Virtual Navigation for Blind People: Transferring Route Knowledge to the Real-World

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Abstract

Independent navigation is challenging for blind people, particularly in unfamiliar environments. Navigation assistive technologies try to provide additional support by guiding users or increasing their knowledge of the surroundings, but accurate solutions are still not widely available. Based on this limitation and on the fact that spatial knowledge can also be acquired indirectly (prior to navigation), we developed an interactive virtual navigation app where users can learn unfamiliar routes before physically visiting the environment. Our main research goals are to understand the acquisition of route knowledge through smartphone-based virtual navigation and how it evolves over time; its ability to support independent, unassisted real-world navigation of short routes; and its ability to improve user performance when using an accurate in-situ navigation tool (NavCog). With these goals in mind, we conducted a user study where 14 blind participants virtually learned routes at home for three consecutive days and then physically navigated them, both unassisted and with NavCog. In virtual navigation, we analyzed the evolution of route knowledge and we found that participants were able to quickly learn shorter routes and gradually increase their knowledge in both short and long routes. In the real-world, we found that users were able to take advantage of this knowledge, acquired completely through virtual navigation, to complete unassisted navigation tasks. When using NavCog, users tend to rely on the navigation system and less on their prior knowledge and therefore virtual navigation did not significantly improve users' performance.

Keywords: virtual environment, indoor navigation, route knowledge, accessibility, assistive technologies, orientation and mobility, travel aids

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1. Introduction

Independent navigation while visiting unfamiliar (or complex) places is a major challenge for people with visual impairments (PVI) often due to a lack of confidence and knowledge about the environment (Giudice and Legge, 2008; Williams et al., 2013). Navigation assistive technologies try to increase users' independence by providing guidance to a destination (Fallah et al., 2013; Katz et al., 2012; Loomis et al., 1998; Petrie et al., 1996), alerting users to surrounding Points-Of-Interest (POIs) (BlindSquare, 2018; Blum et al., 2011; Kacorri et al., 2016), or both (Ahmetovic et al., 2016; Sato et al., 2017). Although useful to support navigation of PVI, these systems still have several limitations and challenges. For instance, mainstream *GPS*-based solutions are still inaccurate and indoor solutions are unavailable in most environments (due to technical challenges or special infrastructure needs).

One possible solution to overcome the challenges of *in-situ* navigation assistance is to acquire spatial and route knowledge indirectly, prior to navigation (Brock, 2013; Montello, 2001). Previous research has shown the ability of both tactile (and interactive) maps (Brock, 2013; Ducasse et al., 2018; Papadopoulos et al., 2017b; Zeng et al., 2014) and virtual navigation (Chebat et al., 2017; Lahav and Mioduser, 2008) to convey spatial knowledge of the environment to PVI. However, interactive maps usually require larger devices and/or tactile overlays (Ducasse et al., 2018; Guerreiro et al., 2015; Kane et al., 2011) and most virtual navigation solutions require specialized equipment (Kreimeier and Götzelmann, 2019; Yatani et al., 2012; Zhao et al., 2018).

In order to explore virtual navigation using off-the-shelf devices, we had previously developed a virtual navigation smartphone app that enables route simulation as a sequence of turn-by-turn instructions and relevant landmarks and POIs (Guerreiro et al., 2017). This app provides two interactive navigation methods that enable users to navigate pre-defined routes either by moving through the important elements of the route (VirtualLeap) or by mimicking real-world navigation through step-by-step walking (VirtualWalk). In that work, we performed a study using route reconstruction (with LEGO blocks) to evaluate blind users' acquisition of route knowledge using smartphone-based virtual navigation, which showed users' ability to build accurate sequential representations of the route (Guerreiro et al., 2017). While such kind of evaluation is common in the literature (Kitchin and Jacobson, 1997; Miao et al., 2017; Yatani et al., 2012), it does not show how route knowledge evolves over time, and most importantly, whether it actually empowers independent real-world navigation of an unfamiliar environment.

Based on this observation, we iterated on the development of our virtual navigation app and conducted a user study with 14 blind participants aimed at understanding: 1) the **acquisition of route knowledge** through smartphone-based virtual navigation and **how it evolves over time**; 2) the ability of virtual navigation to support **independent, unassisted real-world navigation** of short routes; 3) its ability to **improve user performance when using an accurate *in-situ* navigation tool** – NavCog (Sato et al., 2017) – for long routes, seeking to assess if the knowledge acquired virtually is leveraged when also receiving *in-situ* assistance. To analyze these questions, participants virtually learned two routes of different complexity for three consecutive days and were asked to describe them at

Figure 1: After learning routes at home with our virtual navigation app, participants leveraged the knowledge acquired about the required turns, landmarks and Points-of-Interest (POIs) to perform real-world navigation tasks. This example shows one participant navigating a 60-meter route *unassisted*: He walks through the first segment (a), and turns at the floor change to tile (b). He continues walking knowing that he should pass by a couch (c), and makes a right turn at the correct location (d).

the end of each day. Afterwards, they visited the Carnegie Mellon University (CMU) and were asked to physically navigate four different routes (the two routes learned virtually, plus two unfamiliar routes).

We found that participants were able to grasp most information of shorter routes on their first day. Overall, their knowledge increased over time for both short and long routes, reaching a comprehensive understanding of the route structure and its landmarks and POIs.

As research in virtual route knowledge acquisition often involves query-based or route-reconstruction evaluations, we emphasize the impact on real-world navigation in dense indoor routes. Our analysis suggests that smartphone-based virtual navigation can support blind people in independent, unassisted navigation of short routes (Figure 1). We also test its impact on real-world navigation with NavCog, since the prior knowledge acquired virtually can potentially complement *in-situ* assistance. We demonstrate that when traveling long routes in an assisted manner, the user tends to rely on NavCog, and therefore prior virtual navigation did not increase the performance of real-world navigation with *NavCog*. Still, in the event of a system failure, two users were able to leverage their prior knowledge to continue on their path or quickly recover from errors.

2. Related Work

In this section, we describe prior research supporting blind people's Orientation and Mobility (O&M), which can either assist the user while physically navigating the environment or convey spatial knowledge prior to navigation.

2.1. In-Situ Navigation Assistance

PVI use primary travel aids, such as a guide dog or a white cane to help them navigate an environment (Giudice, 2018; Wiener et al., 2010). Although training and further experience can improve their O&M expertise, PVI often have a fragmented knowledge of the environment and avoid visiting unfamiliar places by themselves (Giudice and Legge, 2008; Williams et al., 2013).

Navigation assistive technologies try to guide the user to a destination or to convey information about the surroundings. In outdoor environments, several applications specifically designed for PVI try to complement the user's knowledge by alerting about nearby POIs such as shops or restaurants (BlindSquare, 2018; Blum et al., 2011; Kacorri et al., 2018a; APH, 2018; Yang et al., 2011). However, the information conveyed can be overwhelming if not restricted by the system (Panëels et al., 2013). These approaches usually provide the radial orientation and euclidean distance to the POIs, without considering the environment structure nor route information. On the other hand, mainstream solutions such as Google Maps, or other specialized solutions for blind navigation such as *TrekkerBreeze* (HumanWare, 2019), focus on reaching a destination using turn-by-turn instructions. However, outdoor solutions often rely on GPS to localize the user, which still present relatively low localization accuracy for blind navigation with an average of approximately 4.9 meters (van Diggelen and Enge, 2015). Some research efforts try to complement these limitations by detecting elements that are relevant for navigation, such as crosswalks using computer vision (Mascetti et al., 2016; Shangguan et al., 2014), bus stop landmarks using crowdsourcing (Hara et al., 2015), or by providing assistance for public transit passengers (Flores and Manduchi, 2018b).

There have been increasing research and commercial efforts to provide indoor localization and navigation assistance for PVI (Dias et al., 2015; Fallah et al., 2013; Riehle et al., 2013; BlindSquare, 2018; Sato et al., 2017). These efforts include approaches where users do not require any hardware besides their own devices (*e.g,* their smartphone). For instance, *Navatar* (Fallah et al., 2012) uses the smartphone sensors (accelerometer and gyroscope) to understand the user's movement, combined with user input near relevant landmarks to confirm the user's location. Similarly, *Safe Return* (Flores and Manduchi, 2018a) uses these sensors to understand the user's route and support backtracking. Alternatively, camera-based approaches can use the user's (or specialized) devices to guide the user to a particular target or avoid veering (de Jesus Oliveira et al., 2018; Fiannaca et al., 2014; Manduchi and Coughlan, 2014), or to detect and avoid obstacles (Aladren et al., 2016; Filipe et al., 2012; Li et al., 2016; Peng et al., 2010; Tian et al., 2013; Zeng et al., 2017). Other approaches use sensor installations in the environment, such as Wi-Fi (Cheng et al., 2005), BLE beacons (Luca and Alberto, 2016; Sato et al., 2017), or a combination of sensors (Ishihara et al., 2017) to provide accurate localization. BLE beacon-based localization, in particular, is now a popular approach for indoor navigation assistance and has been implemented in environments such as universities (Ahmetovic et al., 2016), shopping malls (Sato et al., 2017), airports (Guerreiro et al., 2019; Iozzio, 2014; Kunkle, 2017), train/metro stations (Wired, 2014; Ganz et al., 2018; Kim et al., 2016), among others. For instance, NavCog (Sato et al., 2017) besides providing turn-by-turn instructions, also alerts about relevant landmarks (e.g. floor changes or obstacles) and POIs (e.g. shops or restaurants) within close proximity, showing an average localization error below 1.65 meters (Ahmetovic et al., 2017; Murata et al., 2018; Sato et al., 2017). Recent research in this project has also been trying to improve and adapt the interface and navigation instructions by analyzing user trajectories and user behavior (Guerreiro et al., 2018; Kacorri et al., 2018b; Ohn-Bar et al., 2018). While these systems are very useful and are likely to become gradually available in more indoor locations, currently there are only a few locations with such systems implemented.

2.2. Map Exploration and Virtual Navigation

An alternative to in-situ navigation assistance is to obtain prior knowledge of a route or environment (Brock, 2013; Denis, 2017; Montello, 2001). Frequent examples are verbal descriptions, maps or virtual simulation. Verbal descriptions can be provided by other people, but can also be found in the sequential instructions of apps like *Google Maps*. Tactile maps and 3-D models enable blind people to explore a map/model with their fingers and are known to provide accurate spatial representations of an environment (Herman et al., 1983; Wiener et al., 2010). Recent research has been trying to ease the access to such solutions, for instance by creating customizable 3D printed maps or tactile displays (Giraud et al., 2017; Leo et al., 2016; Taylor et al., 2016), or to make use of touchscreen devices to enable interactive map exploration (Guerreiro et al., 2015; Kane et al., 2011; Su et al., 2010), often using screen overlays (Brock et al., 2015; Ducasse et al., 2018) or special devices (Zeng et al., 2014). However, most solutions still have low resolution that difficult presenting detailed information or require larger or very specific devices.

A solution to overcome the low resolution of maps, is to enable virtual navigation of an environment. Several solutions have been trying to immerse the user in the environment in an attempt to better support mobility training (Lahav et al., 2015; Moldoveanu et al., 2017; Seki and Sato, 2010) and/or spatial learning. Previous research integrates audio and haptic feedback to the elements in the virtual environment (De Felice et al., 2011; Kunz et al., 2018; Lahav and Mioduser, 2008; Lahav et al., 2018; Lécuyer et al., 2003; Sánchez and Tadres, 2010). Picinali et al. (2014) use 3D audio to simulate the acoustical conditions of the real-world. Other approaches (Evett et al., 2008; Maidenbaum et al., 2013) tried to increase the accessibility of virtual environments by using a virtual cane to estimate distances. In addition to a virtual cane, Kreimeier and Götzelmann (2019) use a VR treadmill for locomotion while walking-in-place. *Canetroller* (Zhao et al., 2018) uses an actual cane equipped with sensors and actuators to control and simulate white cane interactions in the virtual environment, simulating physical resistance, vibrotactile feedback from contact with objects or surfaces, and providing 3D auditory feedback. Cobo et al. (2017) study a distance-exploration approach where the user controls the avatar's direction, without actually moving in the virtual space. Connors et al. (2014) used the context of a video-game to transfer navigation skills to be used in the real-world. All these approaches are useful to convey spatial knowledge, yet they usually require additional equipment and/or the creation of specialized environments.

Recent research and applications are trying to provide blind users with virtual access to real-world locations, by leveraging the prevalence of smartphones and existing geo-location services. For instance, Blindsquare BlindSquare (2018) simulation mode provides information about nearby POIs given a particular location, but does not support navigation. SpaceSense (Yatani et al., 2012) enables the user to move through route intersections with turn-by-turn instructions, but requires a vibrotactile matrix addon to convey the location of POIs. In our prior work (Guerreiro et al., 2017), we made use of the smartphone alone to simulate navigation, integrating turn-by-turn instructions and the route POIs and landmarks. Our app enabled PVI to acquire route knowledge, evaluated using route reconstruction methods. Though useful, these methods are limited in understanding whether the knowledge acquired virtually can be transferred to the real-world (Kitchin and Jacobson, 1997; Papadopoulos et al., 2017a). Overall, there is a lack of understanding on how smartphone-based virtual navigation can provide route knowledge, how it evolves over time, and if it can be leveraged in the real-world.

3. Smartphone-Based Virtual Navigation

In our prior work (Guerreiro et al., 2017), we described a virtual navigation app that allowed PVI to learn unfamiliar routes as a sequence of turn-by-turn instructions and route landmarks or POIs. In this article, we present a new version of the navigation app that was re-designed and developed based on the findings of our first user study. Moreover, we hypothesize that the knowledge acquired virtually about the structure and characteristics of a route, can be valuable to support unassisted navigation, but also to increase users' confidence and performance when combined with *in-situ* navigation tools.

Our virtual navigation app is built on top of *NavCog* (Sato et al., 2017), an open-source[1] iOS navigation app for blind people. In order to maintain consistency between the virtual and real-world navigation experiences, we use the same data structure as *NavCog*, which consists of a graph-based geographical route representation and of manually annotated POIs and landmarks.

3.1. Background on NavCog

We use *NavCog* because it provides turn-by-turn navigation instructions with high, practical localization accuracy (Ahmetovic et al., 2017; Sato et al., 2017), which results in very few navigation errors. The instructions are based on previous research (Banovic et al., 2013; Nicolau et al., 2009; Pérez et al., 2017; Wayfindr, 2017) on how to better support blind people's navigation and knowledge of the environment – e.g. landmarks, obstacles and POIs. We collected POI information based on a taxonomy analysis for indoor navigation (Pérez et al., 2017) and edited the map accordingly.

At the start of each route segment, *NavCog* (Ahmetovic et al., 2016; Sato et al., 2017) reads the next instruction – *e.g.*, "*proceed 70 feet and turn left*". While in that segment, the system provides periodic information about the distance to the turn location, and an "*approaching*" message right before the turn. At the turning point, *NavCog* provides a verbal instruction – e.g "*turn right*" – and a short vibration and sound effect. Another vibration and sound effect are provided when the user completes the turn (reaching the correct orientation), together with the next instruction. The system also announces landmarks and POIs when users are within close proximity – *e.g.*, "*a restroom is on your right*" –, so that they can walk confidently and acquire knowledge of the environment. We used landmarks as features that provide physical or tactile cues to help users confirm their location and navigate more effectively, such as doors, floor changes and obstacles. POIs, such as classrooms and facilities are places that may interest users during navigation.

[1]HULOP: http://github.com/hulop

Gesture		Command
1 finger	swipe up	Go to the next turn/POI
	swipe down	Go to the previous turn/POI
3 fingers	swipe up	Go to the next turn
	swipe down	Go to the previous turn
	tap	Read current status
2 fingers	swipe up	Start virtual walk/speed up
	swipe down	Speed down
	tap	Stop reading
1-3 finger(s)	swipe left	Turn left
	swipe right	Turn right
Gyro sensor	rotate left	Turn left
	rotate right	Turn right
4 fingers	tap on lower	Go to the beginning
	tap on upper	Go to the end

Table 1: List of gesture commands for virtual navigation

3.2. Virtual Navigation Interface

The virtual navigation app provides the same instructions as *NavCog*, but includes additional commands to simulate the navigation in the virtual environment. Our interface relies on two navigation modalities (described below) adapted from the first version of the app (Guerreiro et al., 2017), which were equally able to provide users with sequential representations of the real-world. Our adaptations intend both to make use of standard gestures in iOS VoiceOver – to make the interaction more consistent – and to extend the functionality of the navigation methods, which can both be used at all times. The list of available commands is presented in Table 1. Updating the users' location can be achieved with up and down swipes, while orientation changes rely on left/right swipes or phone rotation using its gyroscope.

3.2.1. Virtual Leap

This mode allows users to jump through the relevant route elements, such as turning points, POIs, landmarks, and floor transitions. When the user swipes up, it reads the distance from the current to the next route element – *e.g.,* "*walked 30 feet*" – and the current instruction based on the user's location – *e.g.,* "*turn right*" or "*a restroom is on your right*". A one-finger swipe up moves the user to the next relevant element, while a three-finger swipe up moves the user immediately to the next turn, ignoring landmarks and POIs. This gesture aims to support a common strategy that is learning the route structure first, before learning the POIs and landmarks (Guerreiro et al., 2017). Swipe-down gestures move users to the previous relevant element. The behaviour described so far is the same as the Virtual Leap modality first developed in our prior study (Guerreiro et al., 2017) and allows users to quickly move through the relevant route elements sequentially. However, in the prior version turns were performed automatically by the system after moving the user to a turning point. In contrast, we now require a deliberate action – a swipe left or right – to perform the turn. While this introduces an additional step that may slightly increase the virtual navigation time, this step intends to help users learning and better recalling the route (in particular the turning points). In *VoiceOver* swipe left/right is assigned to move the current focus to the next/previous item, but we assumed that in this context it is more intuitive for turning.

3.2.2. Virtual Walk

This mode allows users to move their virtual location step by step, mimicking walking on the route at a certain speed while experiencing the same instructions as *NavCog*. The user initiates the virtual walk with a two-finger swipe up and can adjust the speed – previously reported useful in (Guerreiro et al., 2017) – with a two-finger swipe up or down. This contrasts with the original method, which used tilting the phone as the walking controller. This aimed at a more consistent interface, but also to enable automatic walking without requiring users to keep their hand with a specific inclination. In VoiceOver, two-finger swipe up/down is assigned for reading all content, one by one, and therefore can be a natural mapping to this gesture. This method generates foot step sounds to indicate the walking speed, in order to increase the presence in the virtual environment (Nordahl et al., 2012). When arriving to a turning point, users stop and receive a short vibration and sound effect. They are then required to turn by rotating the phone – captured by the gyroscope. This intends to leverage the reduced cognitive processing of actual turning to update the user's mental model (Klatzky et al., 1998). After completing the turn, the system automatically resumes the virtual walk.

3.2.3. Miscellaneous Commands

Left or right turns can be done with 1-3 finger(s) in order to reduce the errors, as users may be performing up-down gestures also with 1-3 finger(s). Other commands are assigned to gestures for similar concepts of *VoiceOver* commands. For example, a two-finger tap stops screen reading and a three-finger tap provides information about the user's current location – the current focus in *VoiceOver*. A four-finger tap on the lower part of the screen moves users to the beginning of the navigation route, while on the upper screen it moves them to the destination.

4. User Study

We conducted a user study approved by our Institutional Review Board. Our main goal was to explore the use of smartphone-based virtual navigation to learn a route before visiting it in the real world. In particular, we aim to analyze: 1) the acquisition of route knowledge and how it evolves over time; 2) its ability to support independent, unassisted real-world navigation of short routes; 3) its ability to further improve users' performance when traveling long routes assisted by NavCog.

User	Age	Navigation Aid	Visual Acuity	Time Learning Short Route (s)	Time Learning Long Route (s)
P1	69	cane	totally blind	970	3600
P2	64	cane	totally blind	1514	3517
P3	41	guide dog	light perception	1106	3464
P4	43	guide dog	totally blind	2794	3600
P5	62	guide dog	light perception	1140	3472
P6	69	cane	light perception	1016	2339
P7	47	cane	totally blind	2211	2915
P8	69	cane	totally blind	1481	1528
P9	45	guide dog	totally blind	1843	3563
P10	69	cane	light perception	1152	2822
P11	43	cane	totally blind	880	2520
P12	41	guide dog	totally blind	1436	3402
P13	59	guide dog	totally blind	304	1162
P14	66	cane	20/400 right eye	1577	1647

Table 2: Participants' characteristics and the total time they spent using the virtual navigation app to learn both the short and long routes.

4.1. Participants

We recruited 14 blind participants (7m/7f), with ages ranging from 41 to 69 (M=56.21, SD=11.57) years old (see Table 2). Thirteen have light perception at most and one can see shapes (P14), but cannot distinguish any information on the screen. We excluded this last participant from the real-world navigation analysis. Two participants did not complete the last two routes (P13 due to fatigue, P1 due to technical problems) and therefore were excluded from the long route analysis. There were six guide-dog and eight white-cane users. All participants own a smartphone and 13 had prior experience with navigation apps. The real-world navigation took approximately two hours and participants were compensated for their time ($25 per hour).

4.2. Apparatus

Participants used their own devices for the virtual navigation phase. One participant had an iPhone 5 and we lent an iPhone 6 to an Android user (P11). All other participants owned an iPhone 6 or 7. Instructions to install the app and how to interact with it were provided via e-mail. Additional instructions on how to interact with an iPhone were provided to the Android user, who showed no difficulties interacting with it. The app logged every interaction with the app, sending the logs to our server periodically.

For the real-world navigation, we instrumented three buildings (connected through indoor bridges) in our campus with the *NavCog* environment. We deployed a total of 884 iBeacons

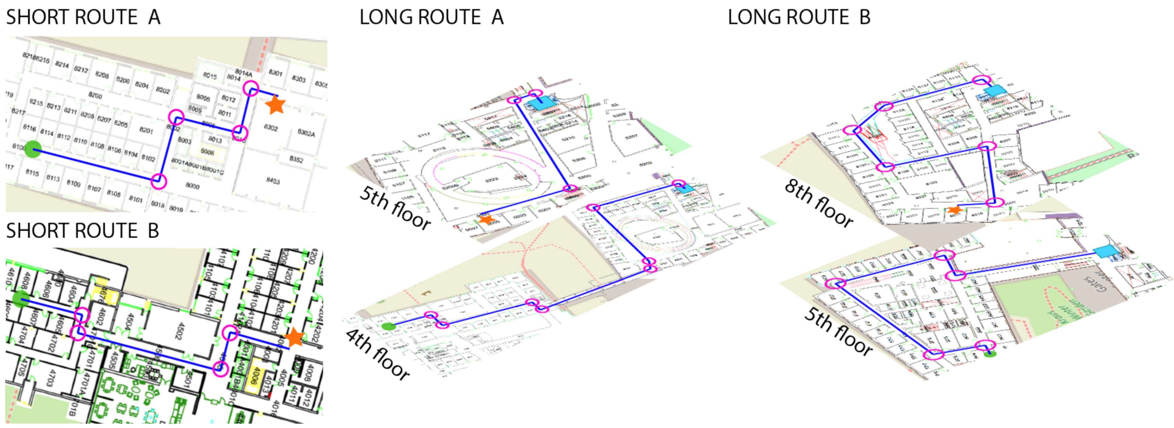

Figure 2: The four routes, two short and two long, used in the user study. The green circle, blue square and orange star represent the starting point, elevator and destination, respectively. The circumference shows the turns.

in an area of $58,800m^2$. We used an iPhone 7 with iOS 10.3.3 and the *NavCog* app logged all events during the navigation tasks. All participants used their primary navigation aid (guide-dog or white-cane) in all real-world navigation tasks. They used their free hand to hold the smartphone and used AfterShokz bone-conductive headphones to receive the audio instructions. These headphones do not block environmental sound, which is important for safe blind navigation (Abdolrahmani et al., 2016; Ye et al., 2014). Video was recorded for analysis purposes from a first- (participant) and third-person (researcher) perspective, using two action cameras (*GoPRO* Hero 4 Black). Two researchers took notes about errors and user behaviour and strategies. We also audio recorded a short semi-structured interview after the tasks.

4.3. Method

There are several methods to assess route knowledge and the cognitive map of blind people, but greater validity can be achieved when a combination of methods is used (Kitchin and Jacobson, 1997). In particular, visiting the real-world environment is very important to assess the benefits of spatial knowledge in the person's navigation (Kitchin and Jacobson, 1997; Papadopoulos et al., 2017a). In this study, we assess route knowledge with verbal descriptions – as in (Blades et al., 2002; Lahav and Mioduser, 2008) – combined with real-world navigation tasks (with and without *NavCog*) to assess how virtual navigation impacts user performance.

We used four routes divided in two groups, short and long (Figure 2). The routes within each group have very similar complexity in order to enable a fair comparison. In particular, they have the same length, number of turns and POIs/landmarks. **Short routes** include one floor, have a length of 60 meters, four turns and six POIs/landmarks (e.g. floor change, restroom, doors). **Long routes** include two floors, using the elevator, with a length of 210 meters, eleven turns, and 22 POIs/landmarks.

Participants learned two routes at home (one short, one long) - from now on referred as

familiar routes - using our virtual navigation app, for three consecutive days. Route selection was counterbalanced, meaning that different participants had access to A or B routes (Figure 2). In order to assess their route knowledge, we asked for their verbal descriptions (of both routes) at the end of each day over the phone. The phone interviews were recorded using the laptop after asking for participants' permission. The researcher later transcribed the interview and annotated the order of the items mentioned by the participants. Then, the metrics were calculated.

In the day after completing the virtual navigation phase, participants visited our campus to perform real-world navigation tasks, where they were asked to navigate the four routes (two **familiar** and two **unfamiliar**). For the short routes, participants navigated without any assistance (besides the guide dog or white cane) in the familiar route and with *NavCog* in the unfamiliar route. We set *NavCog* as an upper baseline due to its high accuracy and low number of navigation errors (Sato et al., 2017). All participants started with the short routes due to the greater difficulty to navigate a route unassisted. For the long routes, participants used *NavCog* to assist their navigation in both familiar and unfamiliar routes. This is based on the length and complexity of the route and on our goal to understand if prior knowledge acquired through the app is able to increase the navigation performance when combined with NavCog.

The study had a within-subjects design, as participants were exposed to all conditions. Within short and long routes, the task order was counterbalanced, accounting both for routes (A or B) and for condition (familiar or unfamiliar). This guarantees that no advantage is given to a particular route or condition.

4.4. Procedure

4.4.1. Day 0 - Instructions and Practice

We made our virtual navigation app available for participants to download and install. We provided (via e-mail) all instructions required to install and interact with the app and made sure that participants were aware of the tasks they would be asked to perform. They were informed that they could check the app help page or ask the researchers for clarifications at any time. During *Day 0*, participants had access to a practice route that they could freely explore in order to learn how to interact with the app and to practice the navigation commands.

4.4.2. Days 1 to 3 - Virtual Navigation

From *Day 1* to *Day 3*, participants had access to two routes (either A or B) that they could navigate (virtually) on their own. Participants had a limit of 20 minutes **per day**, for **each route**. On the one hand, we wanted participants to use the app in a real-world scenario, considering that they would be visiting an unknown location in a few days. On the other hand, we wanted to guarantee comparable times of app usage among participants in order to enable a fair comparison.

At the end of each day, one researcher called the participants to ask for a verbal description of both routes. Participants were instructed to *"learn as much as possible about the routes, including turns, distances and POIs"*. They were instructed *"not to take notes nor* *recording their interaction with the device"*. After *Day 3* participants lost access to the two routes.

4.4.3. Day 4 - Real-world Navigation

On the day after completing the virtual navigation phase, participants visited our campus. After we explained the procedure, participants completed a demographics questionnaire.

All participants started with the short routes, followed by the long routes. Before starting the first task with *NavCog*, participants were given usage instructions and performed a practice navigation task. In all tasks, participants were instructed that the goal was to *"focus on the route and reaching the destination"*. They were also instructed to try to recover from errors by themselves, both in unassisted tasks (short, familiar route) and in tasks with *NavCog*. The researchers never intervened. When using *NavCog* participants were told that the app would correct them when they deviate from the intended path. In the unassisted task, participants could ask the researchers to go back to the starting point in case they felt lost or were not sure about their location.

After each trial, participants were asked to describe the route, to rate how easy/difficult was the task to complete (Sauro and Dumas, 2009), and how confident they were during navigation, using a 7-point *Likert* scale. Participants performed two additional tasks to assess the relevance of *in-situ* instructions (Ahmetovic et al., 2019), but its analysis is out of the scope of this paper. At the end, we performed a short semi-structured interview to get more feedback about their experience with virtual navigation.

4.5. Design and Analysis

During virtual navigation, we collected participants' **time spent** per route, per day. In order to assess their route knowledge from the verbal descriptions, we adapted and extended metrics from previous research (Guerreiro et al., 2017; Passini et al., 1990; Yatani et al., 2012) – which we refer to route knowledge metrics herein:

- **FormElementsError**. It reflects the number of wrong, missing or extra turns included in the description and is analyzed using the Levenshtein distance (Levenshtein, 1966) between the correct route and the participant's description. Besides turns, we also include the elevator, a central element in the route.
- **POIsMentioned**. The total number of POIs/landmarks that were mentioned by the participant.
- **POIsCorrectLocation** The total number of POIs/landmarks that were mentioned in the correct segment of the route and on the correct side.
- **DistanceAccuracy**. Accuracy of route segment length estimations go from 0 (not mentioned) to 1 (high accuracy). Similarly to previous research (Guerreiro et al., 2017), we based our values on current smartphones approximate GPS 4.9 meters (16ft) accuracy (van Diggelen and Enge, 2015). High accuracy was defined as less than half

of this value (8ft). Medium/acceptable accuracy (0.75) was defined as less than the 4.9 meters, while low accuracy means everything above that threshold. All vague answers (e.g. "*long*", "*shorter*") were categorized as low-accuracy, except when defining very short segments (*e.g.,* 2 or 3 meters) with "immediate turn" or "few steps" (categorized as medium accuracy).

In order to evaluate users' performance during real-world navigation we rely on metrics for time and errors:

- **Time**. The navigation time, in seconds, from the start to the destination. We subtracted the time spent waiting for and while in the elevator, as it does not depend on the user. We also stopped the time when users stopped to address the researchers or in case of system failure (both were rare).
- **Missed Turns**. All turn attempts that were incorrect or were not made at the exact turning location. It accounts for all wrong, early or late turns performed by the user. *Wrong* accounts for a turn leading the user to an incorrect path; *Early* refers to deliberate attempts to turn before reaching the turning point; *Late* refers to passing a turning point and needing to go back to correct it.
- **Longer Recovery Errors**. A more conservative metric for missed turns, which intends to capture more problematic errors instead of missed turns that are quickly corrected by the user (*e.g.,* a 2-meter early-turn where the user immediately finds the opening to make the turn). Due to participants' individual walking speeds, we decided to use distance and navigation direction. Long Recovery Errors comprise all missed turns where participants either deviated too far from the turning point (more than 4.9 meters, the measure for medium accuracy) or showed hesitation about the direction of the turning location (walking forward and backward to understand the turning location).

An additional metric reflects the number of times that users needed to *Restart* the navigation from the starting point because they were lost (in the condition without *NavCog*).

We ran Shapiro-Wilkinson tests to all dependent variables to check for normality. In order to compare how knowledge evolved over time, we ran Repeated Measures ANOVA when the variables have a normal distribution (only *POIsCorrectLocation* metric in the short routes) and the Friedman test otherwise (with Wilcoxon Signed Rank test post-hocs with Bonferroni correction). In order to analyze the real-world performance, we compared the familiar and unfamiliar conditions with between-subjects comparisons for each route in separate, as we noticed a difference in difficulty between routes (despite the similar complexity in theory).

5. Results

In this section, we first present the analysis of participants' route knowledge during and after the virtual navigation phase, where we look into their descriptions of the routes

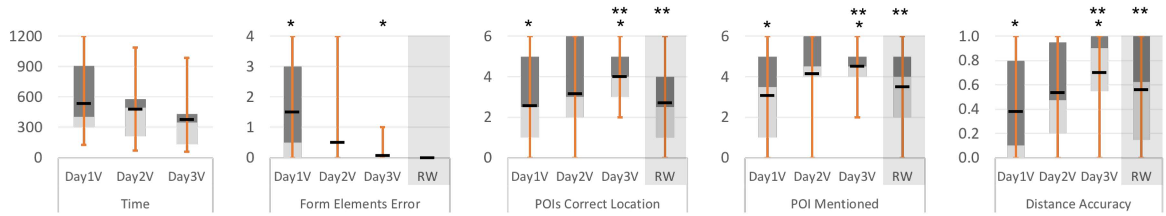

Figure 3: Box plots (showing first quartile, median, third quartile, minimum and maximum) of all metrics, per day, for the virtual navigation and verbal description of the short routes. The black marker represents the mean, and RW refers to the descriptions after real-world navigation. Asterisks represent pairs where post-hoc statistic tests showed significant differences.

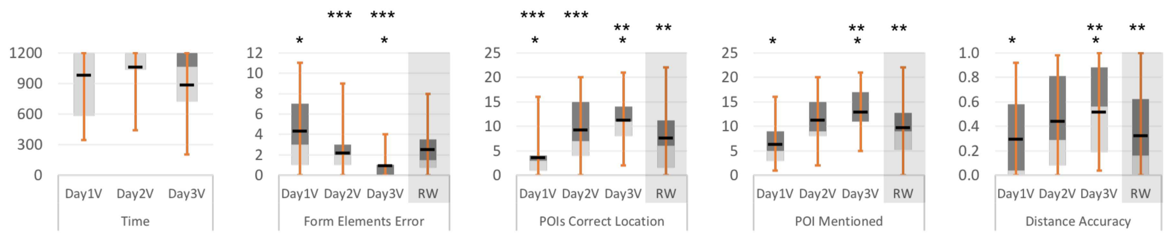

Figure 4: Box plots of all metrics, per day, for the virtual navigation and verbal description of the long routes. The black marker represents the mean, and RW refers to the descriptions after real-world navigation. Asterisks represent pairs where post-hoc statistic tests showed significant differences.

explored at home using our virtual navigation app. Then, we evaluate real-world navigation performance both in familiar and unfamiliar routes. Finally, we describe users' strategies and behaviour based both on observation and users' feedback.

5.1. Virtual Navigation and Verbal Descriptions

Participants were required to learn two routes using the virtual navigation app. Herein, we analyze users' verbal descriptions to evaluate their route knowledge over time. In addition, we describe participants' usage of the app, both in terms of time and functions used. The metrics for the route knowledge assessment with the verbal descriptions are depicted in Figures 3 and 4 for short and long routes, respectively.

5.1.1. Short Routes

Participants did not use the whole time they had available to explore the short routes. Although they had 20 minutes (1200 seconds) to learn each route, most participants used less than 10 minutes, in all three days (means of 536.36, 478.43 and 373.64 seconds). There is a decrease in time spent over the three days, but differences are not statistically significant ($\chi^2(2)$=3.000, p=0.223).

All other metrics show an increasing tendency in route knowledge over time, portrayed by the decrease in *FormElementErrors* – the number of wrong, missing, or extra turns included in the description – and the increase of POI knowledge – POIs mentioned and in the correct location – and distance estimation accuracy. Repeated measures tests showed significant differences among the three days for all route knowledge metrics ($p<0.05$ in all cases). The post-hoc tests showed significant differences ($p<0.05$) only between the first and third days, but not between consecutive days (again for all metrics). This can be explained by a slight, gradual increase over the three days, but also because most participants had a consistent, high route knowledge over all days for this route. For instance, half of the participants identified all turns correctly on the first day, while ten and thirteen (all except P6) on the following days, respectively. Most participants failing to identify all the turns on the first day were either overwhelmed with the long route (P9 reported confusion between the two routes) or spent little time exploring this route (P8 and P13 spent less than 4 minutes).

The POI metrics and distance accuracy show that some participants were able to acquire comprehensive route knowledge starting on the first day, while others needed further exposure to better learn the route. For instance, four participants (P2, P5, P11, P12) missed one or none POI and five participants (the same four plus P3) had a distance accuracy above 0.75 on the first day, but four other participants focused mostly on the turns and mentioned none or one POI.

5.1.2. Long Routes

The complexity of the long routes required more effort from participants. The majority spent all (or almost) the available time learning the route. Overall, nine, eleven and eight participants spent more than 15 minutes in this route over the three days, respectively. Yet, there were no significant differences in the time spent in the long route among the three days ($\chi^2(2) = 5.070$, $p = 0.079$).

As expected, the overall performance was lower when compared to short routes due to the higher number of turns and POIs. However, Figure 4 also shows a clear tendency of an increasing route knowledge over time. For instance, eight participants ended the third day knowing the entire sequence of turns in this route (two and three participants in the first and second day, respectively). Besides showing significant differences between the first and third days, the post-hoc analysis showed a clear difference in *FormElementsError* between the second and third day ($p<0.01$; and $p=0.075$ between *Day1* and *Day2*).

POI metrics also show significant differences among the three days ($p<0.001$). For instance *POIsCorrectLocation* increased significantly from the first to the second and third days ($p<0.005$ for both; and $p=0.240$ from *Day2* to *Day3*). This gradual increase is illustrated, for instance by the fact that one (P11), six and seven participants (respectively, over the three days) listed correctly at least half POIs in the correct segment and side. It increases to three, six and ten if we consider *POIsMentioned*. In addition *DistanceAccuracy* shows an increasing tendency over the three days ($p<0.005$ from *Day1* to *Day3*; $p=0.063$ from *Day1* to *Day2*; $p=0.270$ from *Day2* to *Day3*).

These results show a consistent increase in route knowledge over time. Moreover, even though route complexity is considerably higher than in shorter routes, a subset of the participants was able to acquire high route knowledge on the first day. For instance, three users (P3, P11, P12) knew all the turns (*FormElementsError*=0) and had a *DistanceAccuracy* above 0.75.

Gesture		Usage Ratio Short	Long	Total
1 finger	swipe up	34.0%	45.5%	41.5%
	swipe down	24.7%	13.8%	17.6%
3 fingers	swipe up	0.7%	0.8%	0.7%
	swipe down	1.5%	1.5%	1.5%
	tap	2.9%	2.0%	2.3%
2 fingers	swipe up	2.3%	2.1%	2.2%
	swipe down	1.4%	0.7%	0.9%
	tap	0.7%	0.5%	0.5%
1-3 finger(s)	swipe left	13.2%	14.4%	14.0%
	swipe right	13.5%	13.0%	13.2%
Gyro sensor	rotate left	2.1%	3.4%	2.9%
	rotate right	2.7%	2.4%	2.5%
4 fingers	tap on lower/upper	0.4%	0.1%	0.2%

Table 3: List of the ratio of gesture commands usage in short routes, long routes, and in total. The percentage adds up to 100 in each column.

5.1.3. Virtual Navigation App Usage

In order to understand how participants used the app, we looked into the application logs ana analysed the frequency of each gestures. The average number of gestures performed per participant was 1179 (SD=573, Min=166, Max=2623) during the virtual navigation phase (16,506 gestures in total), excluding practice. Table 3 shows each command usage ratio. Moving to the next element was by far the most frequent gesture used, which was expected as it provides a fast way to jump through the route relevant points. Moving to the previous element was also often used, showing that users leveraged the ability to navigate forward and backward, learning the route at their own pace. Although the *Virtual Walk* command (2-finger swipe) was used less often, five participants used it more than 10% of the times in comparison with 1-finger swipe. This is a high number considering that users can go through the whole route just by making the gesture once. P5 referred that she started with 1-finger, because it enables her to go back-and-forth as she wishes, but then changed to the walking mode as it requires less effort and allows to have a more realistic view of the route. On the other hand, P11 and P13 did not use *Virtual Walk*.

The turn gesture was performed nearly five times more often with swipes than by rotating the phone because it is faster to perform. However, some participants saw benefits in using phone rotation to better understand the route structure. For instance, P12 referred that he would use the swipe gesture for regular turns, but would use the rotation for slight turns in order to grasp what it represented. P5 referred that she would also rotate her body when rotating the phone, in order to help her building a mental image of the route, which was a behaviour also reported in our prior study (Guerreiro et al., 2017).

5.2. Real-World Navigation

After exploring two routes using our virtual navigation app, participants performed four real-world navigation tasks, including short and long routes. In this section, we analyze performance based on completion time and navigation errors (missed turns, and longer recovery errors) and collect users' feedback on task easiness and confidence.

5.2.1. Short Routes

For the familiar route (learned virtually at home), participants performed the navigation tasks without any assistance besides their primary navigation aid. In the unfamiliar route, they used *NavCog* to help them reach the destination. Although we anticipated similar difficulty for both routes (A and B), *Short Route B* revealed to be more challenging for participants. *NavCog* users were always able to reach the destination, but two participants (P8 and P13) were not able to complete *Short Route B* when navigating a (familiar) route unassisted. When asked to describe the route after the navigation, both users described the required turns, but were unaware of the distances and most POIs. A probable explanation is that P13 spent considerably less time than the others exploring this route (a total of five minutes over the three days), while P8 often confused the two routes in her verbal descriptions.

Figure 5 shows an expected advantage for *NavCog* in the time participants took to reach the destination, which can be explained by the number of missed turns that users needed to recover from (Figure 6), but mainly by two participants (P5, P11) who needed to restart the navigation. These two participants had a very good knowledge of the route (including distances), but a slight misunderstanding influenced their navigation. For instance, P5 thought that she should turn when the "*floor changes from carpet to tile*", while the instruction referred to a "*floor change to tile*". As she did not find the carpet floor, she continued walking in the expectation to find it assuming she misunderstood the distance. After restarting, she had a perfect trajectory being one of the fastest users in this route (including *NavCog* users).

Despite these differences, we found no statistical differences (Table 4) between the two conditions in none of the routes, for all metrics (time, and the two error metrics). This can be explained by the small number of users, but also by the very good knowledge that most

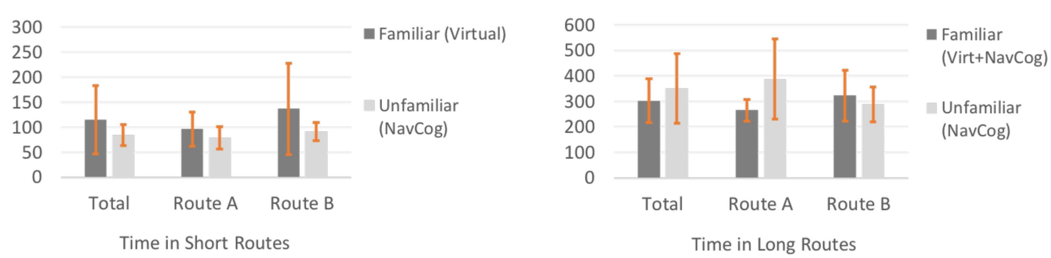

Figure 5: Time participants took to reach the destination, showing total values and divided by route. Error bars show the standard deviation.

Figure 6: Box plots (showing first quartile, median, third quartile, minimum and maximum) of the error metrics, per route and condition, in the short routes. V represents unassisted routes, familiar through virtual navigation, while N represents unfamiliar routes navigated with *NavCog*. The black marker represents the mean.

Short	**A**			**B**		
Metric	Time	Missed Turns	L.R. Errors	Time	Missed Turns	L.R. Errors
Independent t-test (T=)				1.317		
Mann-Whitney (U=)	12.00	9.50	21.00		14.00	18.50
Significance (p-value)	0.198	0.198	1.000	0.253	0.302	0.701

Table 4: The statistical tests performed for the three performance metrics (Time, Missed Turns, and Longer Recovery Errors) in the short routes. We ran independent t-tests for variables with a normal distribution and Mann Whitney U tests otherwise.

participants had of the short familiar route. This knowledge led them to make very few errors and to immediately understand and recover when they missed a turn. For instance, four virtual navigation participants did not miss any turn, while five missed one but were immediately able to recover from it.

When asked about task easiness (from 1 - Very Difficult to 7 - Very Easy), participants provided very similar scores for both conditions (Median=6 for both, IQR_V=2, IQR_N=1), in both routes ($p>0.05$). However, their confidence while navigating *Short Route A* was significantly higher with *NavCog* ($Median_V$=6, IQR_V=0.75; $Median_N$=7, IQR_N=0; $p<0.05$).

When verifying the users' descriptions after navigating the familiar route in the real-world (Figure 3), their route knowledge was significantly worse when compared to *Day3* in all metrics ($p<0.05$) except *FormElementsError*. This can be explained by participants focusing mostly on the information that was useful to complete the navigation task. When asked to describe the unfamiliar route (where they used *NavCog*), most participants referred that they were focused on the instructions and did not recall the exact path they followed nor what they found on the way. This result was expected, since we deliberately asked participants to focus on the navigation and on reaching the destination. Yet, we wanted to

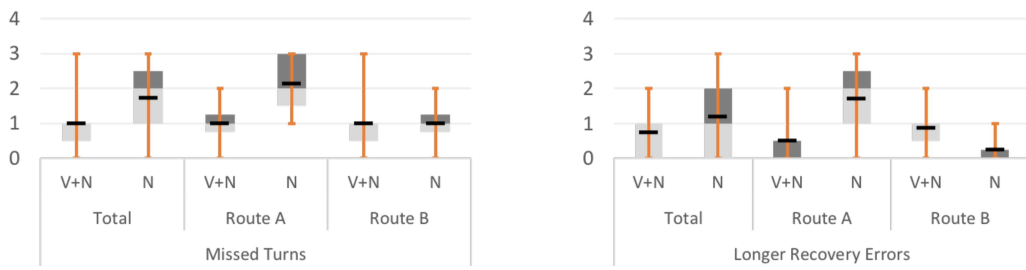

Figure 7: Box plots of the error metrics, per route and condition, in the long routes. *N* represents NavCog (unfamiliar route), while *V+N* represents the combination of virtual navigation and NavCog (familiar route). The black marker represents the mean.

Long	**A**			**B**		
Metric	Time	Missed Turns	L.R. Errors	Time	Missed Turns	L.R. Errors
Independent t-test (T=)	-1.504			0.596		
Mann-Whitney (U=)		5.00	5.50		13.00	7.00
Significance (p-value)	0.167	0.076	0.095	0.566	0.835	0.144

Table 5: The statistical tests performed for the three performance metrics (Time, Missed Turns, and Longer Recovery Errors) in the long routes. We ran independent t-tests for variables with a normal distribution and Mann Whitney U tests otherwise.

understand what knowledge they would gain after navigating an unfamiliar route.

In addition, we found no correlations between users' route knowledge (any metric) after virtual navigation (on *Day3*) and their performance (time, missed turns, and recovery type) in that familiar route. This can be explained by participants' high route knowledge after three days exploring the short route.

5.2.2. Long Routes

Participants used *NavCog* to explore both familiar and unfamiliar long routes. Although slight differences can be observed, the analysis of both the task completion time (Figure 5), and error metrics (Figure 7) showed no significant differences between conditions (Table 5), in both routes (A and B). Results show some missed turns, which are often by a few steps away from the turning point and therefore users were able to quickly recover from them. Longer recovery errors, in both conditions, were sometimes caused by a decrease in localization accuracy. Since *NavCog* provided timely instructions in most turns, participants trusted its instructions even when their previous knowledge indicated an inconsistency. For instance, P5 commented "*hmm, this should be a shorter hallway*" when the system provided a late turn instruction, but continued walking until listening to the instruction.

On the other hand, participants were able to leverage their route knowledge in the rare occasions that the system failed. For instance, *NavCog* lost its location for two participants (P2 and P12) after getting off the elevator (5th floor) in *Long Route A*. P2 remembered and was able to complete the quick sequence of left turns, before informing the researchers that the system had stopped. More impressively, P12 was able to complete the route and reach the destination without any assistance from that point.

When asked to rate task easiness and confidence during navigation, responses were very similar for both conditions, in both routes (overall values, easiness: Median=6, IQR_{V+N}=1, IQR_N=0.5; confidence: Median=6, IQR_{V+N}=2, IQR_N=1.5). However, some participants reported very high confidence when navigating familiar routes. P10 stated: "*I was gonna impress you* [If navigating the long route unassisted]*... this will be piece of cake with the app*"; after walking part of the route with a fast pace, he commented "*set the time, this will be record breaking*". Again, users' descriptions right after navigating the familiar route in the real-world (Figure 3) were significantly more incomplete than the ones on *Day3*, but now for all metrics ($p<0.05$). A possible explanation for this result is the time that passed between the last virtual navigation day and the real-world tasks. However, both the need to travel several routes in a day and the errors made during navigation may have also influenced this result. A relevant observation is that participants often mentioned the POIs/landmarks that they were able to perceive during navigation (e.g., when they sensed a *column* with their cane, they were more likely to mention it in their description) and had more difficulty describing areas where they missed a turn.

It was interesting to note that most participants with greater knowledge about POIs and landmarks (*POIsCorrectLocation* and *POIsMentioned* after virtual navigation (*Day3*), took less time to complete the real-world navigation task in that route, missed less turns, and had less long recovery errors. A slight tendency is suggested by moderate correlations between *POIsMentioned*) and the navigation *time* (rho=-0.560, p=0.073), *missed turns* (rho=-0.551, p=0.079) and *longer recovery errors* (rho=-0.582, p=0.130), yet not statistically significant.

5.3. Observation and User Feedback

In order to complement the quantitative analysis in the previous sections, we looked into the users' observed and self-reported strategies to help informing the design of future virtual navigation approaches.

5.3.1. User Behavior in Unassisted Tasks

We performed a fine-grained analysis of user behavior when performing the navigation tasks. During the navigation tasks, two researchers took notes about user behaviour and discussed to define the main themes from their notes. Then, one of the researchers observed all videos to identify such behaviours. No new themes emerged after video observation. The video-observations intended to provide a better understanding of user strategies and challenges, and inform the design of interfaces that support transferring route knowledge to the real-world[2].

[2]In this paper we focus on the video-observation of unassisted tasks. Please refer to (Guerreiro et al., 2018) for an in-depth analysis of user behavior when using an indoor navigation system (without prior knowledge of the route).

When navigating short, familiar routes participants needed to leverage their previous knowledge and employed interesting strategies to help them reach the destination.

Anticipation. Guide-dog users often prompted their dog to turn a little before the actual turn, while white-cane users often started to sense the wall before the turn in order to avoid missing it. This proved to be a good strategy in most occasions, except when (two) participants misjudged the distances and attempted to turn too early and therefore followed a different path. Given this strategy, it may be relevant to provide additional feedback concerning the number of possible turns before the actual turn.

Use of Landmarks. It is well known that PVI use known landmarks to help them navigate an environment. Such use was supported by this study, in particular when landmarks were located at the turning points instead of in the middle of a route segment. For instance, "*turn left at floor change*" in *Short Route A* and "*turn left at the elevator*" on *Short Route B* rarely resulted in missed turns. It was also clear that some landmarks, such as floor changes, are easily identified by white-cane users but may not be noticed by guide-dog users. In addition, a slight misunderstanding about a particular landmark (recalling "*floor change from carpet to tile* instead of "*floor change to tile*"), may cause a navigation error if users over-rely on such landmark.

In addition to turn landmarks, white-cane users sometimes searched for landmarks to assess their current location (e.g. a couch in *Short Route A* - Figure 1) and perform the turn at the correct time ("*OK* [After touching the couch with the cane] *now it should be just 20 feet more*)".

Sensing the Walls. Or Not. Participants had different strategies when navigating unassisted. While some white-cane users relied heavily on the walls to know when to make the turn (*e.g.,* to check for the end of the corridor or when reaching the elevator, or sensing the lateral wall to look for the next possible turn), others were able to use their senses and perception of the environment to understand the location intersections and act according to their mental representation of the route. Such ability is possible, for instance, due to users' echolocation skills (Kolarik et al., 2014).

Guide-dog users rarely needed to sense the walls, as the dog often stops at an intersection waiting for the user to decide where to go. Still, in some occasions the dog continued moving forward resulting in a late turn. The ability to quickly recover from such error depended either on the participants' echolocation abilities (by understanding that they just passed an intersection) or mental representation of the route (by knowing that the route segment should be shorter rather than longer). Although not frequent, one guide-dog user (P12) tried to feel the wall with his hand when the dog stopped at a *T-intersection* just to make sure he was at the end of the corridor (as he knew from his experience with the app that he should turn at the end of the corridor).

Misjudging Distances. It was more frequent for users to perform a late turn than an early turn, in particular in short segments, as users thought the segment to be longer. The techniques previously mentioned in this section helped preventing longer recovery errors – *e.g.,* by sensing the walls to know when to turn – or quickly recovering from them – *e.g.,* using echolocation skills to understand when passing by an intersection. However, in some cases users with a very good mental representation of the route verbalized their surprise about passing the turning point (*"I know it should be 20 feet, but this did not seem 20 feet"*). This different perception of length occurred most often due to users' difficulties to estimate distances, but sometimes due to a mismatch between the user's position in the real-world and what is considered during virtual navigation. This happens because the virtual navigation app considers the center of the corridor, which does not always correspond to the user's position.

5.3.2. User Feedback

Participants' feedback was very positive both regarding *NavCog* and the virtual navigation app. Moreover, participants provided positive feedback about the use of bone-conductive headphones, but would prefer to use the phone in their pocket instead of carrying it.

Strategies. When asked about the strategies used to learn the routes, participants reported two main approaches: picturing the mental image of the route (e.g. "*I made the drawing in my mind*" – P11), or memorization of the instructions (e.g. "*I was reciting like a poem*" – P5). The latter supports previous research suggesting that PVI build their mental representation of the environment as a sequence of route-based instructions (Millar, 1994; Thinus-Blanc and Gaunet, 1997), while the former suggests an ability (or at least willingness) to build a more comprehensive cognitive map of the environment.

Additional strategies include separating the long routes in two (before and after the elevator), aggregating turns ("*one left and then three rights as if going back to the same place*" – P13) or centering the information around specific elements of the route (e.g. "*what is on each floor*", "*what is around the kitchen*" – P7).

Confidence. Although there were no significant differences in participants' self-reported confidence navigating long familiar and unfamiliar routes with *NavCog*, a subset reported increased confidence when they knew what to expect in each route. P12, who had an accurate mental representation of the route mentioned that he "*knew the route well, so probably would not need that much information in the real world*". P10 stated that the prior knowledge enabled him to navigate faster ("*I was going extra-fast, because this is the route I practiced*"). However, most participants referred that during navigation they relied mostly on *NavCog*, because it provided the instructions they needed, neglecting the prior information acquired.

Suggestions. Most participants' suggestions focused on the substitution of slight turns for a more concrete measure such as clockwise or degree information. Also, two participants referred to their preference for announcing consecutive turns in the same instruction, in order to be prepared and avoid missing the second turn. An unexpected comment made by four participants was that they would also use the virtual navigation app *in-situ*, when *NavCog* is not available. Such approach is not new (Oh et al., 2017) and can benefit from the lessons learned in this user study and on research on how to provide directions to assist blind people navigating unfamiliar places (Nicolau et al., 2009; Scheuerman et al., 2017).

6. Discussion

In this section, we revisit our main research goals and discuss our main findings.

6.1. Acquiring Route Knowledge with Virtual Navigation

The analysis of the participants' verbal descriptions supports previous research reporting blind people's ability to leverage virtual navigation to build a sequential representation of the structure of simple, short routes (Guerreiro et al., 2017; Yatani et al., 2012). Participants increased their route knowledge over time, and some of them acquired a very complete understanding of the route on their first day. Moreover, most of them used less than half the time they had available in all three days, most often because a short time was enough to learn the route. Participants with lower route knowledge on their first day spent a short time in this route, resulting in confusion between both routes. However, this was often surpassed on the second and third days.

Previous research focuses mostly on short routes or small environments (Brock et al., 2015; Chebat et al., 2017; Guerreiro et al., 2017; Yatani et al., 2012), so including a longer, complex route provides novel information on route knowledge acquisition in a more demanding context. Although the long routes were overwhelming at first for some participants, they were able to gradually build their route knowledge over time, prioritizing learning the turns over landmarks and POIs (usually learned later in time). Learning the distances was a greater challenge for most participants, which was also observed in previous studies (Guerreiro et al., 2017; Radvansky et al., 1995). However, a subset (five) included medium to highly accurate distance information over the three days. In contrast, some participants completely disregarded this information, suggesting that new approaches to convey distances are needed. Future solutions should allow for reduced complexity of distance instructions, rather than using feet/meters information in all segments.

The ability to combine VirtualLeap and VirtualWalk, at all times, was also used by participants and provided more interactivity to the virtual navigation. While VirtualLeap resembles a sequence of instructions, actually moving the user in the map (in the case of VirtualLeap by jumping through the relevant elements) enables an egocentric view of the environment by always referring to the different elements from the users' point of view. Still, when users wanted to better understand what would be their real-world experience, they shifted to *VirtualWalk* as it resembles more as a simulation of their real-world navigation. Interactivity also enables users to learn the route at their own pace, as some participants moved back in the route more often in order to learn a particular segment before proceeding.

6.2. Supporting Unassisted Navigation in Short Routes

All but two participants were able to leverage the knowledge acquired with virtual navigation to reach the destination of the short route. Most importantly, most of them had an overall performance that is comparable to navigation with *NavCog*, showing that participants were able to transfer the knowledge acquired during virtual navigation to the real world in short routes. In line with research that uses virtual navigation to improve real-world navigation skills (Chebat et al., 2017; Connors et al., 2014; Lahav et al., 2015), these results suggest virtual navigation as a promising approach to increase blind people's independence with the advantage of using off-the-shelf technologies available on the market. Overall, participants believe that they would visit unfamiliar places more often than they do now, if the application includes locations of interest such as shopping malls.

While most participants were successful in performing this task, two were not able to reach the destination and two needed to restart the navigation to complete it successfully. Although the first two participants did not have a very clear mental representation of the route, further research can be done in order to understand how to better support unassisted navigation with virtual navigation. Our design choice to use the same instructions as *NavCog* aimed at consistency between the two apps, which should be helpful when combining both as the user can anticipate what instructions to expect. However, *NavCog* assumes good localization accuracy, but in unassisted navigation users need to rely on their own distance estimation, which has been shown to be difficult to recall and to judge by this and previous studies (Guerreiro et al., 2017). This suggests that virtual navigation may require additional or alternative instructions that may be more useful to particular groups of users. One example (apart from the landmarks currently used) is to leverage the ability to sense the wall with the white cane by referring to *"turn on the second available left*", instead of using distance in feet or meters.

6.3. Complementing Real-World Assistance in Long Routes

There were no significant differences in performance between the familiar (through virtual navigation) and unfamiliar long routes. This can be explained in part by the good localization accuracy provided by *NavCog*. In both conditions, participants relied heavily on *NavCog* and ended up only using their prior knowledge when they realized some mismatch with their mental representation of the route. These results support the use of accurate *in-situ* navigation tools like *NavCog*, but there are some downsides in relying exclusively on such approaches. First, turn-by-turn navigation tools may negate route learning (Fenech et al., 2010); second, accurate solutions are not widely available. Future research should study the benefits and opportunities for combining virtual navigation with a broader range of systems.

An interesting result supporting benefits from combined usage of virtual and real-world navigation tools was that in the event of a system failure, two participants were able to continue the navigation, one of them reaching the destination. Knowing that blind people avoid traveling in unfamiliar places (Giudice and Legge, 2008; Williams et al., 2013), the prior knowledge acquired using virtual navigation can be used to increase their confidence, even when assisted by *in-situ* navigation tools. Additional anecdotal evidence include minor errors that were immediately perceived and corrected by users who knew that the current segment should be shorter/longer.

In addition, previous studies with NavCog reported very few navigation errors (Sato et al., 2017), but our environment presented additional challenges such as very narrow corridors where a small localization error (*e.g.*, 1.5 meters) could result in an early or late turn. However, it was interesting to notice that participants often recovered very fast from these minor errors that did not seem to affect their navigation experience, suggesting that the current localization accuracy levels may generate acceptable minor errors (Abdolrahmani et al., 2017), and support practical, indoor navigation (Ahmetovic et al., 2017).

6.4. Limitations

Despite the valuable findings and insights, this study has some limitations, such as the relatively small number of users that is frequent in studies with blind people. This seemed to gain more relevance as the pairs of routes used, although having the same complexity in theory, seemed to present different difficulty levels. We selected two short and two long routes that comprise both wide and narrow corridors, as well as a variety of POIs and landmarks. Although we cannot claim that they represent all indoor environments, we believe they are representative of a large set of possible indoor environments that a blind user may encounter. In addition, in real-world navigation it is very difficult to control external factors, such as other pedestrians or overall noise. Although it may impact users' performance, we believe that not eliminating these factors provides more insights on the actual usefulness and performance of our approach in real-world scenarios.

We also intended to evaluate the impact of (self-reported) smartphone and O&M expertise on users' performance, but such comparison was not possible to perform as all participants rated themselves very high (6 or 7 in a 7-point scale).

Although results show that both our virtual navigation app and NavCog (by themselves or combined) can support independent navigation of people with visual impairments, our analysis and observation have also revealed limitations and open challenges for future research. In particular, the route elements used in this study were manually annotated in the map editor and therefore the POIs and landmarks were static. In order to better cope with dynamic elements, the system needs to recognize and adapt to such changes. Moreover, NavCog users needed to carry the smartphone in one hand and their primary navigation aid in the other hand; this need sometimes affects navigation (e.g., when opening a door). However, using the smartphone in the pocket would reduce localization accuracy as the user's body obstructs the beacon signals.

7. Conclusions

We presented a smartphone-based virtual navigation app that enables blind people to gain route knowledge and familiarize with the environment before visiting a particular location. The results described in this paper analyze route knowledge acquisition over time using this app and its impact on real-world navigation with and without *in-situ* navigation tools. While some participants only needed one day to grasp the important elements of the routes, most were able to gradually increase their knowledge in both short and long routes and to reach a good understanding of the route structure and its relevant elements. The virtual exploration of short routes enabled most participants to transfer their route knowledge to the real-world and reach the destination unassisted, most of them with a performance that was comparable to the use of *NavCog*. Although results did not show a clear quantitative benefit of combining virtual and real-world navigation assistance in long routes, we observed that the knowledge acquired virtually allowed two participants to cope with system errors to easily recover and continue the navigation on their own.

In future research, we plan to understand if using instructions that are specifically designed to support unassisted navigation can be more useful when compared to the instructions that are provided by in-situ navigation tools like *NavCog*. Also, in this study we assessed how route knowledge evolved over three consecutive days; we aim to understand its dynamics over longer periods of time and how it compares to *in-situ* route learning, for instance through route repetition tasks. Moreover, evidence that blind people often build a mental representation of the environment based on sequential route-based instructions (Denis, 2017; Millar, 1994; Thinus-Blanc and Gaunet, 1997), led us to focus on the acquisition of route knowledge by using tools that guide the user following a pre-determined route. However, our virtual navigation app also supports an exploration mode where the user is able to freely navigate in the environment. Besides route knowledge, such approach may support the creation of a comprehensive cognitive map of the environment. Yet, further exploratory research is needed to understand not only how can it convey relevant spatial information to the user, but also how to provide a good user experience without being overwhelming.

8. Acknowledgments

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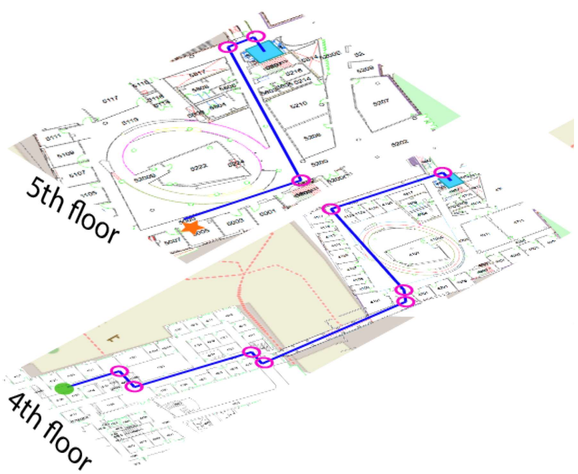
Graphical Abstract

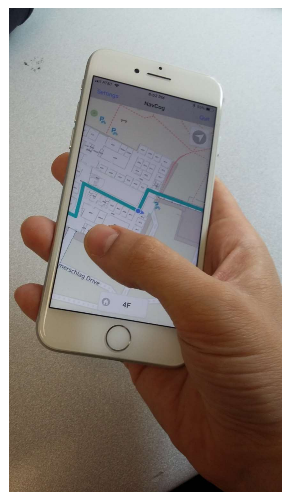
(1) Unfamiliar Real-World Routes

Independent navigation is challenging for blind people, in particular in unfamiliar environments



(2) Smartphone-Based Virtual Navigation

Learn routes at home with an interactive app and evaluate route knowledge acquisition and evolution over time



(3) Independent Real-World Navigation

Impact of route knowledge acquired virtually in unassisted and assisted navigation