

When Routes Fail: Redistribution After Network Edge Removal in a Virtual Reality Evacuation Experiment

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Abstract Sudden infrastructure failures can disrupt evacuation networks and force rapid route reconfiguration under time pressure. Less attention has been given to discrete route choice after abrupt topological disruption. This study investigates how individuals redistribute across alternative paths after removal of a critical network edge in an immersive virtual reality (VR) flood scenario based on an urban district in Frankfurt, Germany.

Participants (N = 128) initially followed a designated evacuation route. Midway, a bridge collapse removed a key network edge, forcing rerouting at a downstream divergence node with three outgoing branches. We model the street system as an undirected graph with locally directional choice sets and quantify redistribution using empirical branch probabilities, a chi-square test against uniform allocation, and Shannon entropy.

Results reveal systematic, non-uniform redistribution across branches. Branch-selection frequencies corresponded to differences in directional continuity and path length, with the shortest and most directionally aligned branch selected most frequently. We did not observe statistically detectable differences across the demographic or experience-related attributes examined. Because geometric attributes were observed at a single divergence node, these findings indicate correspondence rather than causal effects of individual route properties. Even without crowd interaction, consistent branch distributions emerge and highlight how immersive experiments can inform network-level resilience analysis.

Keywords Pedestrian evacuation · extreme events · flooding · escape routes · urban emergencies · route choice · behavior analysis · Virtual Reality

1 Introduction

Evacuations during extreme events depend on the reliability of transport and pedestrian networks [1]. When hazards evolve rapidly—such as floods, wildfires, or infrastructure failures—critical links within these networks may become unavailable, forcing evacuees to adapt their routes under time pressure [2]. In such situations, safety does not only depend on the existence of alternative paths, but on how individuals reconfigure their movement when confronted with sudden topological disruption [3].

Previous research has examined a wide range of factors influencing evacuation behavior, including risk perception, trust in authorities, prior disaster experience, and social influence [4–6]. Studies have also investigated how spatial knowledge and environmental familiarity shape exit selection and route efficiency [7, 8]. Technological approaches such as immersive virtual reality (VR) environments have increasingly been used to study evacuation decision-making under controlled yet realistic conditions [9–11].

However, much of the existing literature focuses on travel time, congestion effects, or path efficiency. Comparatively less attention has been paid to discrete route choice behavior following abrupt infrastructure failure. From a network perspective, such scenarios can be conceptualized as sudden edge removal in a spatial graph, requiring redistribution across remaining outgoing links.

Pedestrian evacuation can involve a sequence of route-choice decisions as individuals update their choices while acquiring new spatial information [12]. In a spatial network, these decisions can be represented as local selections among the outgoing branches available at junctions. When many individuals face the same topological constraints, their repeated choices can aggregate into system-level redistribution patterns: convergent selections at shared divergence nodes may concentrate flow on particular links and contribute to structural bottlenecks, thereby connecting micro-scale route choice with macro-scale network load [13–15].

Understanding this redistribution process is critical for resilience planning. If evacuees systematically concentrate on specific alternatives, structural bottlenecks may emerge even in the absence of social interaction. Conversely, a more balanced redistribution may indicate inherent robustness in network geometry. Identifying whether route reconfiguration is primarily shaped by structural properties or by informational and individual factors remains an open question.

This study therefore addresses the following research questions:

1. How do evacuees redistribute across alternative branches following the removal of a critical network edge?
2. How do the observed redistribution patterns correspond to the geometric properties of the available routes?
3. Does redistribution depend on individual characteristics such as demographic or experiential factors?

We address these research questions through an immersive VR flood evacuation experiment situated in an urban district of Frankfurt, Germany. Participants initially followed

a designated evacuation route. Midway through the scenario, a bridge collapse removed a critical connection, forcing rerouting at a clearly defined divergence node with three alternative branches. We analyze route selection as a discrete outcome and model redistribution patterns across outgoing edges of the disrupted network.

By focusing on route choice under sudden topological disruption, our work contributes to evacuation research in three ways:

1. it introduces a controlled experimental protocol that operationalizes abrupt infrastructure failure as edge removal in an urban evacuation setting;
2. it quantifies behavioral redistribution at a clearly defined downstream divergence node, capturing how individuals reconfigure their routes when a critical connection becomes unavailable; and
3. it identifies branch choice patterns that can indicate preferential rerouting patterns in a disrupted network.

2 Literature Review

2.1 Evacuation under Infrastructure Disruption

Evacuation processes are highly sensitive to infrastructure availability. When hazards such as floods, earthquakes, or wildfires damage critical links, evacuees must rapidly adapt to changing network conditions. Previous studies show that evacuation decisions are shaped by factors such as risk perception, trust in authorities, and perceived environmental stability [4, 16]. Social networks and prior disaster experience further influence compliance and adaptive behavior during evacuations [5, 6, 17].

Infrastructure disruption introduces additional uncertainty by altering the feasible route set available to evacuees. Compound risk situations, such as inaccessible shelters or blocked roads, can further complicate evacuation processes and disproportionately affect certain population groups [18, 19]. From a network perspective, such disruptions can be conceptualized as the removal of critical edges in a spatial graph, which may substantially alter system efficiency and load distribution [20, 21].

Despite growing attention to disaster resilience, relatively few empirical studies isolate the behavioral consequences of sudden link failure within an otherwise functioning evacuation network.

2.2 Route Choice and Exit Selection in Evacuations

Within pedestrian and crowd dynamics, route and exit selection is recognized as a core behavioral process, supported by a substantial body of empirical work spanning laboratory, field, and virtual-reality studies and distinguishing strategic, tactical, and operational levels of decision-making [22]. Route selection during evacuations has been examined across both indoor and outdoor environments (e.g., [7, 8, 13, 23, 24]). Exit choice

is influenced by familiarity, visibility, and perceived safety [7, 8]. Architectural cues and landmark salience can significantly affect wayfinding performance and spatial orientation [25]. Similarly, spatial knowledge completeness has been shown to influence route efficiency in VR-based evacuation studies [26].

Empirical trajectory data from evacuation drills demonstrate that evacuees do not distribute uniformly across available alternatives. For example, analyses of theater evacuation drills reveal systematic preferences for specific aisles and exit routes, indicating that local branching decisions can generate systematic redistribution patterns [13].

Recent experimental work further suggests that route choice may be influenced by hazard-related behavioral tendencies such as avoidance behavior and phototropism, which can bias decisions at junctions even when multiple alternatives are available [27]. Conversely, route and direction choices can also be shaped by social influence from nearby evacuees, with individual attributes moderating how peer behavior is perceived [28–30]. Such influence depends on the behavioral layer considered (e.g., movement initiation versus direction choice) and on context, and may favor either following or avoiding others [30].

While much of the existing literature focuses on efficiency-oriented performance measures such as route efficiency, evacuation time, or flow-related outcomes [13, 26, 31], these indicators do not fully capture the discrete decision processes occurring at critical junctions. From a behavioral perspective, evacuation can be understood as a sequence of local branching decisions, each redistributing individuals across available network alternatives [12]. Pedestrians typically base such decisions on locally available information, combining relatively stable cues such as path length with dynamic cues such as observed congestion, and only occasionally revise an initial choice as conditions change [32]. Understanding these branching mechanisms is therefore essential for anticipating bottlenecks and load concentration during evacuations, which are among the collective self-organization phenomena central to pedestrian and evacuation dynamics [15].

2.3 Technological Approaches and Experimental Platforms

Immersive virtual environments are increasingly used to investigate evacuation behavior under controlled yet realistic conditions [9–11, 26, 33]. VR-based studies enable systematic manipulation of environmental conditions while maintaining spatial immersion, making them particularly suitable for studying behavioral adaptation in disrupted evacuation scenarios [9].

In parallel, multi-agent simulation models have been widely applied to analyze evacuation route choice and network design under disaster conditions, including hierarchical evacuation networks and contraflow strategies [31]. Such models typically rely on behavioral assumptions about route choice, yet empirical validation of discrete reconfiguration decisions under abrupt infrastructure failure remains limited.

Importantly, immersive experiments enable the controlled removal of network elements without exposing participants to real-world risk [11]. This makes VR particularly suitable for studying adaptive behavior following sudden infrastructure failure—an aspect that is difficult to isolate in observational field data.

2.4 Network Perspective and Behavioral Redistribution

From a network-theoretic standpoint, sudden infrastructure failure can be conceptualized as edge removal in a spatial graph [34]. Such disruptions alter shortest paths and may shift flow distributions across remaining edges [20, 21]. In the pedestrian dynamics literature, graph-based evacuation models have explicitly examined how blocked or broken escape routes force dynamic rerouting and redistribute pedestrians onto the remaining links [35], while network-based flow models reproduce the resulting collection, spillback, and concentration of pedestrians at downstream constraints [14]. Related research on transport network resilience shows that disruptions produce characteristic spatial patterns of system degradation and recovery, with resulting flow redistribution depending on both structural and behavioral factors [36, 37].

At the behavioral level, evacuation route choice is shaped not only by individual characteristics and perceived risk but also by the spatial configuration of the available path network [38]. Network robustness studies therefore suggest that targeted edge removals can induce systematic redistribution patterns rather than uniform diffusion [39–41].

However, while network resilience has been studied extensively at aggregate levels, empirical behavioral evidence on how individuals redistribute at specific divergence nodes remains limited. Collective patterns may emerge even in the absence of direct interaction when individuals respond to shared structural constraints [13, 39–41]. Identifying whether route redistribution reflects preferential rerouting shaped by network geometry is therefore crucial for linking individual decision-making to system-level resilience.

2.5 Research Gap and Study Objective

Despite substantial progress in evacuation modeling and behavioral research, empirical evidence on how individuals redistribute across alternative routes after the sudden removal of a critical network edge remains limited. Much of the existing literature focuses on efficiency-oriented performance measures such as route efficiency, evacuation time, or flow-related outcomes, or investigates route choice in intact networks without abrupt structural disruption. Consequently, little is known about how evacuees reconfigure their decisions when confronted with a sudden topological change that alters the feasible path set.

From a network perspective, such disruptions can fundamentally reshape local decision contexts by turning a previously optimal route into an infeasible one. Understanding how individuals redistribute across the remaining alternatives is therefore essential for anticipating localized bottlenecks and structural concentration effects in disrupted networks.

This study addresses this gap by experimentally isolating route reconfiguration at a single, well-defined divergence node following abrupt edge removal in a controlled virtual evacuation scenario. Using VR, we observe how individuals redistribute across alternative paths when a critical bridge becomes unavailable and analyze whether this redistribution reflects preferential rerouting in the underlying network geometry.

3 Methodology

3.1 Experimental Design

The study was conducted in an immersive virtual reality (VR) environment representing an urban district in Frankfurt, Germany (Figure 1(a)). Participants experienced a simulated flood evacuation scenario in which they were required to follow a designated evacuation route toward a predefined target area.



(a) Virtual reconstruction of the study area used in the evacuation scenario.



(b) VR setup used in the experiment.

Figure 1 Virtual environment and experimental setup used in the study. (a) Screenshot of the Unity-based urban environment representing the study area in Frankfurt used for the evacuation simulation (derived from Google 3D Tiles; Map data © Google). (b) Participants navigated the scenario using an HP Reverb G2 head-mounted display and a Cyberith Virtualizer Elite 2 omnidirectional treadmill, supporting walking-based locomotion in VR.

The experiment was implemented in Unity and executed using an immersive VR setup consisting of an HP Reverb G2 head-mounted display and a Cyberith Virtualizer Elite 2 omnidirectional treadmill (Figure 1(b)). This configuration was selected to study evacuation routing under conditions that would be difficult to reproduce safely in the field. Immersive VR enabled controlled presentation of a flood event and scripted bridge collapse while holding the urban environment, hazard timing, and feasible route set constant across participants. The omnidirectional treadmill supported walking-based locomotion rather than joystick-based navigation, preserving movement-based wayfinding cues relevant to branch choice at the divergence node. The standardized Unity protocol further allowed repeatable scenario delivery across sessions and continuous (headset) position logging for trajectory analysis (Section 3.2).

The virtual environment was based on a three-dimensional reconstruction of the study area derived from Google 3D Tiles and adapted for immersive use in Unity. To maintain visual realism while ensuring stable performance, the flood event was represented through a gradually rising water surface, and the bridge collapse was implemented as a scripted animation rather than a full physical simulation.

Participants were recruited from undergraduate courses at TU Darmstadt. The study was approved by the ethics committee of the Technical University of Darmstadt (EK 110/2024), and all participants provided written informed consent before taking part.

In total, 143 participants were recruited for the experiment. One participant was excluded before the scenario began because the VR head-mounted display could not be fitted, leaving 142 who entered the simulation. Of these, six withdrew due to simulator sickness during or shortly after entering VR, and eight additional participants started but did not complete a valid evacuation run, yielding incomplete or unusable trajectory records. After these exclusions, the final analytic sample comprised 128 participants with valid trajectories (79 male, 49 female) with a mean age of 23.0 years ($SD = 2.4$, range = 19–35).

The target sample size was determined by convenience and laboratory capacity within the available recruitment period. The number of completed sessions was constrained by the use of a single immersive VR workstation, the time required for individual briefing, equipment setup, scenario completion, and post-session screening, and shared access to the teaching laboratory during the study term. No formal a priori power analysis was conducted. The final sample of $N = 128$ valid trajectories therefore reflects feasible recruitment under these VR-specific logistical constraints.

Procedure and Survey Measures

Before the VR session, participants completed a pre-survey assessing demographic characteristics, prior VR experience, and self-reported familiarity with the study area on a five-point Likert scale (higher scores indicating greater familiarity).

Participants then received a briefing on the evacuation task and the use of the VR equipment. They studied a printed map showing the designated evacuation route and target area. Participants could study the map until they reported that they knew the route; no time pressure was applied at this stage. Route knowledge was not formally tested after map exposure.

After entering the simulation, participants followed the indicated evacuation route toward the target area (Figure 2). Midway through the scenario, a critical bridge crossing the river Main collapsed due to the simulated flood event. The collapse was triggered as participants approached the bridge, causing the disruption to unfold directly within their field of view. This removed a key network edge and forced participants to reroute toward the target area using alternative paths.

Downstream of the collapsed bridge, participants reached a divergence node where three alternative branches were available (Figure 3). In the network model described below, this junction is denoted as the divergence node v_d . The available branches differed in their spatial configuration and relation to the original evacuation route:

- e_0 : Direct branch leading straight toward the target area,
- e_1 : Shortcut branch reconnecting with the original evacuation route via a side street,
- e_2 : Original-route branch following the riverbank back toward the collapsed bridge and the path taken before the disruption, guided by the Main Plaza Tower as a visible landmark.

Although additional street segments are visible at the junction in the underlying map geometry, they did not constitute relevant evacuation alternatives in the scenario design. In particular, reverse movement back across the intact bridge returns participants toward the disrupted approach rather than toward the target area, and other map-visible openings either do not continue as coherent evacuation corridors toward the destination or were not taken by any participant. Accordingly, the effective choice set at the divergence node (Section 3.2) consisted of the three routes described above, which were also the only outgoing directions observed in the trajectory data (Section 4; Figure 6).

The route chosen at the divergence node v_d constitutes the primary behavioral variable analyzed in this study, operationalized as the first outgoing branch taken when leaving the junction.

Participants completed the evacuation individually and were not exposed to other evacuees during the experiment, thereby preventing social interaction or crowd dynamics from influencing route choice behavior.

3.2 Experimental Network

Network Representation

The urban street system can be read as a network of places where people choose directions and street segments they can walk along. *Nodes* represent junctions and decision points where routes meet, and *edges* represent walkable street segments connecting those nodes. Following [34], this structure is represented as a spatial graph

$$G = (V, E),$$

where V is the set of nodes (junctions and decision points), and

$$E \subseteq \{\{v_i, v_j\} \mid v_i, v_j \in V\}$$

is the set of edges connecting pairs of nodes.

Although the physical network is topologically undirected, route choice at a given location is modeled as a locally directional action. For a node $v \in V$, the set of feasible outgoing actions is defined as

$$\mathcal{A}(v) = \{(v \rightarrow v_j) \mid \{v, v_j\} \in E\}.$$

Thus, while the network allows bidirectional movement along individual street segments, the decision problem at a node is modeled as a locally directional outgoing choice

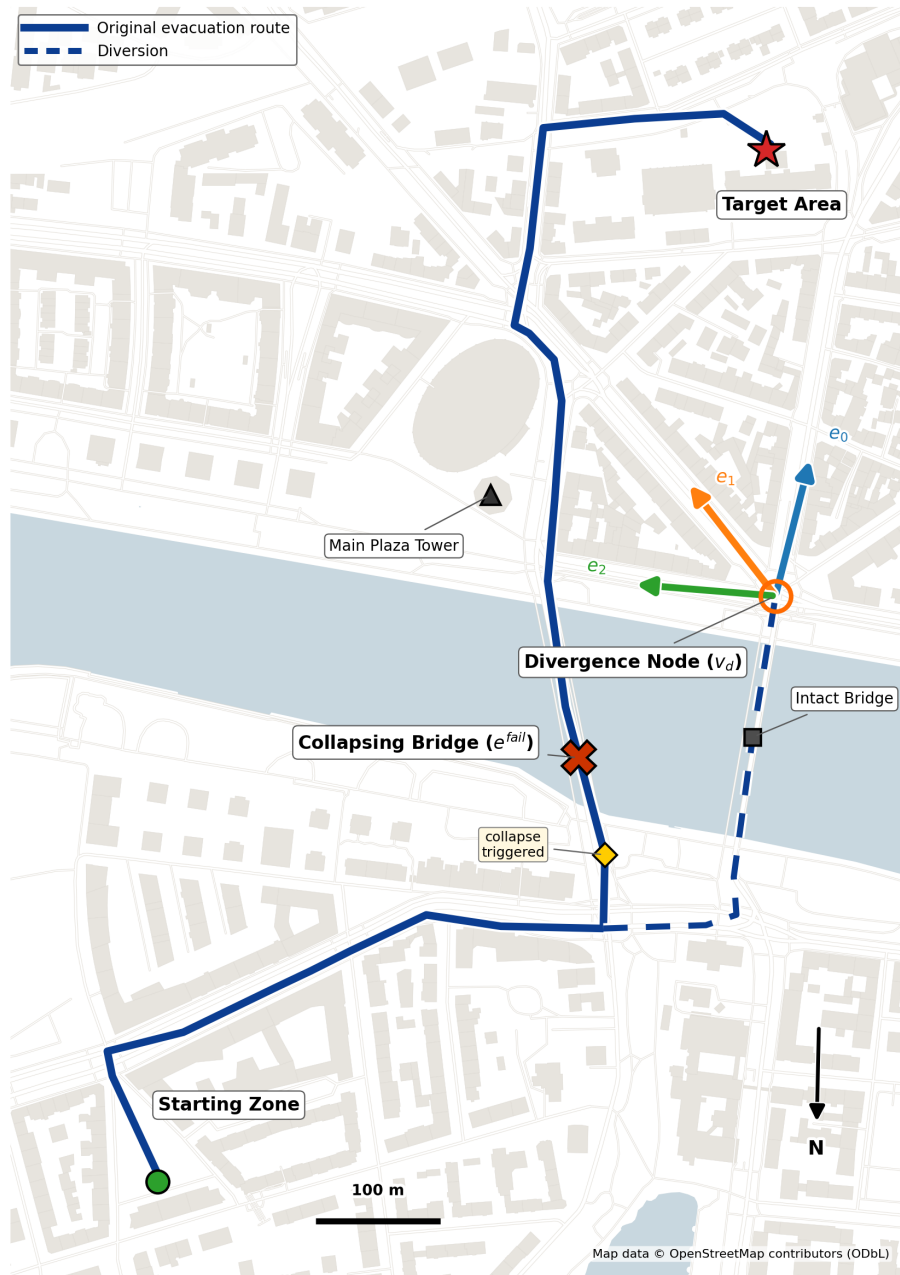


Figure 2 Study area and disrupted evacuation route in Frankfurt. Participants initially followed the original evacuation route until a bridge collapse removed the critical edge e^{fail} . The disruption forced rerouting at the downstream divergence node v_d , where three alternative branches (e_0 – e_2) were available. Map data © OpenStreetMap contributors (ODbL).

relative to the evacuee's current position and heading. In the VR scenario, participants were not restricted to forward-only motion and could turn around along available streets. The analysis nevertheless treats junction behavior as a discrete outgoing choice at v_d rather than as unrestricted movement over the full undirected graph.



Figure 3 First-person view approaching the divergence node v_d in the immersive VR environment, illustrating the participant perspective at the critical rerouting location after the bridge collapse. The virtual city model was derived from Google 3D Tiles (imported via Blossm), UV-baked, and adapted for Unity. Map data © Google.

Disruption as Edge Removal

In the experiment, the bridge collapse made one street crossing temporarily unusable (Figure 2). In network terms, this corresponds to removing the failed crossing from the set of available links: evacuees can no longer traverse that segment, but the junctions and remaining streets stay in place. At time $t = t^*$, the critical bridge edge $e^{fail} \in E$ is therefore removed from the network:

$$E' = E \setminus \{e^{fail}\}.$$

The disrupted network becomes

$$G' = (V, E').$$

All subsequent decisions occur in G' .

Divergence Node and Choice Set

Let $v_d \in V$ denote the divergence node downstream of the disruption. From this node, three alternative edges are available:

$$\mathcal{A}(v_d) = \{e_0, e_1, e_2\}.$$

These correspond to:

- e_0 : Direct branch,
- e_1 : Shortcut branch,
- e_2 : Original-route branch.

To further interpret redistribution patterns, the three available branches were descriptively characterized using two geometric properties: approximate path length from the divergence node to the target area, and initial angular deviation of each branch from the participant's incoming movement direction at the divergence node. The angular deviation captures the extent to which a branch preserves directional continuity relative to the evacuee's current heading when approaching the node from the disrupted bridge, with smaller deviations corresponding to a continuation of forward movement. For readability, path length is also reported as a *detour factor*, defined as the ratio of approximate path length to the Euclidean distance between the divergence node and the target area (approximately 360 m). Because this Euclidean denominator is identical for all three branches, the detour factor is a linear rescaling of path length and does not provide independent geometric information; it is retained only as a normalized expression of the same distance ordering. These measures were derived from map-based distance estimates and are intended as descriptive indicators for interpreting observed branch preferences.

Trajectory Recording and Preprocessing

During each session, the Unity application logged headset tracking data as CSV time series sampled at approximately 90 Hz (median interval 11 ms). Each record contained an elapsed session timestamp and HP Reverb G2 tracking variables, including headset position (x, y, z), head orientation (forward and up unit vectors), and gaze direction. Additional controller poses, heart rate, and pupil-dilation fields were also logged by the experimental system. For a subset of participants, however, these sensors did not yield usable signals, and the remaining measurements were not sufficiently complete or validated for analysis. We therefore did not analyze physiological stress responses. Participant trajectories were defined from headset position in the x - z plane.

Positions were recorded in Unity world coordinates, with y denoting elevation and x and z spanning the horizontal plane used for trajectory plots and branch assignment. Exported coordinates were multiplied by a factor of 0.2 after loading to match in-scene meter units.

Figure 4 provides a raw-data overview of all recorded participant trajectories in the horizontal x - z plane, prior to any branch assignment. The shared corridor from the starting zone converges on the divergence node v_d (circled), after which the paths disperse toward the target area. This view links the raw movement data directly to the subsequent analysis and improves transparency from data to results.

Trajectory Intercept Analysis and Branch Assignment

Discrete branch choices were extracted with the VERTA pipeline [42]. For each participant, the Unity-exported headset trajectory was loaded, scaled to in-scene meter units (factor 0.2), and screened for completeness. Trajectory intercept analysis at v_d then converted each continuous path into a discrete choice. A circular analysis radius was centered on the junction center. The radius was chosen to place the intercept beyond the immediate junction mouth, where the three outgoing corridors are already angularly separated in plan view, while remaining close enough to v_d that the first exit still reflects the local branch

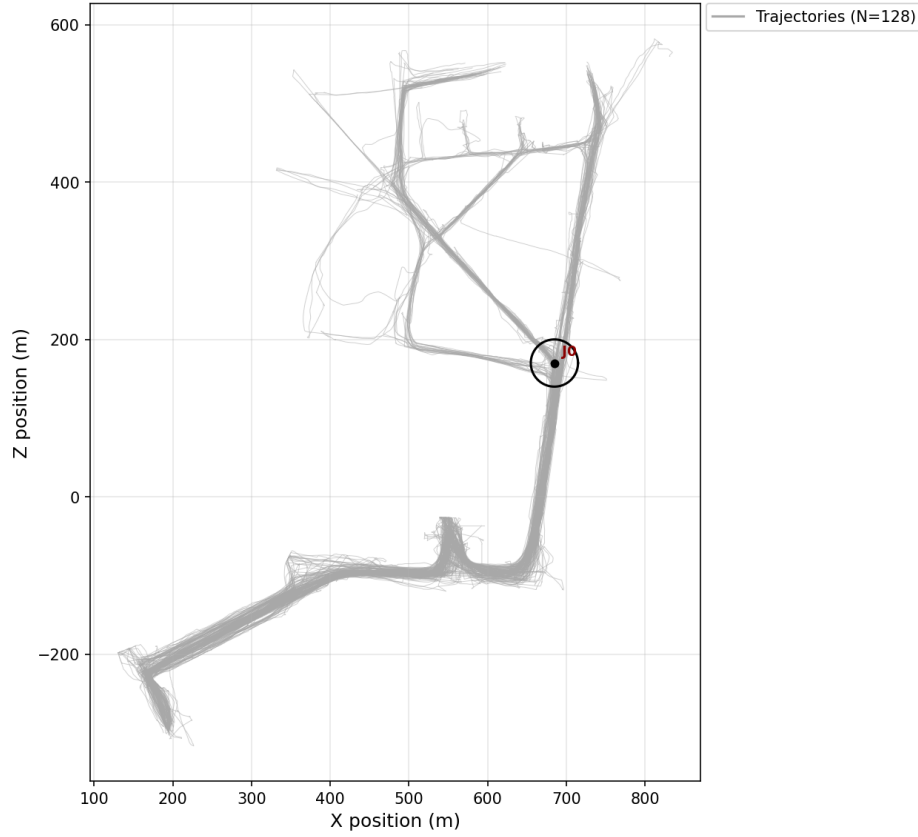


Figure 4 Raw participant trajectories ($N = 128$) in Unity x - z coordinates (m), with the vertical axis omitted. Each gray line is one VR headset path and the divergence node v_d is marked (circle). The node is labeled $J0$ (junction 0) by the VERTA analysis pipeline [42] and corresponds to the divergence node v_d used throughout this paper.

commitment rather than later downstream decisions. The main analysis uses $r = 100$ m (Figure 5).

Operationally, a trajectory was treated as having entered the junction once it crossed into the circular neighborhood of v_d . The *intercept point* was then defined as the first subsequent *outward* crossing of the analysis circle. The angular position of that intercept around the junction center identified the *outgoing branch* $e_k \in \{e_0, e_1, e_2\}$, yielding one discrete outcome $Y_i = k$ per participant. If a participant later turned back into the circle and crossed it again, only the first outward intercept was retained; later re-entries and re-exits were ignored. All valid trajectories yielded an intercept under this rule, and visual inspection of the full paths confirmed three well-separated outgoing corridors corresponding to e_0 – e_2 (Figure 6).

To assess whether the discrete counts depend on the chosen radius, we repeated the intercept assignment for alternative radii of $r \in \{50, 100, 150\}$ m. Branch counts were identical across these settings ($n_{e_0} = 62$, $n_{e_1} = 45$, $n_{e_2} = 21$). At $r = 50$ m the three exit sectors were already visually separable, though with less angular separation than at larger radii; $r = 100$ m was retained for the main analysis as a compromise between clearing the

junction mouth and remaining local to v_d .

Discrete Route Choice

For each participant $i \in \{1, \dots, N\}$, a discrete choice variable is defined as

$$Y_i \in \{0, 1, 2\},$$

with

$$Y_i = k \quad \text{if participant } i \text{ selects edge } e_k \text{ at } v_d.$$

Branch selection Y_i was derived from the intercept analysis described in Section 3.2. The empirical selection probability for branch k is given by

$$\hat{P}_k = \frac{1}{N} \sum_{i=1}^N \mathbf{1}(Y_i = k),$$

where $\mathbf{1}(\cdot)$ denotes the indicator function.

Test of Uniform Redistribution

To evaluate whether redistribution across branches is consistent with uniform allocation, the null hypothesis is defined as

$$H_0 : P_0 = P_1 = P_2 = \frac{1}{3}.$$

In the absence of structural preference, evacuees would be expected to distribute approximately uniformly across the available alternatives. Rejection of H_0 indicates only that selection frequencies differ among branches; it does not attribute that difference to any particular geometric or individual factor.

The test statistic is given by

$$\chi^2 = \sum_{k=0}^2 \frac{(n_k - E_k)^2}{E_k}, \quad E_k = \frac{N}{3},$$

where n_k denotes the observed number of selections of branch k .

To quantify the degree of concentration in redistribution, we computed the Shannon entropy [43] of the observed branch distribution as a measure of redistribution concentration:

$$H = - \sum_{k=0}^2 \hat{P}_k \ln \hat{P}_k.$$

Individual Heterogeneity of Route Choices

To assess whether redistribution depends on individual attributes, we conducted Kruskal–Wallis tests across the three branches for continuous and ordinal variables. Age was treated as a continuous variable, while self-reported familiarity with the study area was collected on a five-point Likert scale in the pre-survey. Gender and prior VR use were recorded as categorical variables, and therefore analyzed using chi-square tests of independence.

4 Results

This section presents the results in three parts. First, we analyze how participants redistributed across alternative branches following the disruption (Section 4.1). Second, we relate the observed patterns to the geometric properties of the available routes (Section 4.2). Finally, we examine whether this redistribution varies across individual characteristics (Section 4.3).

4.1 Branch Redistribution after Edge Removal

Evacuees selected the direct and shortcut alternatives more frequently, while still distributing across all available routes.

Figure 5 visualizes the intercept analysis at v_d (Section 3.2) and the resulting redistribution across the three alternatives.

Complementing the discrete intercepts, Figure 6 shows the full participant trajectories colored by the branch selected at v_d . This spatial view makes the redistribution tangible: the initially shared approach corridor fans out into the three alternatives downstream of the divergence node, with the direct branch e_0 carrying the largest share.

Across all valid participants ($N = 128$), branch choices were distributed as follows: direct ($n_{Y_0} = 62$, $\hat{P}_0 = 0.484$), shortcut ($n_{Y_1} = 45$, $\hat{P}_1 = 0.352$), and original-route ($n_{Y_2} = 21$, $\hat{P}_2 = 0.164$).

To test whether redistribution across the three alternatives was consistent with uniform allocation (Section 3.2), we evaluated the null hypothesis $H_0 : P_0 = P_1 = P_2 = \frac{1}{3}$. The observed distribution deviated significantly from uniformity ($\chi^2(2) = 19.891$, $p = 4.80 \times 10^{-5}$; expected counts $E_k = N/3 = 42.67$). This test establishes only that the three branches were not chosen equally; it does not identify which attributes caused the imbalance. Explanatory interpretation is therefore limited to descriptive comparison with route geometry (Section 4.2) and to tests of individual heterogeneity (Section 4.3).

The resulting entropy was $H = 1.015$, compared to the theoretical maximum $H_{\max} = \ln 3 = 1.099$, corresponding to a normalized entropy of 0.924. This indicates a moderately uneven redistribution across the available branches. While route choices are not uniformly distributed, the entropy remains relatively high, suggesting that evacuees distribute across multiple alternatives rather than concentrating on a single dominant route.

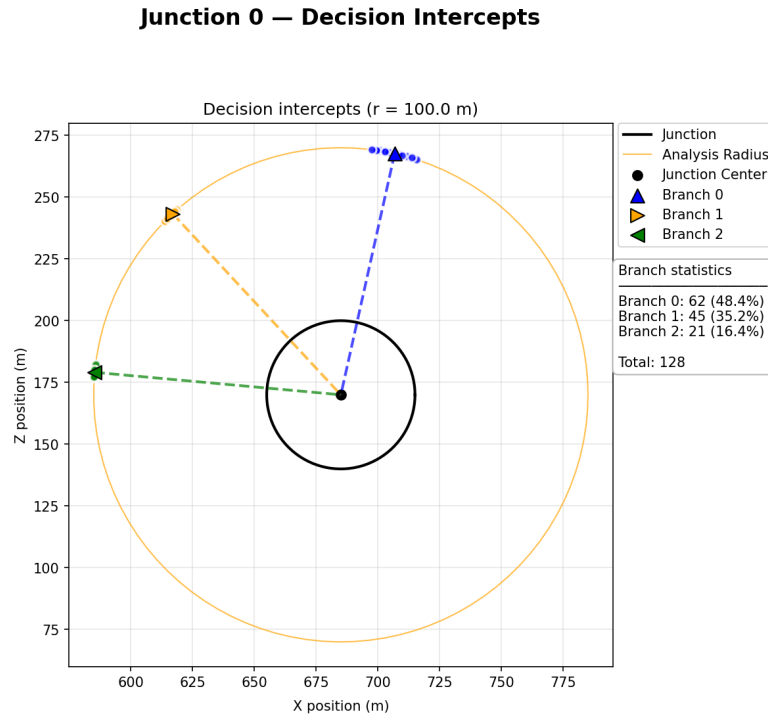


Figure 5 Intercept analysis at the divergence node v_d in Unity x - z coordinates (m). The 100 m analysis radius (orange circle) and color-coded intercept markers assign each trajectory to e_0 direct (blue), e_1 shortcut (orange), or e_2 original-route (green). Branch counts: 62 (48.4%), 45 (35.2%), and 21 (16.4%) for $N = 128$.

4.2 Descriptive Relationship Between Geometric Route Properties and Branch Selection

The most frequently selected branches were also the shortest and most directionally aligned alternatives.

A descriptive geometric comparison of the three branches (Table 1) showed a clear ordering of the available alternatives. The direct branch e_0 had the shortest approximate path length (380 m; detour factor 1.06) and no initial angular deviation from the incoming movement direction. The shortcut branch e_1 was longer (540 m; detour factor 1.50) and deviated by approximately 45° . The original-route branch e_2 was the longest alternative (640 m; detour factor 1.78) and showed the largest initial angular deviation (approximately 90°). This ordering is consistent with the observed redistribution pattern: the direct branch e_0 , which provides the shortest and most directionally aligned route, was selected most frequently, followed by the shortcut e_1 , while the original-route branch e_2 was chosen least often.

The correspondence between this geometric ordering and the observed branch frequencies is consistent with route geometry contributing to the redistribution pattern. However, it should be interpreted descriptively. Because all participants encountered the same three branches at a single divergence node, path length, angular deviation, and branch identity

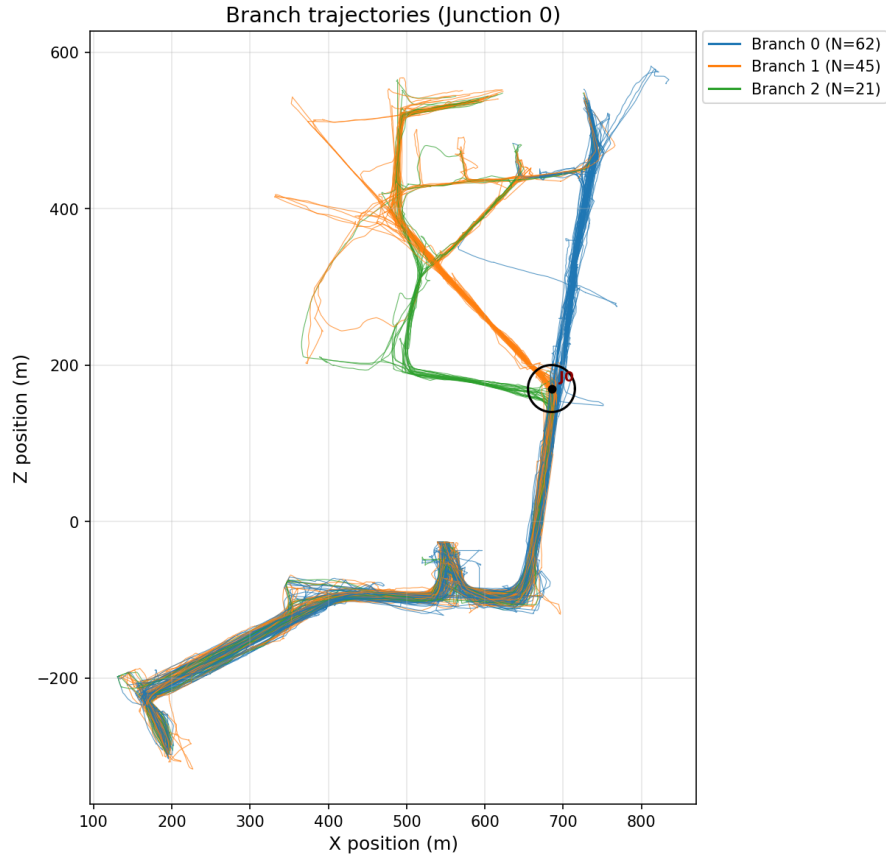


Figure 6 Participant trajectories ($N = 128$) colored according to the first outgoing branch selected at the divergence node v_d (circle): e_0 direct (blue, $n = 62$), e_1 shortcut (orange, $n = 45$), and e_2 original-route (green, $n = 21$). Coordinates are shown in the Unity x - z plane in meters, with the vertical y -axis omitted. The panel title “Junction 0” (J_0) is the VERTA pipeline [42] label for the divergence node v_d . The paths share a common approach and separate after the disruption. Colors indicate only the initial branch assignment at v_d ; subsequent movements and decisions at later junctions are shown for spatial context but were not included in the present route-choice analysis.

were not independently varied. The present analysis therefore cannot isolate the causal contribution of any individual geometric property.

Table 1 Descriptive geometric characteristics of the three alternative branches from the divergence node to the target area. Detour factor equals path length divided by the common Euclidean distance of approximately 360 m and is therefore a rescaled form of path length, not an independent measure.

Branch	Approx. path length (m)	Initial angular deviation	Detour factor
e_0 (Direct)	380	0°	1.06
e_1 (Shortcut)	540	45°	1.50
e_2 (Original-route)	640	90°	1.78

4.3 Individual Heterogeneity

In our sample, we did not observe statistically detectable differences in branch redistribution across demographic or experience-related attributes. We first describe the branch-wise composition of the sample and then test whether these individual attributes differ across the three branches.

Table 2 reports the distribution of age, study-area familiarity, gender, and prior VR use for each branch. The three subsamples were closely comparable. Median age ranged from 22 to 23 years across branches (overall median 22.5, IQR 22–24), with only minor differences in dispersion (age SD ranging from 1.7 years for the direct branch e_0 to 3.2 years for the original-route branch e_2). Self-reported familiarity with the study area was uniformly low (median 2 on the five-point scale in every branch), suggesting that prior local knowledge was unlikely to be a strong driver of route choice in this sample. The gender composition was similar across branches (male share: 56% in e_0 , 64% in e_1 , and 71% in e_2 ; 62% overall), as was the proportion of participants with prior VR experience (32%, 38%, and 29% for e_0 , e_1 , and e_2 ; 34% overall). Participants selecting each alternative were therefore descriptively alike, and no branch was dominated by a particular demographic or experience group.

Table 2 Branch-wise descriptive statistics for the individual attributes examined in the heterogeneity analysis ($N = 128$). Age is reported as mean (SD) and median [IQR]; study-area familiarity (five-point Likert scale, 1 = not familiar, 5 = very familiar) as median [IQR]; gender and prior VR use as counts.

Branch	n	Age		Familiarity	Gender	Prior VR
		mean (SD)	median [IQR]	median [IQR]	(m/f)	(yes/no)
e_0 (Direct)	62	22.7 (1.7)	22 [22–24]	2 [1–3]	35/27	20/42
e_1 (Shortcut)	45	23.4 (2.8)	23 [22–24]	2 [1–2]	29/16	17/28
e_2 (Original-route)	21	23.0 (3.2)	22 [21–24]	2 [1–3]	15/6	6/15
Overall	128	23.0 (2.4)	22.5 [22–24]	2 [1–3]	79/49	43/85

Inferential tests likewise did not detect statistically significant differences between the branch groups. Kruskal–Wallis tests did not reveal statistically detectable differences across branches for age ($H(2) = 0.78$, $p = 0.678$) or familiarity with the study area ($H(2) = 0.58$, $p = 0.747$). Chi-square tests of independence likewise did not indicate a statistically detectable association between branch choice and prior VR use ($\chi^2(2) = 0.64$, $p = 0.726$) or gender ($\chi^2(2) = 1.708$, $p = 0.426$); the corresponding effect sizes were small (Cramer’s $V = 0.07$ and $V = 0.12$, respectively). Taken together, the descriptive and inferential results provide no evidence that the observed redistribution across branches was associated with the individual attributes examined. Given the relatively homogeneous sample, however, these null results should be read as an absence of *detectable* effects rather than as evidence that such effects do not exist.

5 Discussion

This study investigated how individuals reconfigure their routes after the sudden removal of a critical network edge in an urban evacuation setting. By conceptualizing the disruption as edge removal in a spatial graph, we isolated redistribution behavior at a clearly defined divergence node.

5.1 Redistribution Patterns after Edge Removal

The observed branch distribution deviated significantly from uniform allocation, indicating systematic differences in selection frequencies across the three alternatives. The chi-square test demonstrates this non-uniformity but does not explain *why* it occurred; geometric correspondence and individual-attribute comparisons below are descriptive and associative only. Evacuees redistributed unevenly across the available branches, with higher selection of the direct and shortcut routes. Entropy analysis further shows that redistribution remained relatively spread across alternatives rather than collapsing onto a single dominant route. This pattern is consistent with network structure contributing to route choice, while selections remained distributed across all three alternatives.

These findings are consistent with prior empirical studies showing that evacuation route choice is shaped by structured local decision processes rather than uniform allocation. For example, trajectory analyses from theater evacuation drills indicate that evacuees generally orient toward nearby target exits and make junction decisions that preserve progress while adapting to local constraints such as blockage or queuing [13]. Similarly, research on network robustness and infrastructure vulnerability suggests that removing critical components can substantially reshape connectivity and rerouting opportunities in the remaining network [39–41].

From a network perspective, the removal of a critical edge alters shortest paths and reshapes the feasible choice set. The resulting redistribution pattern is consistent with local topology structuring the available rerouting alternatives, even in the absence of interaction between individuals. Rather than being distributed uniformly, branch selections were concentrated on alternatives that preserved directional progress or reconnected with the original route structure.

5.2 Descriptive Relationship Between Geometric Route Properties and Branch Selection

The three available branches can be interpreted as offering different forms of rerouting logic. The direct branch e_0 preserved the overall direction toward the target area and required no immediate additional turning decision, thereby providing the strongest directional continuity after the disruption. The shortcut branch e_1 also led in the correct general direction, while enabling participants to reconnect with the original evacuation route through a side street. By contrast, the original-route branch e_2 followed the river-bank back toward the originally indicated evacuation path and may also have supported

orientation through the visible Main Plaza Tower, but at the cost of a substantially longer detour.

Within this scenario, the observed ordering of branch-selection frequencies was consistent with participants tending toward alternatives that preserved directional continuity and limited path length. The direct branch e_0 combined the shortest path (equivalently, the lowest detour factor) with the smallest angular deviation, while the original-route branch e_2 combined the longest path with the largest angular deviation. This correspondence supports route geometry as one plausible explanation for the redistribution pattern, but it does not establish a causal effect. Because the study contained only one common choice situation, geometric properties were confounded with branch identity, orientation relative to the river, and relation to the originally indicated route. Hazard avoidance may therefore also have contributed: e_2 led back along the riverbank, whereas e_0 led away from the flooded area.

These findings align with prior research showing that evacuation route choice is influenced by spatial configuration and orientation-supporting cues. Studies on evacuation wayfinding highlight the role of familiarity, architectural cues, and landmarks in shaping route decisions [7, 8]. Similarly, VR-based evacuation experiments indicate that spatial knowledge and environmental cues affect route efficiency and decision-making [26]. Our results extend this literature by showing that even under sudden disruption, observed redistribution can correspond descriptively to simple geometric differences among available alternatives.

5.3 Role of Individual Characteristics

Importantly, we did not observe statistically detectable differences in redistribution across the demographic and experiential factors examined. We did not detect statistically significant differences with respect to age, familiarity with the urban environment, prior use of VR equipment, or gender. These comparisons should, however, be read with caution: the participant pool was fairly homogeneous, and the age range in particular was narrow (mostly young adults in their early twenties). With so little variation in age, our data are not well suited to detect an age effect in the first place, so the absence of a significant difference here says little either way rather than providing strong evidence that age does not matter. The same caveat applies, to a lesser degree, to the other individual factors given the low overall familiarity with the area.

These findings differ from studies reporting relationships between individual characteristics and evacuation behavior, including familiarity, risk perception, and social influence [4, 5, 38]. In the present study, however, the measured participant attributes did not explain detectable variation in branch choice. This may reflect the shared and relatively constrained decision environment, but it may also result from the limited heterogeneity of the sample, particularly its narrow age distribution and generally low familiarity with the study area.

The results should therefore not be interpreted as evidence that topology overrides individual differences. They support the narrower conclusion that, within this sample and choice situation, the observed redistribution pattern was not detectably associated with

the demographic and experience-related variables examined.

5.4 Implications for Network Resilience

These findings have implications for evacuation planning and network resilience analysis. In disrupted systems, bottlenecks may emerge not only due to congestion, but also due to uneven redistribution toward preferential rerouting branches. Identifying divergence nodes at which disproportionate rerouting occurs may therefore be important for resilience-oriented design.

More broadly, this study demonstrates how immersive experimental platforms can provide empirical evidence on redistribution dynamics in spatial networks. Even in the absence of crowd interaction, systematic collective patterns can emerge from shared exposure to structural constraints. This supports the view that collective patterns in evacuation scenarios can arise not only from social interaction but also from shared responses to network topology.

5.5 Limitations and Future Work

Several limitations should be acknowledged. First, the experiment was conducted in a controlled virtual environment with a student sample, which may limit the generalizability of the findings. Second, redistribution was observed at a single divergence node; future work should examine multi-node cascades and sequential reconfiguration processes in larger network settings. Third, participants completed the evacuation individually and without exposure to other evacuees, so social influence on route choice, people–people interactions (including leader–follower dynamics), and group decision dynamics were not captured; the collective concentration patterns reported here should therefore be interpreted as emerging from shared environmental constraints—a common network structure, hazard, and route geometry—rather than from direct social interaction. Fourth, simulator sickness occurred in six participants who withdrew before completing the scenario, which may modestly select the analytic sample toward individuals tolerant of immersive VR. Fifth, locomotion relied on a Cyberith Virtualizer Elite 2 omnidirectional treadmill, in which participants are supported by a waist harness and slide their feet across a low-friction platform. This constrains natural gait—typically producing shorter, slower, sliding steps and requiring a brief adaptation period—and differs from unconstrained overground walking; it may also contribute to the simulator sickness noted above. Although the treadmill preserves movement-based wayfinding cues more faithfully than joystick navigation, these altered locomotor dynamics could affect movement speed and, potentially, route commitment at the divergence node.

A further limitation concerns the use of immersive virtual reality itself. Although VR enables controlled and spatially realistic experimentation, it cannot fully reproduce the perceptual, emotional, and physiological conditions of real emergency situations. In particular, we did not analyze subjective risk perception, anxiety, or stress. Although heart-rate and pupil-dilation fields were recorded by the experimental system, these measurements were not sufficiently complete or validated for inclusion in the present analysis, so

physiological stress responses remain uncharacterized. One possible explanation is that the comparatively low-stress, game-like character of the VR task—together with the absence of social interaction and real risk conditions—increased reliance on simple visible route cues. This interpretation remains speculative, however: participants' subjective or physiological stress levels were not tested in this study, so we cannot claim that decisions were made under low stress. Future research could integrate group dynamics, vary disruption scenarios, compare multiple network topologies, and further examine how experimental realism influences adaptive rerouting behavior.

A promising methodological extension is the use of discrete choice models, such as multinomial or conditional (mixed) logit specifications, which are the standard framework for analyzing pedestrian route and exit selection. Two considerations, however, place such modeling beyond the scope of the present design. First, a conditional logit on branch-level geometric attributes (e.g., path length and angular deviation) is not identifiable here: redistribution was observed at a *single* divergence node that was identical for all participants, so the branch attributes do not vary across decision-makers and are collinear with the alternative-specific constants. Detour factor, being a constant rescaling of path length at this node, would likewise not be separately identifiable. Separating the effect of geometry from a generic preference for a given branch would require multiple choice situations with varying attributes, for example additional divergence nodes or a stated-choice design. Second, a multinomial logistic model on individual covariates (age, gender, study-area familiarity, prior VR use) would be estimable, but the heterogeneity analyses in Section 4.3 already indicate no statistically detectable associations between these attributes and branch choice, and the smallest branch subgroup ($n = 21$) limits the stability of a multi-parameter model. We therefore report the aggregate redistribution and descriptive heterogeneity results and leave formal discrete choice modeling—ideally on a design with several disruption points and varying branch geometries—to future work.

6 Conclusions

This study examined route reconfiguration behavior following the sudden removal of a critical network edge in an urban evacuation setting. By modeling the street system as a spatial graph and isolating redistribution at a single divergence node, we analyzed how individuals adapt when a previously available connection becomes infeasible.

The results demonstrate three key findings. First, redistribution was not uniform across the three alternatives, indicating systematic differences in selection frequencies rather than equal allocation. Second, the ordering of branch-selection frequencies corresponded descriptively to differences in path length and directional continuity among the available alternatives. Third, we did not observe statistically detectable differences in redistribution across the demographic and experience-related attributes examined, including gender, age, prior use of VR, and spatial familiarity.

Together, these findings show that a shared disrupted network can produce systematic, non-uniform route redistribution. In the investigated scenario, branch-selection frequencies corresponded descriptively to differences in path length and directional continuity.

The single-node design does not, however, allow the causal contribution of individual geometric properties to be isolated. Even in the absence of crowd interaction, shared exposure to structural constraints can generate systematic collective patterns.

From a resilience perspective, understanding how edge removal induces localized redistribution at divergence nodes is essential for anticipating potential bottlenecks under disruption. Immersive experimental platforms provide a controlled environment to isolate behavioral responses to topological disruptions, enabling empirical observation of redistribution dynamics that are difficult to capture in real-world disasters.

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Ethics Statement This study has been approved by the ethics committee of the Technical University of Darmstadt (EK 110/2024). All participants gave written informed consent to participate in the study.

Data Availability Individual-level survey responses and trajectory recordings are not available to third parties, including upon request, due to ethical and data-protection restrictions. To support transparency, the manuscript reports the aggregate branch counts, geometric route characteristics, descriptive statistics, effect sizes, and test statistics underlying the reported findings (Tables 1 and 2, and Section 4).

The documented analysis script (`analyze_route_choice.py`) is provided as supplementary material accompanying this article. The script documents the computational procedures used to calculate the branch counts, the chi-square test of uniform redistribution, the entropy measures, and the heterogeneity statistics reported in Section 4.

Neither the study design nor the analysis plan was formally preregistered in a public registry. The study protocol was, however, reviewed and approved by the institutional ethics committee (see the Ethics Statement). In the interest of transparency, the test of non-uniform redistribution at the divergence node corresponds to the study's primary research question, whereas the geometry and individual-heterogeneity analyses (Sections 4.2 and 4.3) are reported as exploratory.

Conflict of Interest The authors declare that they have no conflict of interest.

Author Contributions Niklas Suhre: Conceptualization, Methodology, Formal analysis, Data curation, Writing – Original draft / Meng Cai: Conceptualization, Formal analysis, Writing – Review and editing / Michael Kraus: Writing – Review and editing, Supervision / Uwe Rüppel: Writing – Review and editing, Supervision / Eva Kassens-Noor: Writing – Review and editing, Supervision

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