Replication of Wayfinding Studies in Different Geographic Areas. A Simulation Study

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Keywords: Route Selection, Human Wayfinding, Experiments, Replicability

Summary: *Replication of real-world wayfinding studies is not a trivial task. Even less if it is to be replicated in a different geographic environment. The selection of one or several routes is one of many decisions to be made. Only recently (2021), a reproducible, systematic and score-based approach for route selection for wayfinding experiments was published. Besides allowing for selecting a route within a selected experimental area, it claims to be able to find similar routes in different geographic areas. However, it remains unclear if similar, according to this route selection framework, routes lead to similar study results. In order to answer this question, an agent-based simulation comparing Turn-by-Turn and Free Choice Navigation approaches (between-subject design) is run in one European (Vienna) and one African (Djibouti City) city. First, a route in Vienna is selected and, second, the 5 most and the 5 least similar routes in Djibouti City are found. These routes are used in the simulation in order to scrutinize if more similar routes lead to more similar results regarding the arrival rate as a metric. The results suggest that the route selection framework is suitable for replication studies for the Turn-By-Turn navigation approach but needs further improvement for the Free Choice Navigation approach by adding features describing the neighborhood of the route.*

1. Introduction

The replication of studies is not a trivial task, as many factors need to be considered and kept as similar as possible to make the results comparable. The route selection is crucial for replicating wayfinding studies. There are two possibilities regarding the experimental area. It can be kept constant, although some elements of the environment may have changed over time and potentially impact study results. The second option is to replicate a wayfinding study in another geographic area. In the second case, the route selection task is not as simple as in the first case (using the same route). The routes from both studies, the original and the replicating one should be similar regarding the wayfinding task.

We recently presented (2021) a framework [14] that allows systematic route selection, i.e., how to select a route from a given experimental area with many potential routes. Furthermore, we hypothesized that this framework would increase the replicability of wayfinding studies by finding similar routes in different geographic areas. If this assumption can be verified, then the above-mentioned problem of selecting similar routes in different geographical areas can be solved or at least mitigated. Therefore, we will use the previously proposed route selection framework, first, to identify an average-based [14] route in a European city (Vienna) and, second, to find the most and the least similar routes in Djibouti City in Africa. Two navigation systems (see Section 3.2) will be compared on these routes with respect to the arrival rate. Since the framework can capture route characteristics, more similar routes in Djibouti City should lead to more similar results to those achieved in Vienna. As in our previous study [13], this hypothesis will be scrutinized through a simulation study.

The contribution of this work is two-fold: First, the suitability of the route selection framework for replication studies is investigated. Our results suggest the ability of the route selection framework to support replication studies in other geographic regions. Furthermore, it should increase the comparability of wayfinding studies if the selected experimental areas with their respective routes are similar enough. Second, we shed light on the importance of route selection in wayfinding studies by analyzing the arrival rates on single routes.

2. Related Work

In this section, we discuss relevant literature, first, about reproducibility in the domain of GIScience in general and, second, about replication in the wayfinding domain. In this work, the terms reproducibility and replication are used in the sense of Claerbout/Donoho/Peng [2]. Reproduction means recreating the results with the same methods and input data that the authors provide. The related concept of replication means coming to the same conclusion by conducting a new study.

2.1 Reproducibility in GIScience

Reproducibility has seen considerable interest in the GIScience domain within the last years (e.g., [9, 3]). Ostermann and colleagues assessed 87 papers from GIScience conferences between 2012 and 2018 regarding reproducibility [17]. None of the assessed works was easily reproducible. This study replicated a study considering the AGILE conference [16]. In conclusion, both conference series are similar regarding reproducibility. Konkol and colleagues conducted a study about computational reproducibility in geographic research [10]. They studied the understanding of open reproducible research (ORR) through surveys, interviews and a focus group. They found that the meaning of ORR diverges considerably among the participants of the European Geosciences Union General Assembly 2016. Furthermore, the authors tried to reproduce the results and figures of 41 open access articles from Copernicus and the Journal of Statistical Software. They encountered technical issues of different severity levels in 39 works.

2.2 Replication in Different Geographic Areas in the Wayfinding Domain

Several studies have been conducted replicating real-world studies in virtual environments. Kuliga and colleagues [11] conducted a wayfinding study in a building and then replicated it three times in different virtual replicas. All four conditions yielded similar results regarding superfluous distances and absolute angular pointing errors. Savino and colleagues compared wayfinding in real-world and virtual environments [20]. They found differences between both navigation aids (paper map and smartphone) in both conditions regarding stopping time and task load, among others. No new route was selected in both studies, as the virtual environment reflected the real world.

Wayfinding studies replicated or conducted in a different geographic area are usually based on questionnaires rather than actual wayfinding studies (see e.g., [12, 15]). To the best of our knowledge, there is no work replicating an actual pedestrian wayfinding task in a different geographic area. One reason for this might be the difficulty of selecting appropriate routes. Our work contributes to the realization of replication studies in the wayfinding domain, which are conducted in different geographic areas by facilitating the route choice.

In many wayfinding experiments (e.g., [6, 5]) in which at least two navigation systems are compared, one of the conditions is a map-based Turn-By-Turn navigation approach (e.g., Google Maps). The replication of this widespread baseline condition is rather simple (App availability) but still time-consuming. Given that many empirical results are available for this and other approaches, there might be a possibility to avoid the replication of baseline approaches in every experiment. This would allow comparing novel systems against existing ones by reproducing the experimental setup but having to collect the results for the novel approach only.

3. Experimental Setup

In this section, the agent-based simulation study with its two navigation systems, Turn-by-Turn (TBT) and Free Choice Navigation (FCN), is described in detail. We will elaborate on both experimental areas and all potential routes with pre-defined features. As in our previous work [13], the study follows a between-subject design with 6000 agents. The choice between a between-subject or within-subject design is of less importance, as long as both groups do not differ significantly regarding their environmental spatial abilities (see Section 4), which mainly influence the performance (see Section 3.2).

3.1 Experimental Areas

As the original experimental area (source city), the city center (surface area 2.5 km^2) of Vienna is chosen (see Figure 1). According to the classification by Thompson et al. [22], the network layout is of type high transit. The city for which suitable routes for a replication study need to be found is Djibouti City in Africa (see Figure 2), which is of network type irregular [22]. The selected experiment area is of similar size (surface area 2.27 km^2) and lies in the western Part of Djibouti City (see Figure 2). The size of the experimental areas is of less importance, as long as there are routes of the desired length (see Section 3.3). Bigger experimental areas mean more potential routes and result in longer computation times.

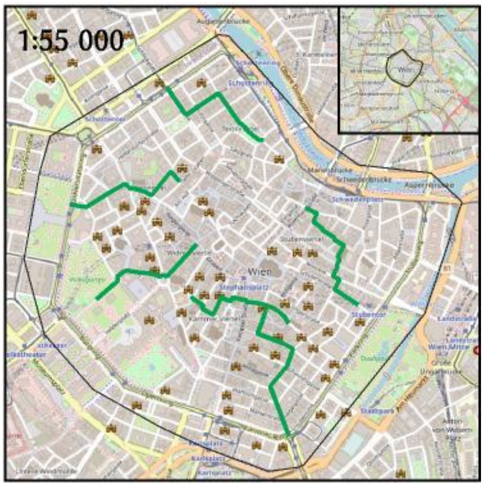

Figure 1: The experimental area in Vienna with six sample routes. Basemap © OpenStreetMap.

Figure 2: The experimental area in Djibouti City with six sample routes. Basemap © OpenStreetMap.

For both experimental areas, the raw network data were downloaded from OpenStreetMap (OSM)[1]. The intersections and their characteristics were calculated using the Intersections Framework [4], whereas street segments between two intersections were extracted with a custom script. For both areas, a networkx graph was created, which was used for the simulation.

3.2 Navigation Systems

Following our previous work [13], we compare the same two navigation approaches, namely

[1] https://www.openstreetmap.org, last access March 25th, 2022

Free Choice Navigation (FCN) and Turn-by-Turn (TBT). The primary reason to use a navigation assistance system is the desire to reach a defined destination. Therefore, the arrival rate is chosen as the success metric. An agent successfully reaches its destination if the walked distance does not exceed 150% of the shortest path length [13].

3.2.1 Turn-by-Turn (TBT)

In this condition, the agent will be guided along the shortest path between origin and destination and receives only at turning points navigation instructions. It is a popular approach that is often used as baseline in navigation experiments (e.g., [8, 21]). Whenever agents have to go straight ahead (continuation within a 20° cone concerning the current walking direction) at a junction, then no instruction is issued, and the agent will not turn. Every agent has a fixed probability to interpret generic navigation instructions correctly, which ranges between 0.8 and 1. We expect such a high probability [13] because navigation instructions are followed every day by millions of users. The agent interprets a turning instruction using a weighted random choice: The branch indicated in the instruction obtains a weight equal to the agent's probability to interpret generic navigation instructions correctly. The remaining probability is distributed equally over all remaining branches, excluding the one indicated in the instruction and the most recently taken branch. Once the agent reaches the destination, the trial ends.

3.2.2 Free Choice Navigation (FCN)

Free Choice Navigation is a navigation paradigm aiming for more freedom of choice during navigation, trying to balance the number of free choices, given instructions and a maximum allowed route length [13]. The following example shows the working mechanism: Anna, a good wayfinder, navigates to an art gallery. Before the navigation starts, Anna receives information about the beeline direction and distance to the art gallery. The system does not issue any instructions at the first two junctions because the beeline direction should still be clear to the user after such a short period. In this situation, Anna decides on her own which branch to take. The third junction, however, is rather complex and has six branches. Anna is quite sure about the beeline direction towards the art gallery, but two branches seem to be good choices to her. Based on internal computations which take her spatial abilities and the environmental structure into account, the navigation system becomes aware of this difficulty (see our previous work [13]). Consequently, Anna receives an instruction because one of the branches results in a considerable deviation from the acceptable route length. The instruction is interpreted correctly and Anna continues her way to the art gallery.

This example illustrates which components influence the internal computations of the navigation system: the user's environmental spatial abilities, the features of the current junction and the already traversed route. If an instruction is issued, a similar procedure as above applies, with the difference that the last taken branch is not excluded but has a lower probability of being taken. Another difference is that the agent's probability to interpret the generic navigation instruction correctly (as well between 0.8 and 1) depends linearly on its environmental spatial abilities. For more details, please refer to the original paper [13].

3.3 Route Selection

In this section, an average-based route in the source city and the most/least similar routes in the target city are selected. Our previously proposed route selection framework was used for these tasks [14].

As pre-emptive criteria [14], we set the route length between 550 m and 1000 m (see e.g., [18, 19]) and the number of decision points on a route to 12 (according to OSM) to avoid trivial route length. Only shortest paths were considered suitable for our experimental design. Given that the two navigation approaches depend on the geometry of the route and the network (see Section 3.2), geometry-based routes features were selected [14]: average number of branches, number of n-way intersections (e.g., 3-way intersections), regularity of decision points [4], number of right, left and non-turns and length-related features (average, median and standard deviation of segment lengths and total route length). All features were equally weighted. To find all possible routes meeting the set criteria, we followed the original paper

[14] and used SageMath 9.1 with its SubgraphSearch function[2]. In Vienna, 11737 shortest paths meeting the above-mentioned criteria were found and 9064 in the experimental area in Djibouti City.

3.3.1 Vienna

For every route in Vienna, the weighted Euclidean distance (called score) to the hypothetical route, which shows closest to average values for all criteria, was calculated [14]. Four routes yielded a minimal score of 0.12 (0 would indicate a perfect match). Actually, there are only two distinct routes, since every route is present twice. Two distinct routes traversed from start to destination and vice versa result in four routes. All four routes are very similar, and they differ regarding the direction and a turn while entering a square (see Figure 3). Due to these similarities, no route could be defined as better than the others, and consequently, all four routes are considered suitable.

For each of these routes, the five most and five least similar routes in Djibouti City were found using the framework. Five routes were chosen due to two reasons. First, arrival rates for five routes are more representative than considering one route only. Second, five seems a reasonable number in the route selection process because higher-ranked routes may not always be suitable for the experiment due to uncaptured characteristics in the route features (e.g., data not available). In this case, lower-ranked routes need to be considered too. The route selection framework is an assistance system, and local knowledge will always help to make the final decision, potentially excluding higher-ranked routes. This expert knowledge does not impede reproducibility, if the decision is well documented.

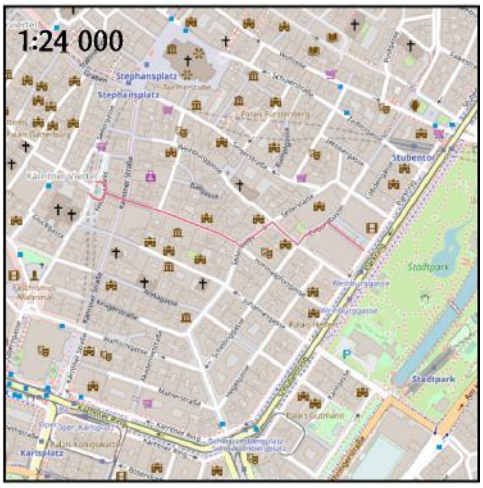

Figure 3: Routes in Vienna. The four routes differ in direction and a turn while entering a square. Basemap © OpenStreetMap.

3.3.2 Djibouti City

While searching for the most and least similar routes in Djibouti City, two further features were added to increase the similarity to the source routes. Both features concentrate on the order of one of the above-mentioned features (see Section 3.3). The sequence of right, left and non-turns (e.g., ’rnrlrnl’) and the sequence of the cardinality of decision points (e.g., ’3334343’) along the route were considered, as they potentially influence the simulation results (e.g., more branches lead to more difficult decisions).

In Vienna, the Euclidean distance was calculated between every route and a hypothetical average route (hence the term average-based). In Djibouti City, the latter is substituted by the routes found in Vienna, respectively (see Section 3.3.1). As the two newly added features are strings, the Levenshtein distance was used to calculate the difference.

[2] https://doc.sagemath.org/html/en/reference/graphs/sage/graphs/generic_graph_pyx.html, last access March 4th, 2022

For each of the four considered routes coming from the source city, the five most and least similar routes in the experimental area in Djibouti City were calculated. The Euclidean distances for the most (M=0.903, SD=0.096, MIN=0.683, MAX=1.022) and least (M=3.334, SD=0.417, MIN=2.49, MAX=3.641) similar routes differ considerably.

4. Simulation Results

For each route, the whole simulation was run 100 times in order to counterbalance the influence of the weighted random choice function (see Section 3.2). Each route was walked by two (TBT and FCN) groups of 3000 agents. The presented numbers are the means of the corresponding route(s) for all 100 runs (different seeds). To ensure that the common ability of agents to interpret navigation instructions correctly did not influence the results, a Wilcoxon Signed-Rank Test on these abilities of the agents was performed. No significant (α = .05) differences between both conditions were found n = 3000 (Z = .00, p = .99, r = .00). The general influence of the these abilities on the Free Choice Navigation approach was discussed in our previous paper [13]. For each city, the parametrization (FCN) with the best balance between arrival rate and freedom of choice was used [13].

Vienna			Djibouti City			
			Most Similar Routes		Least Similar Routes	
Route	TBT	FCN	Mean TBT	Mean FCN	Mean TBT	Mean FCN
0	0.962	0.954	0.923	0.857	0.854	0.916
1	0.966	0.96	0.953	0.905	0.846	0.909
2	0.967	0.932	0.962	0.906	0.856	0.914
3	0.951	0.953	0.956	0.909	0.854	0.916

Table 1: Arrival rates for four equivalent (Euclidean distance score) routes in Vienna and their five most/least similar counterparts in Djibouti City. TBT - Turn-By-Turn, FCN - Free Choice Navigation, Mean - mean for 5 routes. The figures are rounded to three decimals.

4.1 Vienna

In the European city, both navigation systems reached a high arrival rate of around 0.95 (see Table 1). On three routes (0-2), TBT led more agents to the respective destination than FCN. On one route (3), FCN performed better than TBT. In general, the achieved arrival rates in Vienna are very similar for both navigation systems.

4.2 Djibouti City - Turn-By-Turn

For agents using the TBT navigation system, the most similar routes in Djibouti showed an arrival rate of around .95, which is close to the arrival rate in Vienna (see Table 1). The first route (0), however, is an exception, having a lower arrival rate of .923. The least similar routes in Djibouti showed an arrival rate of around .85, representing a considerable difference to both the most similar routes and the routes from the source city. For every route from the source city, the most similar routes in the target city yielded more similar results than the least similar routes.

4.3 Djibouti City - Free Choice Navigation

For agents using the FCN navigation system, the most similar routes in Djibouti showed an arrival rate of around .9, which is different from the arrival rate in Vienna (around 0.95, see Table 1). The first route (0), again, is an exception having a lower arrival rate of .857. The least similar routes showed an arrival rate of around 0.91, similar to the most similar routes. Moreover, the least similar routes in Djibouti yielded higher arrival rates than the most similar routes.

4.4 Djibouti City - TBT versus FCN

Comparing both navigation systems on the five most similar routes in Djibouti City shows that more agents reached their destination with TBT than with FCN. The opposite is observed while considering the least similar routes. In this case, FCN is superior to TBT regarding the arrival rate (see Table 1).

5. Discussion and Limitations

This section will discuss the results by comparing the arrival rates between and within cities, navigation approaches and the most and least similar routes. Furthermore, we discuss the limitations of our work.

The four selected routes in Vienna yielded similar arrival rates for both navigation systems (see Table 1). Only one route (2) led to a bigger difference of around 3%. This is not in line with the original work [13] in which TBT had, on average, a 5% higher arrival rate (100% vs. 95%). This indicates that route selection is crucial in experimental design because it can change the drawn conclusions and the outcome of a wayfinding study. For the TBT condition in Djibouti City, the route selection framework helped to find routes that yield, on average, a similar arrival rate as the corresponding source route. The least similar routes yielded considerably worse results (around 85%) compared to both the source routes in Vienna and the most similar routes in Djibouti City. This indicates the suitability of the route selection framework with the selected route features, as the lower-ranked routes yielded less similar results than higher-ranked routes. As Vienna and Djibouti City represent quite different layout types [22], we expect the framework to work as well in other geographic areas.

The FCN condition in Djibouti City shows a different picture, in which both the most similar and the least similar routes yielded high arrival rates but not as high as the source routes (see Table 1). Moreover, the least similar routes yielded better results in terms of arrival rate than the most similar routes. This can be explained by the interplay between the chosen route features and the navigation approach. One of the ideas of Free Choice Navigation is to give more freedom to the wayfinder. This increases the chances of not taking the shortest path, which is supposed to be taken in the TBT approach. The simulation data support this hypothesis (see Table 2).

Vienna			Djibouti City			
			Most Similar Routes		Least Similar Routes	
Route	TBT	FCN	Mean TBT	Mean FCN	Mean TBT	Mean FCN
0	107	597	79	344	52	282
1	105	601	85	658	58	242
2	121	380	89	375	57	190
3	139	398	67	329	52	282

Table 2: Number of uniquely walked routes taken by successful agents for four equivalent (regarding the Euclidean distance score) routes in Vienna and their five most/least similar counterparts in Djibouti City. TBT - Turn-By-Turn, FCN - Free Choice Navigation, Mean - mean for 5 routes. The figures are rounded to integers.

In the FCN condition, more unique routes are taken by successful agents in both Vienna and Djibouti City. With an increasing number of unique routes, the neighborhood around the route plays a more vital role. A route might be easy to navigate, but once a navigation error occurs, the wayfinder might find itself in a difficult to navigate area due to complex junctions, dead-ends or detours [1]. The selected properties (see Section 3.3), however, regard route properties only, without considering the neighborhood of the route itself. The route selection framework could be improved by including additional features, which capture the previously used characteristics but adapted for the neighborhood. Completely new features like centrality measures (graph theory) calculated for the route neighborhood could also help to improve the process of finding similar routes. This could be as well a first step to tackle the problem of conducting the baseline condition over and over again in wayfinding experiments (see Section 2.2). Previously collected empirical data could be used as a proxy if the neighborhoods and routes are highly similar.

However, the definition of such a neighborhood is not a trivial task and depends on the navigation system. Some routes are more likely to be taken with a given navigation system. We suggest incorporating features describing this neighborhood while considering the navigation system to define its spatial extent. One possibility to define the spatial extent of the route's neighborhood is the Potential Route Area (PRA) [8]. However, the PRA is based on shortest paths only, which are not necessarily taken.

The selected metric is important too. Regarding the number of unique routes (see Table 2), the results are as expected, more similar routes yielded more similar results than less similar routes. Regarding the arrival rate, the results are partially in line with our expectations (see Table 1). Therefore, the selected route features should consider the navigation system and the success metric.

The achieved arrival rates in Djibouti City are not entirely in line with the previously conducted simulation study [13]. Our study used 40 (Djibouti City) routes instead of the whole route population as in the original paper. A wayfinding study is usually conducted with a small-sized subsample of routes. The differences within the cities (see Table 1) and between our study and the original work [13] suggest that the selected route can impact study results (see Section 6).

5.1 Limitations

We could have added more complexity to the simulation with respect to the original study, but we wanted to keep our results comparable. In order to find similar routes, other similarity metrics could have been used. Toohey and Duckham [23] compare four different trajectory similarity measures, but all of them rely purely on route geometry. Han and colleagues used deep learning to calculate route similarity [7]. The authors, however, define the similarity based on node-wise distance over the underlying spatial network, although their architecture incorporates information about direct neighbors for a node, whose importance can be set by a parameter. In contrast to the selected route selection framework [14], however, the resulting similarity is not readily explainable.

6. Conclusion and Future Work

In our work, we wanted to verify if the proposed route selection framework can find similar routes in different geographic areas and, thus, make it suitable for replication studies. Our results reveal the suitability for the widespread Turn-By-Turn navigation approach and suggest the incorporation of further neighborhood features into the framework in order to work with navigation approaches that cover more potential routes between start and destination like Free Choice Navigation. This work is a first step towards the replication of wayfinding studies in different geographic areas.

For future work, there are several strands to follow. Further success metrics needs to be tested with our approach to see whether the results are applicable beyond the arrival rate and the number of uniquely walked routes. The definition of the neighborhood for a route is an open problem. We believe that it should depend on the tested navigation system. Furthermore, features describing this neighborhood are to be defined and verified. Our results suggested the importance of route selection on study results. We will scrutinize this hypothesis with a further simulation study in which we will run a wayfinding experiment on all suitable potential routes within the experimental area and compare the results. A further research direction is the prediction of the arrival rate or any relevant success metric based on the route and neighborhood features without running the simulation. One possibility would be the usage of deep learning.

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