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Evacuation travel paths in virtual reality experiments for tunnel safety analysis

Enrico Ronchi [a,*], Max Kinateder [b], Mathias Müller [c], Michael Jost [b], Markus Nehfischer [b], Paul Pauli [b], Andreas Mühlberger [d]

[a] Department of Fire Safety Engineering, Lund University, Lund, Sweden
[b] Department of Psychology (Biological Psychology, Clinical Psychology, and Psychotherapy), University of Würzburg, Würzburg, Germany
[c] VTplus, Würzburg, Germany
[d] Department of Psychology, Chair of Clinical Psychology, and Psychotherapy, University of Regensburg, Regensburg, Germany

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ABSTRACT

A case study on the analysis of evacuation travel paths in virtual reality (VR) tunnel fire experiments is presented to increase the understanding on evacuation behaviour. A novel method based on the study of the parametric equations of the occupants' evacuation travel paths using vector operators inspired by functional analysis theory and the new concept of interaction areas (IAs) is introduced. IAs are presented and calculated in order to represent the distance of an occupant from a reference point (e.g., an emergency exit, the fire source, etc.) over time. The method allows comparisons of travel paths between experimental groups as well as comparisons with reference paths (e.g. user-defined paths, real-world paths, etc.). Results show that a common assumption employed by evacuation models (the use of a hypothetical path based on the shortest distance) may be an over-simplistic approximation of the evacuation paths.

1. Introduction

A series of tragic events such as the Mont Blanc Tunnel fire in 1999 and the Saint Gotthard fire in 2001 attracted the attention of the transportation safety community on the study of tunnel fire evacuations. These accidents demonstrated that fire evacuation assumes particular importance among the accidents in a road network due to the possible serious consequences in terms of loss of lives [1]. In order to understand how the occupants' behaviours affect tunnel safety, the study of evacuation movement became the focus of dedicated research (e.g., [2,3]).

Different methods can be adopted for the study of human behaviour in fire accidents and the evacuation movement of the occupants. Research methods include case studies (i.e. the analysis and/or reconstruction of actual events [4,5]), modelling techniques [6–8], and evacuation experiments (i.e., hypothetical scenario experiments, laboratory experiments and field experiments) (see [9]). Among different types of evacuation experiments, the use of virtual reality (VR) is ever more frequent since it allows high experimental control, no ethical restrictions due to physical harm, logistic and economic advantages. VR has been employed in the field of fire safety research for different scopes such as the study of occupant training on tunnel evacuation [10,11], pre-evacuation behaviours [12], or the impact of way-finding installations [13].

To date, tunnel evacuation experiments (both at real settings [14–17] or VR [18] are generally focused on the study of the effects of different conditions or variables on the occupants' performance in terms of exit usage and its impact on total evacuation times. This information is crucial since it permits the evaluation of different design solutions, factors affecting human behaviour, emergency management strategies, etc. [9]. Nevertheless, this information does not allows a quantification of the impact of those variables on the occupants' movement and navigation in space over time, e.g. it does not address a quantitative evaluation of evacuation travel paths.

VR experiments allow a detailed reconstruction of the evacuation travel paths in space and time. Data about exit usage and evacuation times are generally treated using quantitative methods (e.g., inferential statistics) [10]. In contrast, analysts often provide general qualitative comments on the paths of the occupants and the impact of different factors on their behaviour. The use of a quantitative method to analyse occupant movement would instead permit the comparison of travel paths (e.g., for validation purposes) and this may increase the use of the experimental results.

The study of travel paths is particularly important in the context of fire safety science since the occupants' life safety is

* Corresponding author.
E-mail address: enrico.ronchi@brand.lth.se (E. Ronchi).

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importantly affected by the exposure to toxic products [19] and therefore by the position of the occupants in space over time, in relation to safe and dangerous locations in a given scenario. Thus, it is important not only to study the time spent inside the tunnel (affected by emergency exit usage), but also the position of the occupants during the passage of time (which affects their exposure to hazardous conditions). The study of travel paths should also take into account their impact on total evacuation time, which includes the pre-evacuation phase. In this context, it should be noted that route choice may increase travel distances and cause longer movement times. The consequence could be an increased impact of movement times on evacuation times. In order to investigate evacuees' behaviour, the present work introduces a new method for the study of travel paths from tunnel evacuation experiments.

Data on people movement in VR may have limitations in terms of their external validity (occupant behaviours in VR may differ in a real evacuation scenario). In fact, due to methodological, ethical, and practical reason, it is almost impossible to perform fully valid VR experiments [20]. On the other hand, previous studies showed that VR experiments are a useful tool to evaluate the causal relations between independent variables and human behaviour [21,22]. VR studies allow full experimental control which is very difficult to achieve with other experimental methods due to the complex nature of tunnel fire scenarios and even impossible to achieve in unannounced drills. A set of questions can be prompted by these issues. How do we investigate the limitations and the uncertainty associated with experimental VR travel paths? How do we quantitatively compare evacuation movement in a VR environment with other data (from the real world, other VR or modelling studies)?

The overall objective of this paper is the definition and exemplary application of a quantitative method to analyse tunnel evacuation travel paths. The goal is not to exactly replicate the conditions of a given fire emergency, but to provide a tool for the study of evacuation behaviour, in particular studying the paths adopted by evacuees during their movement towards a safe place. The scope is therefore to provide a methodology which can be used for the evaluation of the assumptions used by computational modelling tools (i.e. evacuation models). The proposed method for the analysis is based on the study of the parametric equations of the evacuation movement of the occupants. The results of the proposed research will lead to an improved description of the participants'/occupants' behaviour and thus, contribute to a better understanding of evacuation behaviour. An illustrative case study consisting of a set of VR tunnel evacuation experiments performed in the 3D multisensory CAVE (i.e., Cave Automatic Virtual Environment) laboratory of the Department of Psychology of the University of Würzburg, Germany is presented. The case study employs the method to investigate evacuation travel paths towards an emergency exit during a simulated tunnel emergency. Finally, a discussion on the advantages and limitations associated with the use of the method is presented.

2. Method

In order to study the evacuation travel paths in a quantitative way, the present work suggests the use of operators inspired by the concepts of functional analysis theory [23]. Functional analysis is a branch of mathematics using generalisations of measures of vectors applied to functions. In this paper, the term functional analysis is used to refer to generalisation of linear algebra, analysis and geometry. Evacuation travel paths are studied through the analysis of the coordinates where people are located in the VR environment over time (represented using parametric equations).

It should be noted that the present work makes use of the term *sequence* to refer to a finite sequence of points (representing the coordinates of pedestrian paths) or a finite number of pedestrians. The term *convergence* is used to refer to the average value that these finite sequences tend to.

Tunnels are generally simple (generally straight) geometries without compartmentation in which the relative distance of the occupants to the hazard (i.e. the fire source and its characteristics) and the time spent inside the tunnel are generally the main factors affecting life safety. In addition, previous experiments [9,16] showed that the likelihood of occupants using an emergency exit and their movement speed is affected by their position in the cross section (i.e. their proximity to the wall). For these reasons, the present work suggests to perform a quantitative assessment of evacuation travel paths by investigating people movement as a two-dimensional problem where the average coordinates are calculated and studied.

The method proposed for the study of VR evacuation travel paths can be summarised in three main steps:

1) The variables of interest (the parametric equations of the evacuation travel paths) describing the travel paths are identified.
2) The convergence of the variables of interest and acceptance criteria for the uncertainty associated with the estimation of the mean coordinates are identified. The analysis is performed by calculating a set of convergence measures (inspired by functional analysis theory) of the VR coordinates of the experimental travel paths towards the average.
3) A quantitative comparison of travel paths is performed.

The method can be used to perform two main types of analysis: (1) Validation studies: A comparison between VR travel paths and reference paths (e.g., evacuation paths from the real world, paths obtained from other models which are already validated, etc.); (2) Analysis of different conditions: the comparison of different subsets of travel paths against each other permits the study of the impact of different variables on people movement.

2.1. Occupant trajectories

Occupant trajectories are the travel paths that pedestrians follow through space as a function of time. In VR experiments the data about occupant position and orientation is measured and recorded with the VR simulation system. The data consists of a finite sequence of the coordinates in space over discrete time-steps. Thus, each occupant trajectory corresponds to a parametric equation. It is possible to obtain a set of n finite sequences for each j^{th} occupant corresponding to n experimental travel paths:

$$Occ_j = \left(x_j(t_i),\ y_j(t_i),\ t_i\right), \quad \text{for } 0 \le t_i \le t_{exit} \tag{1}$$

where:

$x_j(t_i)$ is the set of x_j coordinates for each j^{th} occupant during the experiments.
$y_j(t_i)$ is the set of y_j coordinates for each j^{th} occupant during the experiments.
t_i is the time-step for a total of q time-steps, based on the experimental data.

The trajectories of the occupants can be represented using sequences which use the x or y coordinates of the j^{th} occupant in space as the dependent variable and the time-step t_i as the independent variable. Each j^{th} occupant experimental travel path will be represented using a set of sequences corresponding to its coordinates. For instance, Eq. (2) presents a sequence of values