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Passive and active navigation of virtual environments vs. traditional printed evacuation maps: A comparative evaluation in the aviation domain ☆

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ABSTRACT

Printed maps are the most common tool to prepare people for emergency evacuation in contexts such as public buildings or transportation. Unfortunately, they are poorly understood and often ignored by people. Virtual environments (VEs) could be a more effective method to support people in acquiring spatial knowledge about the real-world environment to evacuate. This paper pursues three main goals. First, we propose a VE-based tool to support spatial knowledge acquisition for evacuation purposes, using aviation as a real-world domain in which such knowledge is crucial for passengers' safety. Second, we study in detail one of the VE design choices (active or passive navigation), comparing a version of our tool in which users navigate by actively controlling their position with another version in which users are passively led along pre-defined routes. Third, we contrast the two versions of the tool with the traditional, printed diagrammatic map provided to passengers by airlines. Results of our study show that the VE-based approach produces objectively better spatial knowledge when users are asked to pinpoint their assigned position in the environment, and that active navigation produces a performance improvement in a subsequent virtual evacuation. Moreover, the VE-based approach is perceived as more enjoyable, easier to comprehend and more effective than printed maps when active navigation is available.

1. Introduction

During emergency evacuations, previously acquired spatial knowledge of the environment plays a crucial role in reducing risks to occupant's safety. Unfortunately, the printed evacuation maps that typically provide emergency-related spatial knowledge in buildings (e.g., hotels, schools, companies) and in transportation (e.g., aircraft, trains, ships) are very limited. Such maps provide only an abstract diagrammatic representation that: (i) can present comprehension problems, (ii) needs cognitively complex geometric operations to translate the knowledge provided by the map into actual routes in the environment, (iii) is difficult to mentally match with the real-world environment, especially in case of emergency evacuation, which requires fast actions and decisions to maximize probability of survival, (iv) does not allow users to preview what they are going to see from their real-world egocentric view when following an evacuation route.

Compared to printed evacuation maps, virtual environments (VEs) in the form of desktop 3D interactive simulations of real-world environments might offer a more useful tool to prepare people for emergency evacuations. Indeed, there is significant evidence that VEs can be used to help people acquire spatial knowledge about real-world places and navigate those places more efficiently and effectively (Arthur et al., 1997; Foreman et al., 2000; Klatzky et al., 1998; Richardson et al., 1999; Ruddle et al., 1997; Waller et al., 1998; Wilson et al., 1997b; Witmer et al., 1996).

The purpose of our project is to leverage the power of VEs to create novel tools for emergency evacuation preparedness and to evaluate on users if such tools are actually more effective than the printed maps currently in use. In particular, we focus on aviation as a real-world domain in which fast and efficient evacuation is fundamental to increase passengers' chances of avoiding harm. In a previous paper (Chittaro and Buttussi, 2015), we proposed a VE-based serious game aimed at educating passengers about safety procedures (e.g., brace position, usage of the life vest) in the case of an emergency water landing and evacuation scenario. In this paper, we propose a VE-based tool that combines a VE representation of the cabin with an electronic map of an aircraft to support spatial knowledge acquisition for evacuation purposes. We study in detail one of the VE design features

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(active and passive navigation), highlighting the effects on users' knowledge and behavior of a version of the tool in which users navigate by actively controlling their position and a version in which users are passively led along pre-defined routes. Moreover, we contrast the two versions of the tool with the currently employed solution, i.e., the printed diagrammatic maps (safety cards) provided to passengers by airlines.

Our work advances the state of the art in spatial knowledge acquisition through VEs in several directions:

- We try a VE-based approach to provide emergency-related spatial knowledge in a domain (aviation safety) in which it has never been studied before.
- We investigate if a combination of VEs and electronic maps provides advantages over a paper map in terms of spatial knowledge acquisition, a question that received inconsistent answers in the literature.
- We contribute to the body of knowledge on active and passive navigation, studying the effectiveness of the two conditions when combined with a global electronic map of the considered environment. Passive navigation would be an ideal solution for passengers who are not familiar with interactive applications and for in-flight entertainment (IFE) systems that are not equipped with interactive controls. However, the literature provides inconsistent results on the differences between active and passive navigation in terms of spatial knowledge acquisition and usability.
- Unlike other studies in the literature, we test user performance in a virtual evacuation in clear as well as reduced visibility, thus simulating more realistic emergency conditions.
- Besides quantitative metrics of spatial knowledge, we take into consideration subjective usability metrics such as enjoyment or comprehension that might have a significant impact on the acceptability of a specific tool by the general public.

Results of our study show that a VE-based approach has the ability to improve the acquisition and application of spatial knowledge by prospective passengers, thus bringing a positive contribution to aviation safety. Both VE conditions produced better spatial knowledge when users were asked to pinpoint their assigned position in the aircraft, and the active navigation condition produced a performance improvement in a subsequent virtual evacuation. Users perceived the active navigation condition to be better than printed maps in terms of comprehension, effectiveness, and attention and better than passive navigation in terms of feedback and sense of control, while both VE conditions were perceived as more enjoyable than printed maps.

The paper is organized as follows. Section 2 surveys the research literature on spatial knowledge acquisition from maps and VEs and on active/passive navigation of VEs, motivating our work from the point of view of VE research and highlighting its relevance to aviation safety. In Section 3, we illustrate in detail the VE-based tool we have developed. In Section 4, we present the experimental method used to evaluate the two versions of the tool and contrast them to the traditional map approach followed by airlines. Section 5 presents the results of the experiment while Section 6 discusses findings and limitations of the study. Section 7 contains conclusions and outlines future work.

2. Related work and motivations

In this section, we first survey relevant research on navigation in VEs, examining the differences in spatial knowledge acquired from maps and VEs and motivating the need for investigating passive vs. active navigation. Then, we illustrate why aviation safety is a particularly relevant application domain for this area of research.

2.1. Spatial knowledge acquisition through maps and VEs

Maps are one of the most relied-upon tools to acquire spatial knowledge of an unknown environment. In particular, they allow people to quickly obtain *survey knowledge* (Siegel and White, 1975), making it possible to carry out spatial tasks (e.g., judging relative locations) more accurately and faster compared to learning the environment through direct navigation (Lloyd, 1989; Thorndyke and Hayes-Roth, 1982). However, map learning produces representations of the environment that are orientation-specific: learning an environment from a map makes it difficult to carry out spatial tasks that involve directions that are not aligned with the original orientation of the map (Aretz and Wickens, 1992; Levinew et al., 1984).

Research on the effectiveness of VEs compared to maps for spatial knowledge acquisition obtained mixed results. Witmer et al. (1996) found that the study of a paper map of a complex office building before navigating a VE model of the building or the real-world building had no significant effects on measures of survey knowledge or *route knowledge* (i.e., knowledge of the sequence of features and/or actions that describe a path between two known points (Siegel and White, 1975). Bliss et al. (1997) did not find performance differences in a route-following task in a real-world building between firefighters who trained for 15 min with a VE model and those who trained with a paper map of the building. Philbin et al. (1998) found instead that people who trained with a paper map of a building outperformed people who trained for the same amount of time (10 min) with a VE of the building, both in traveling through the real environment and answering questions about distance between objects in the environment. Ruddle et al. (1997) found that participants who examined a paper map of a large-scale building were significantly more accurate in estimating relative and absolute distances in the real building compared to participants who extensively navigated a VE reconstruction of the building. Similarly, Richardson et al. (1999) found that participants who were exposed for 6 min to a map or real-world navigation of a complex building were better at learning the environment compared to participants who used a VE of the building for the same amount of time.

These studies seem to suggest that VEs allow people to initially acquire route knowledge of an environment and that only a small or simple VE makes it possible to acquire survey knowledge with relative ease (Richardson et al., 1999; Rossano et al., 1999; Witmer et al., 2002).

A few studies in the literature investigated whether a combination of maps and VEs could be more effective than either condition, obtaining again mixed results. Darken and Banker (1998) did not find significant differences in navigation performance of a natural environment between people who trained with a VE+electronic map condition, those who trained with only a paper map and those who trained with a paper map in the real world, except for people with intermediate spatial ability who benefited more from the VE and map combination. In a related study, Goerger et al. (1998) found that errors in estimation of direction were roughly the same for a group of participants who could train in a VE of a complex multi-floor building as well as consult paper floor maps and a group who had access to the floor maps only. However, the map group made fewer route-following errors and was significantly more accurate in distance-estimation tasks. Diaz and Sims (2003) compared a VE-only, an electronic map-only, and a VE+electronic map condition in a spatial knowledge task in which participants learned the locations of several targets in a simulated building. The electronic map-only condition turned out to be the most accurate for distance estimation