. it is relative to the individual's position and orientation in an environment. It can be assumed that route knowledge is acquired through navigational experience (moving through an environment). In addition, there is survey knowledge that provides an overview based on an extrinsic frame of reference, i.e., from an allocentric perspective (Evans, 1980; Hart & Moore, 1973; McNamara, Ratcliff, & McKoon, 1984). Survey knowledge in the form of a so-called “mental” or “cognitive” map allows flexible spatial orientation (e.g. drawing inferences about spatial relations between places, planning of routes not yet travelled). This knowledge can be acquired through direct navigational experience, but it is often conveyed through maps.

Spatial learning is affected by the type of spatial information available in the learning phase. Thorndyke and Hayes-Roth (1982) investigated environmental learning based on either the egocentric perspective (through navigation experience) or the allocentric perspective (through map study). Personnel knowing the building from navigation experience over several months could solve spatial tasks that were based on the egocentric perspective (e.g. estimate directions, estimate walking distances), but had difficulties with tasks that required the allocentric perspective (e.g. locate rooms with respect to two spatial reference points, estimate air-line distances). For participants who had learned the layout of the building by studying a floor map, the reverse was true. Another study replicated these findings with a virtual model of the same building (Ruddle, Payne, & Jones, 1997). It is important to consider the different spatial perspectives during learning, because it is unlikely that spatial knowledge acquired in a particular perspective transfers effortless into another.

Contrary to three-dimensional virtual environments, a map is a two-dimensional “small-scale” representation of a “large-scale” environment from an external viewpoint. A map provides a stable symbolic visual representation of the spatial configuration of the components (places, regions, etc.) of the environment and the layout of the paths between components from the allocentric (survey) perspective. Studying a map can actually contribute to an appropriate mental representation of the spatial structure of a building and may thereby improve wayfinding, i.e. walking routes to destinations in the environment (Devlin & Bernstein, 1995; Gärling, Lindberg, & Mäntylä, 1983; Münzer & Stahl, 2011; Richardson, Montello, & Hegarty, 1999). When only relatively short training time is provided, desktop virtual environment training might not be superior to studying a map for subsequent wayfinding in a real building (Farrell, Arnold, Pettifer, Adams, Graham & MacManamon, 2003).

However, using a map requires cognitive processing of the spatial information shown (depending on the purpose), because the representation is not as flexible as a virtual model. For instance, learning from maps is orientation specific, that is, the mental representation acquired from studying the map is aligned with its orientation at the time of study (Rossano & Moak, 1998; Rossano & Warren, 1989).

In summary, different types of spatial representations and experiences support acquisition of different types of spatial knowledge. Maps can be used for the acquisition of survey knowledge, but maps can also be effective wayfinding aids. Because maps represent a two-dimensional, allocentric, and stable view on a spatial layout, reading maps for different purposes requires cognitive processing. In particular, it might be difficult to understand the spatial structure of a complex multi-level building when it is represented with multiple maps. Virtual environments based on virtual models of buildings are an alternative. Utilizing virtual environments for training purposes show reliable transfer effects of learning to the real world (Bliss, Tidwell, & Guest, 1997; Rossano, West, Robertson, Wayne, & Chase, 1999; Waller, Hunt, & Knapp, 1998; Witmer, Bailey, Knerr, & Parsons, 1996). However, virtual environments are commonly utilized to provide the experience of movement through a building, i.e. the egocentric reference frame is visualized at the cost of the allocentric view.

In the present study, virtual models of complex buildings are visualized both in an allocentric mode (with interactive controls for zoom, selection, and rotation from external viewpoints) as well as in an egocentric mode (virtual movement through the building model). This provides flexible visual access to the spatial structure. Because the virtual model is studied through a “small-scale” representation, it is expected that factors influencing spatial cognitive processing of visualizations (individual differences in spatial abilities in particular) will play a role in learning.

1.2. Individual differences in spatial learning

It has been found that individual differences are large when people acquire spatial knowledge through navigation in real environments (e.g. Ishikawa & Montello, 2006; Kozlowski & Bryant, 1977; Malinowski & Gillespie, 2001), when people deal with spatial representations such as maps (e.g., Liben, Myers, & Christensen, 2010), and when people learn about a spatial environment through interaction with virtual environments (e.g., Durlach, Allen, Darken, Garnett, Loomis, Templeman, & von Wiegand, 2000; Waller, 2000; Waller, Knapp, & Hunt, 2001).

Individual differences in mental spatial abilities (Hegarty et al., 2006; Hegarty & Waller, 2004, 2005; Kozhevnikov & Hegarty, 2001) and self-reported competencies such as sense of direction and spatial strategies (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Kozlowski & Bryant, 1977; Münzer & Hölscher, 2011; Pazzaglia & De Beni, 2001) have been discussed as variables that account for variance in learning about environments. Furthermore, sex differences have been reported for orientation success and environmental learning (see Coluccia & Louse, 2004; for a review).

Visual-spatial abilities are an important predictor of spatial learning if the to-be-learned environment is actively or passively studied from visual media (Hegarty et al., 2006; Moffat, Hampson, & Hatzipantelis, 1998; Waller, 2000). In the present context, two main sources of variance are considered important when interacting flexibly with a virtual 3D model: (1) the ability to encode spatial information from visual input, and (2) the ability to process the encoded spatial input mentally by applying particular spatial transformations. Encoding ability is thought to facilitate initial spatial understanding of the visual representation, whereas spatial transformation abilities are thought to facilitate understanding of