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ORIGINAL ARTICLE

Navigation your way: from spontaneous independent exploration to dynamic social journeys

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Abstract In this article, we describe a novel approach to pedestrian navigation using bearing-based haptic feedback. People are guided in the general direction of their destination via a minimal directional cue, but additional exploration is stimulated by varying feedback based on the potential for taking alternative routes. This extreme navigation method removes the complexities of maps and direction following, concentrating on allowing pedestrians to actively explore their surroundings, rather than offering perfect, but passive, turn-by-turn guidance. We simulate and build two mobile prototypes to examine the possible benefits of this approach, then further extend its impact by considering how social media might be incorporated to provide a real-time, dynamically evolving map of physical locations. The successful use of our mobile prototypes is demonstrated in a realistic field trial, and we discuss the results and interesting participant behaviours that were recorded, validating the predictions from their earlier simulation. We continue by simulating the use of publicly posted status updates and pictures as a proxy for location mapping, showing how these methods can produce comparable navigation results to real-world field trials, highlighting their potential as tools for real-world social journeys.

1 Introduction

Pedestrian navigation has traditionally consisted primarily of physical cues: maps, signs, compasses, or asking strangers for directions. Since the arrival of GPS-capable mobile devices, however, digital navigation tools have improved to simplify navigation even further. At the tap of a button, these increasingly ubiquitous technologies instantly calculate the ideal route from *A* to *B*, guide us with directions between waypoints, and even help us if we somehow manage to stray from the quickest possible path. In short, we need never be lost again.

Perhaps, then, pedestrian navigation has been solved? Turn-by-turn walking directions (largely very direct conversions of car-based navigation systems) are now widely available on many mobile devices and becoming ever more helpful with the addition of on-board sensors to orient a map of our surroundings in real time. With directions always to-hand on the devices we constantly carry, we are assured by device marketing campaigns that we now never need to worry about being lost, taking the wrong path, or losing our bearings in an unfamiliar place. In reality, users of pedestrian navigation systems are often *completely* lost, in that if their device stopped working, they would not know where they were, or what to do next [4, 5], making the device more of a crutch they become dependent on,

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rather than a liberating feature. Furthermore, such systems affect how people learn to navigate independently [2, 19], and make them less able to guide others in the city.

Instead of enjoying their surroundings, people using current pedestrian navigation systems are prompted to speed directly to their goal, heads-down, checking the display for the latest instructions about where to turn next. Such systems can often remove the wonder and enchantment of an individual's exploration, alter their normal exploratory behaviour in a new environment, and make them less aware of their surroundings. Our goal in this research was to remove this division of attention between a navigation device and the real world it describes; instead, we prompt people to fuse their view of a location with the feedback given, allowing a more engaging experience. We aim at empowering users to find their own way and to free them from the need to constantly look at a screen or be passive, micro-managed agents, listening to turn-by-turn instructions. We allow them instead the flexibility to actively take control, and wander where their imagination takes them, with no need to worry about getting back to the 'correct' path. The user actively requests support from the phone when needed, giving them the reassurance that they can always find their bearing to the goal, without having the sense that the phone is 'directing' them.

We envisage this extreme navigation approach not as a replacement for, but as a complement to current systems. In situations where quickest time or shortest path are not particularly important, users might find it more enjoyable to turn off the demands of instruction following. Instead, we imagine people wandering through and impulsively exploring the interesting places around them, with occasional reassurance that they're heading in the right direction. Consider the following scenario, which illustrates the approach:

> Mark is visiting Rome for the first time, and is looking forward to meeting some friends at a good local restaurant. Taking out his mobile, he sees the arranged meeting place just about 2 km away. It's such a lovely spring day, so, with time to spare, he roams freely in the rough direction of his meet-up, taking in the maze of alleys and quirky shops all around him. After 10 minutes, he scans left to right; the device vibrates to reassure him he's still on course, and also indicates that there are many routes to his destination. It feels good finding his own way, so he continues to make his own choices, enjoying the area around him. A little later, he comes to a main junction. Should he turn left or right? He'd better get this right, he thinks. Scanning again, the vibration feedback is now more targeted, and he walks on with confidence...

Recognising that pedestrian navigation might often be more exploratory, taking place in semi-familiar places, in our design, we remove the complexity of direction following. We have previously investigated this low-attention method of navigation to help groups of people find their way to a shared meeting point [39], but here we look more closely at how the technique might work for individuals. In our earlier work, pedestrians casually scanned for feedback to lead them to a mutually convenient meetup location—a dynamically evolving social guide to their shared area. In this article, we consider a single person-focused approach, investigating the efficiency of simple haptic navigation for guiding pedestrians to their goal without the need for waypoints.

A key component of our approach is a re-envisioning of the maps we use while navigating. For many current navigation applications, one crucial requirement is a detailed map of the area, needed in order to be able to plan routes between waypoints. We begin by considering how pedestrian navigation might work without these maps. Indeed, while such maps are widely available for road networks and, increasingly, pedestrianised areas, we feel our approach offers benefits in those areas that may not be fully digitalised—consider navigation through a live music festival, wandering in open parkland, and many places in the developing world. Our first mobile prototype–*static feedback*–offers a simple solution by providing directional assistance in the form of fixed-size, low-resolution vibrotactile feedback. Pedestrians can casually scan to discover the direction of their destination using a handheld device, feeling feedback when they point towards their goal.

Building upon this initial design, we also consider how the maps used in current devices might be appropriated to help users realise the potential for exploration. In our initial prototype, the apparent width of the haptic target remains the same regardless of the navigator's surroundings. Our second prototype—*dynamic feedback*—uses map data to estimate the number of routes in the vicinity of the user's current location and expand or contract the size of the feedback area accordingly. This novel feedback method helps to provide the user with some indication of the degree of choice available when route finding.

In the final part of this article, we turn to consider how it might be possible to construct 'maps' that represent both the exploration possible in the locations the user is navigating through, and the experiences of others in the surrounding area. Our previous social navigation work developed routes by incorporating the current location of a group of users navigating in the same physical area. Here, we investigate techniques for using location data from people *outside* of the navigation process. The most abundant and easily accessible source of public geolocated media is the vast array of social updates, pictures, and videos that are continuously shared by users worldwide. By incorporating this geotagged social content into the navigation process, we allow *social navigation*, helping the user navigate via a constantly evolving social map of the places they pass through. Using the same technique as our dynamic feedback prototype, the angular width the user senses is constantly adjusted as they move. However, in this third design, the feedback reflects the routes possible through the social content shared in the places around them.

In the rest of this article, we present these three methods for pedestrian navigation, beginning by situating the approach alongside previous research. In Sect. 3, we describe the design, implementation, and a realistic simulation of our first two prototypes, continuing in Sect. 4 to evaluate the approach. These prototypes were first described in [31]; here, we discuss their design, development and, particularly, their simulation, in more detail. Our simulated results are validated by those from a real-world field trial, then extended in Sect. 5 by simulations of three potential social navigation methods. Finally, we draw the article to a close by discussing how these implementations might be used as a proxy for accurate location models, concluding in Sect. 6 by highlighting our contributions and pointing to potential future extensions of this work.

2 Background

It is well known that the use of mobile devices while moving can cause problems in situations where visual attention is necessary, and pedestrian navigation is a perfect example of this type of scenario. Seager [33] discusses many of the challenges in screen-based pedestrian navigation. Holland et al. [13] describe potential problems and offer a solution in the form of audio cues to guide users towards a destination. A similar approach was taken by Jones et al. [16] and Strachan et al. [35, 40] by dynamically adapting the music that a user is listening to in order to guide them in a certain direction. While these approaches have shown promise, related early work has found that many users are reluctant to use headphones for this type of task [3], citing concerns about being recognised as tourists, or a feeling of isolation from the environment. Our approach helps to minimise these effects, using vibrotactile feedback to allow a less-restrictive interaction style.

Previous alternatives to turn-by-turn navigation include landmark-based methods such as that described by Goodman et al. [12], who found benefits in using images of recognisable views along a route to guide users. Krüger et al. [19] and Aslan et al. [2] discuss how users learn routes while using mobile devices, finding that turn-by-turn systems often fail to convey appreciation of the navigation environment to their users. Our design takes a minimal approach to pedestrian navigation, removing turn-by-turn instructions to prompt users to explore, rather than hurry through their surroundings.

2.1 Haptics for navigation

Previous research has investigated the use of directional vibrotactile feedback as a navigational guide, with vest- or belt-based systems being the most common approach. Van Erp et al. [38], for example, studied several combinations of vibrational pulses and were able to successfully guide users to walk between waypoints. Pielot et al. [27] used a haptic belt with directional vibration to help users of paper maps orient the map correctly as they walked. The belt vibrated continuously, and users were able to incorporate this background cue into their navigation behaviour. A similar approach was taken by Johnson and Higgins [14], applying the technique to navigation for blind users. Their tactor belt was aimed at helping people avoid obstacles in their surroundings, motivated in part by a desire to lessen the effect of navigation on users' other activities. Our systems have a similar goal: allowing interaction with a navigation device to be thought of as a background task undertaken only when it is necessary or desirable, rather than providing feedback for slight path deviations or upcoming waypoints.

Many haptic navigation systems have used tactors in fairly fixed positions on the user's body, but handheld vibrotactile navigation has only emerged fairly recently. Lin et al. [20], for instance, provided navigational assistance via direction-specific tactons, finding that users were quite able to recognise the haptic cues and take appropriate paths through their environment. Strachan and Murray-Smith [36] investigated the use of simple directional vibration similar to that used in our systems, applying this to help with spatial target selection. Haptic target finding was studied further by Ahmaniemi and Lantz [1], using more complex vibrotactile patterns than in [36], though no significant improvements were found when additional cues (such as 'close to target') were added. Our work builds upon these findings and relates closely to the bearing-based feedback used in [24]. We combine this with the low-attention feedback aims of [34], also drawing upon previous research showing the benefits of handheld directional vibrotactile feedback while moving [29]. In addition, we investigate dynamic directional feedback, created from both physical and social location models. Our aims were to provide a new perspective on the task of pedestrian navigation and demonstrate the potential of these more flexible approaches.

2.2 Social navigation

Previous work has investigated user needs for social navigation during meetup tasks. Olofsson et al. [26] studied requirements during music festivals, for example, and Nicolai et al. [25] explored social location-aware systems by providing users with proximity awareness about people nearby. In our earlier work [39], we provided low-attention navigation awareness to a group of pedestrians walking to a mutually agreeable centre point. In this article, however, we study social navigation as a dynamically evolving guide created by people who are *not* part of the navigation process.

Dourish and Chalmers [8] define social navigation as "an artefact of the activity of another or a group of others," concisely describing this extensive area of research. While much research has concentrated on using social media to navigate digital data [23], others have explored social aspects of physical navigation and exploration through approaches such as geolocated images [21], collections of geotagged content [30], collocated users [37], or specific location-based applications (GeoNotes [9], for example). More recently, these social approaches have also started to appear in consumer-level devices. In-car GPS navigation tools now commonly incorporate live updates to allow both official traffic news and feedback from other drivers in the nearby area. Mobile phones have begun to incorporate similar features, such as allowing the user to activate a live camera display augmented with both points of interest and appropriate social data.

Karimi et al. [17] define a framework for social navigation networks, using a friend-based system to create recommendations for places to go and routes to take. This framework was tested in [18], allowing a groups of users to annotate locations and create personalised recommendations for routes and destinations. In a user study, participants were positive about the utility of the system, but the authors concede that further pedestrian path generation methods are needed. In our social navigation design, we take a different approach—rather than filtering social data within a small group of friends, we adopt a similar technique to the serendipitous search query awareness of [15]. Like the mobile query awareness provided by [6], our social navigation design provides social media location awareness from public social media, using this as an ad hoc replacement for map data, rather than creating specific route or destination recommendations.

3 Static and dynamic navigation prototypes

We created two prototypes to investigate static and dynamic approaches to handheld vibrotactile pedestrian navigation assistance. Our systems use a simple scanning gesture to browse for feedback, with the user holding a mobile device in-hand and feeling for navigation feedback whenever they like.

In our prototypes, the feedback is not given in a turn-by-turn fashion; rather, we use directional vibration to indicate the bearing of the destination, and allow the user to make their own path choices. Previous work has investigated the use of a general directional haptic cue for situations such as bike-based tourism [28], but in our novel approach, we apply the technique to navigation while walking. We build upon our earlier work that investigated the use of handheld directional vibration as a casual method for organising group meetups [39], extending this concept in our second prototype to allow users to get a sense of the path choices around them. This approach, we believe, can offer the user more freedom where appropriate, providing opportunities for off-the-beaten-track exploration. Unlike some previous approaches ([40], for example, which provided feedback varying as function of possible paths), we do not give any indication of the distance to the target, focusing instead on the benefits of giving users familiar and always-available reassurance that they are heading in the right direction.

Our first prototype–*static feedback*–uses a fixed angular width for the feedback given, relying on the user to observe potential route options and make appropriate choices. The second prototype–*dynamic feedback*–varies the width of the feedback area to give more information about the user's immediate environment (as illustrated in Fig. 1). By incorporating this extra aspect, pedestrians are able to sense whether alternative routes are available, but are still free to pick their own path at any point.

3.1 Implementation

Our prototype systems were implemented using Nokia N95 mobile phones. For feedback and device movement sensing, we used the SHAKE SK6 sensor pack [40]. The SK6 provides three-axis accelerometer, magnetometer, and angular rate data and incorporates a pager motor with variable speed control and active braking which we used to produce vibrotactile effects. GPS positioning was provided by the N95's onboard receiver. For this early prototype, the N95 was worn on a lanyard around the neck, and the SK6 was held separately, attached to a dummy mobile phone. This was a design compromise chosen to minimise cross-device sensor interference while still providing a realistically sized object that users could comfortably hold to feel for feedback.

The feedback used was designed based on previous research that showed that feedback can be a function of possible paths through the environment [40] and that vibrotactile angular widths need not be particularly

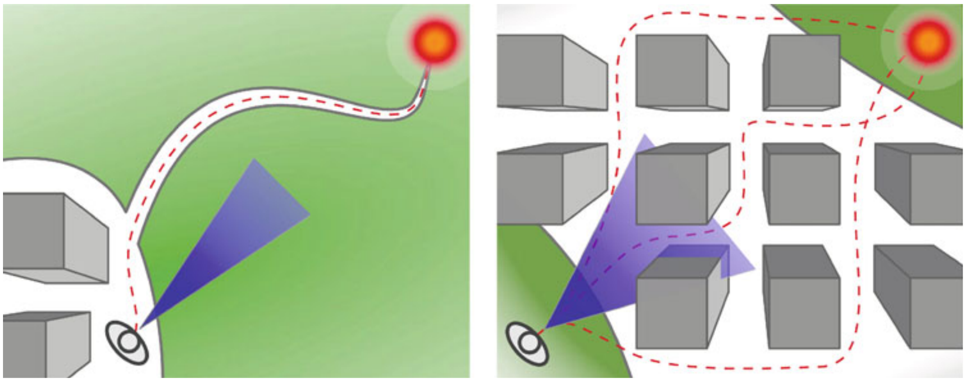

Fig. 1 Dynamic feedback is directly related to path options. When fewer routes are available (*left*), the feedback area (shown in *blue*) is small, expanding when there is more choice (*right*). The centre of the feedback area aims directly at the goal

small—indeed, larger angular widths help to minimise user frustration and have surprisingly minimal effects on user performance [39]. Our systems used the same minimum angular width of 60°, with the static feedback system using this at all times. The dynamic feedback approach altered the target width based on the number of potential alternative paths found. Pathfinding was achieved by precomputing a shortest path matrix using the Floyd-Warshall algorithm [10] on a graph of the study area. During actual usage, potential alternative routes were calculated by testing for paths from points in the area directly in front of the user's GPS trajectory. Routes that added more than 25% to the distance of the shortest path from the user's current location were discarded. The number of paths remaining was used to directly resize the feedback area, but this was limited to a maximum of 120° to avoid the excessively long routes that might result from edge-following behaviour.

3.2 Simulation

In previous work, we have discussed the benefits of using simulations for the design and initial testing of interactive mobile prototypes [39]. Specifically, relatively simple simulations can allow quicker and cheaper testing and refinement of complex mobile systems and are capable of accurately modelling both basic user behaviours and complex external uncertainties.

The systems described here have many parameters and variable external constraints. The angles at which feedback is produced can be altered, for example, or the GPS positional fix quality can vary as the environment changes. Obviously, a simulator cannot capture many of the subtle complexities of human behaviour, but the simple navigation task involved here can be reasonably modelled with a few assumptions. Importantly, the uncertainties in the system (for example, inaccuracy in bearing sensing or limited GPS resolution) can be simulated, and the effects on navigation performance observed and quantified.

We adapted the custom-built Python simulator from [39] to model our navigation prototypes, allowing refinement of their designs without the need for multiple field trials. Through an iterative design and simulation process, we improved the behaviour of the dynamic prototype, arriving at the parameters described above to give a balance of both the potential for environment exploration and reasonable task completion times. The parameters for the simulator were estimated based on simple assumptions about human movement and the way we expected people to use the system (checking the heading only every 30 s or so, for example). The simulator parameters were not estimated from experimental trials. Recent research ([22], for example) has built upon [39] and investigated several possible parameters for angle size in directional vibration, helping to support empirically the results from these simulations.

3.2.1 Agent model

The simulator models the problem as an agent with a simple behaviour system. This agent acts according to the following rules:

1. Walk in the current direction at a fixed rate (with some random wander)
2. Occasionally stop (according to a Poisson process), scan for the target, and then head in that direction
3. If an obstacle is reached, turn to face the smallest angle away from the target where the obstacle is not in the way
4. Stop when within the stopping radius of the destination.

Agent actions are scheduled to happen as Poisson processes, where the average rate of actions can be set; for example, the agent can be set to scan for the target with an expected time interval of 1 min, but with appropriate random variation. The simulator has eight configurable parameters (excluding the definition of the obstacles in the environment). These are GPS noise; feedback angle width; walking rate; scanning time; walking rate; walking variation (Brownian noise component); heading adjustment rate; and GPS update rate. Each agent has a current "true" position, and a GPS noise corrupted "reported" position, along with a current heading. When one of the actions is scheduled to occur (obstacle impact or heading check), the agent pauses for a time, chooses a new heading angle, and continues in the new direction.

While obviously a simple approximation that cannot capture the richness of human behaviour, this model provides estimations of reasonable behavioural characteristics and is sufficient to make informed decisions about design. Modelling the uncertainty, particularly GPS noise, the accuracy of the bearing signal, and the impact of obstructions are what make the simulator powerful. Environmental sources of noise are modelled as spherical Gaussian distributions, with adjustable variance. While this is not a perfect model of the true noise sources, it is sufficient to observe the impact. Some of the uncertainty due to latency in the feedback—which effectively blurs the target width—is folded into the model of angular sensing accuracy. The model can be explored interactively to check whether the agent behaviour seems plausible. The simulation can also be run in a batch mode, where hundreds of repeated runs are performed and overall statistics (such as time to converge and average scanning time) are reported. This allows gathering of statistics on a scale that is entirely infeasible with user trials.

We created an accurate model of the field trial environment and used this for 500 simulated runs of both the static and dynamic feedback prototypes between the same starting and ending points as those used in our trial (detailed in Sect. 4, below). The simulator predicted mean completion times of 20:52 min (SD 7:13) for the static system and 20:33 min (SD 7:19) for the dynamic system. Mean distances walked were 1.32 km (SD 0.42) and 1.30 km (SD 0.42) for the static and dynamic systems, respectively. Simulations were run with Gaussian GPS noise (SD 8 m) and Gaussian angular noise (SD 8°), with agents walking at 1.0 metre per second (±0.2) and checking for feedback every 30 s.

4 Field study

We conducted a field study to investigate the systems' effectiveness in a realistic navigation scenario and to validate our design simulations against the real-world results. The design of our trial was based on methods and recommendations from previous assessments of performance with mobile navigations devices, including both field studies (such as [11] and [41]) and laboratory experiments (such as [32]). Our research questions were as follows:

Viability: Can pedestrians navigate to a destination knowing only its general direction?

Freedom: Does the dynamic feedback prototype's coupling of feedback size to path variance have an impact on users' exploration of their surroundings while navigating?

After an initial pilot study, 24 participants aged from 18 to 65 were recruited for individual trials to help understand potential usage of the system. Fourteen participants were female and 10 were male; 13 were members of university staff and 11 were students. None of the participants worked in areas directly related to HCI.

Before the study, each participant was randomly assigned to use one of the two prototypes, in a between-subjects design. Fixed start and end points were chosen at the edges of the approximately 0.5-km^2 study area, in order to give participants exposure to navigation with the system through both urban and rural areas. The straight-line distance between start and end points was 0.77 km, and the shortest walking route (when keeping to paths) was approximately 1 km. These well-spaced points allowed us to measure participant performance at a much greater distance than that commonly used between turn-by-turn waypoints.

4.1 Measures

In addition to participants' comments and opinions in interviews, and recorded observations from the researcher running each trial, we collected detailed device logs allowing in-depth analysis of participant behaviours against our research questions.

Viability: We measured the success of the system as the overall percentage of participants who found their way to the end point. The viability of the system is reinforced by participant observations and remarks and by looking closely at walking speeds, specifically the variance over the trial and the amount of stopping required.

Freedom: The freedom offered by the dynamic feedback prototype is measured by comparing the variation in paths taken by participants over both systems. In addition, comparison with results from our static feedback prototype allows a measure of the extra cost of any exploratory behaviour.

4.2 Procedure

At the start of each study session, participants were met individually and led through an ethically reviewed consent and user study guidance process. Participants were then talked through the concept and basic usage of the system they would be using and given a short demonstration of the prototype. After a brief training session (less than 1/2 minute per user) in which they felt example feedback, participants were led to the pre-determined starting point on campus. When at the starting point, they began using the system to scan for and attempt to navigate to the end point. No description or guidance about the location of the end point was given, minimising potential effects from participants' prior knowledge of routes to the location. While navigating, participants were free to take any route they wished over the entire study area, while the researcher followed. Upon reaching the end point, a short interview was conducted to gather opinions and experiences, and all participants were rewarded with a bookstore gift voucher as a token of appreciation.

4.3 Results and analysis

All participants successfully completed the navigation task and found the end point with only the vibrotactile feedback to guide them. Participants using the dynamic feedback system completed the navigation task in an average time of 17:24 min (SD 5:25), while those using the static feedback took 19:02 min on average (SD 5:36). The mean distances walked were 1.53 km (SD 0.39) and 1.65 km (SD 0.58) for the dynamic and static systems, respectively, ranging from 0.97–2.39 km for dynamic feedback and 1.08–2.93 km for static feedback. Times and distances were not significantly different between feedback types (ANOVA, time: $p = 0.5$; distance: $p = 0.59$). Clearly, users were able to navigate to the end point without the need for turn-by-turn guidance. The mean times taken and distances walked are longer than those for the shortest path, but the ranges of times, distances, and routes taken (see Fig. 2) suggest that this has been a result of the variance in path choices.

4.3.1 Path choices and walking speeds

Figure 2 shows the routes taken by participants using each prototype and also the shortest path—the likely route for a turn-by-turn navigation system. Interestingly, although both systems used the same destination point, many participants using the dynamic feedback have tended to stick more closely to the main thoroughfare of the university campus, while those using the static feedback have often taken a less well-trodden route. This suggests that the varying vibration has allowed users to combine the feedback given by the system with both the path cues in their immediate environment and any prior knowledge of the area, while participants using the static feedback felt obliged to follow the target direction more closely despite the (unknown) potential for a more appropriate route.

Using methods from [7] for gait phase analysis, we can look at participant walking behaviour in detail. As shown in Fig. 3 (top), there is very little difference in walking speeds between systems throughout the task, though those using the static feedback have a slight tendency to walk faster. When looking at walking rate against the feedback given (see Fig. 3 (bottom)), we can see that participants using the dynamic feedback have probed for feedback more of the time.

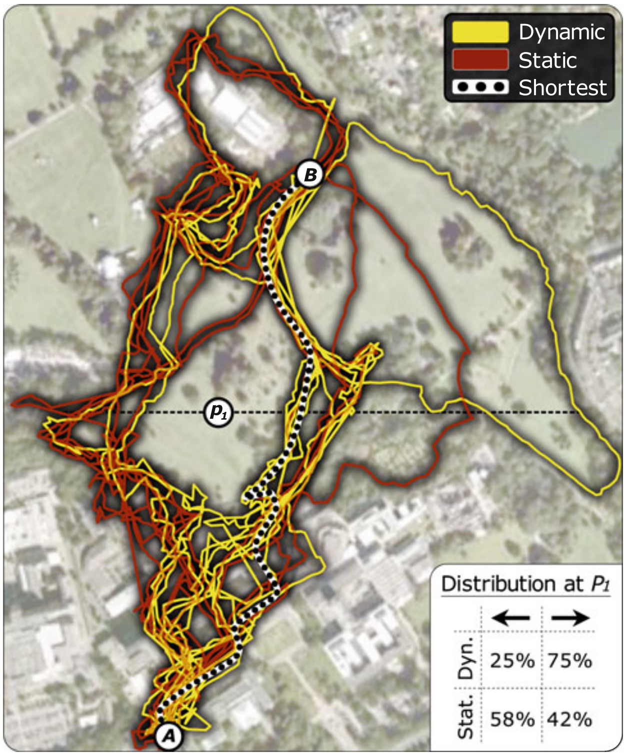

Fig. 2 Routes taken from points *A*–*B* by all 24 participants during the study; shortest path overlaid. *Inset*: distribution between main routes. Participants feeling dynamic feedback tended towards the main campus thoroughfare; those feeling static feedback often took less familiar routes

4.3.2 Comparison to simulated routes

Figure 4 compares results from the simulator with those from the field study. Times taken and distances walked in the trial are within the ranges predicted in the simulation, although in the study participants have walked slightly faster than the 1 metre per second assumed for the simulation.

Interestingly, differences between the two prototypes in the real trial results are not present in the simulated runs. In the real trial, participants using the dynamic feedback reached the goal faster and walked shorter distances, on average. These differences are likely to be a result of the limited walking behaviour model in the simulator—there are many external factors that we were unable to model, such as the possibility that participants have some level of prior knowledge of the study environment layout, subsequently influencing their walking behaviour. Despite this,

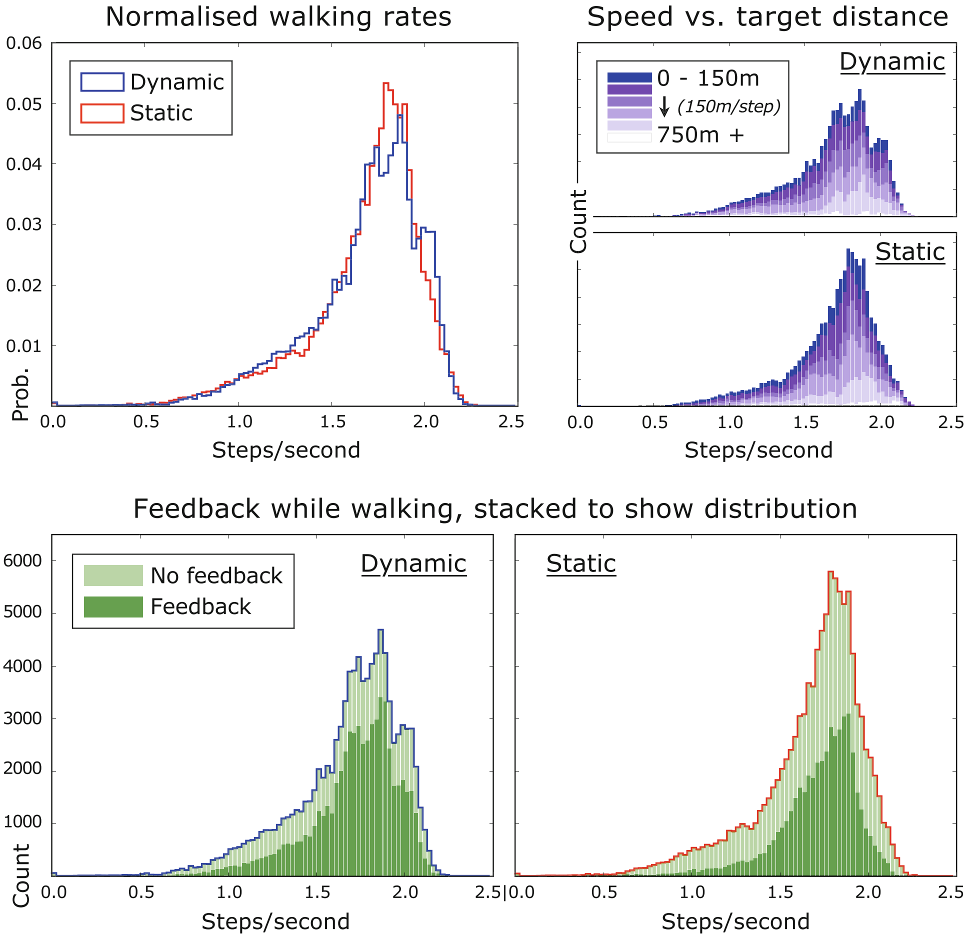

Fig. 3 *Top left*: Walking speeds for each system: speeds are clearly similar. *Top right*: Walking speeds for 150 m segments of the routes taken: similar rates were maintained throughout the task. *Bottom*: Walking speeds while the feedback was activated. Users walked and interacted simultaneously; those feeling the dynamic feedback interacted more, proportionally

however, the times and distances measured in our field study still lie well within the range predicted by the simulator, highlighting its value for predicting the effectiveness of interactive mobile navigation systems.

4.3.3 Participant observations and feedback

Participant observations confirm a tendency to walk at a steady pace for most of their route, with occasional pauses to check for confirmation at major path junctions. All participants except one enjoyed using the systems and were surprised at their effectiveness despite some initial scepticism. Several participants remarked on the ability to “combine technology and knowledge of the environment to pick the right path” and that as they were in no hurry, it was “good to be able to explore”. Three participants said that they would not use haptics for navigation because they preferred to have constant knowledge of their position and destination. The participant who disliked using the system did not like holding the device constantly, but would have liked to repeat the trial with the device kept in a pocket to be used for occasional route updates. Half of the participants using the dynamic system explicitly commented that they liked the varying feedback, finding it helpful to know when they could take a different route; this seems to be reflected in their route choices. Most participants suggested potential use scenarios for this low-attention method of navigation, ranging from searching for catering venues to simple, low-cost tourist guides.

4.4 Discussion

All participants were able to find an unknown target location with only directional vibrotactile feedback as a guide. The lack of turn-by-turn navigation guidance did not have a noticeable effect on walking behaviour, with brief pauses to check bearings being the only times participants stopped over the majority of routes. Users were required to choose their own route to the goal without a map or turn-by-turn guidance but were able to navigate without needing to stop or backtrack unnecessarily. As can be seen in the walking data (and confirmed by participant observations), users preferred to keep track of the target direction most of the time, but were able to do this casually and without sacrificing attention. While the lack of waypoints might be an issue for navigation over much larger areas, users have

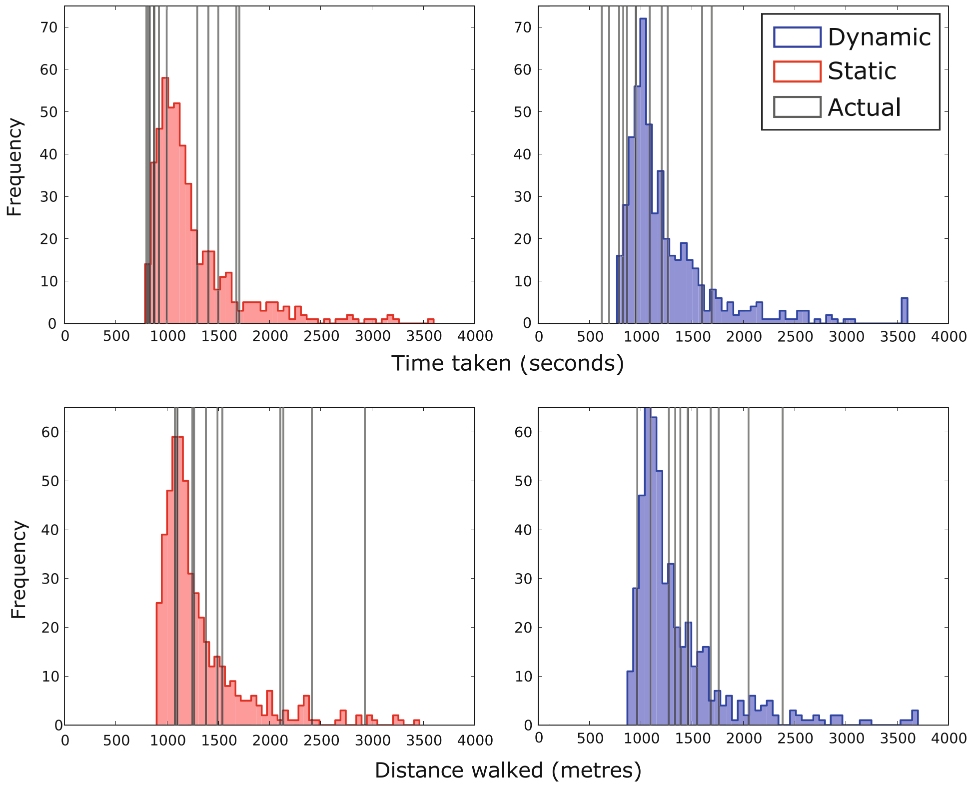

Fig. 4 Predicted times taken and distances walked for each prototype (*shaded areas*; distribution after 500 runs). Actual results are shown as *vertical lines*. The limited pathfinding ability of the simulated agents has caused long tails, but most actual results fall well within the range predicted before the trial

had no trouble selecting appropriate routes over distances averaging at least 1.5 km.

Simulations of user behaviour prior to the trial showed behaviours largely similar to those of actual users, highlighting the benefit of simulations for evaluating mobile device usage. A straightforward reproduction of the study area, combined with a basic model of walking behaviour incorporating the complexities in positional and sensing hardware, has allowed accurate predictions of the results of a real-world field study. Additionally, recent work ([22], for example) has evaluated several aspects of directional vibration for navigation, helping to validate the simulations used here.

The variation in paths between users of the two systems shows interesting behaviours around commonly travelled areas. We aimed to allow users more freedom in route finding while still being able to navigate to a target, and this is evident to some extent in the range of paths taken. Interestingly, many participants chose to follow familiar paths when given the option, though some outliers took the opportunity to explore an area they were not familiar with. Most kept to major paths while in a rural environment, but some (using either system) decided to take more direct routes (over wet parkland) when possible. This is an interesting behaviour, and not an aspect emphasised in our design process, though we suspect that users might prefer actual paths when navigating to self-selected targets. In some cases, these shortcuts have caused the participant to reach a dead end—this is an example of where our design does not offer the precision of a turn-by-turn navigation system. However, even in these cases, users have managed to find the end point with no further assistance.

There is no statistically significant evidence of added costs in user performance while using variable feedback; in fact, on average, users of the dynamic system found the target more quickly and in a shorter distance. The less-precise dynamic feedback did not adversely affect users' navigation abilities, suggesting that this new approach to pedestrian navigation could effectively complement existing turn-by-turn or static haptic methods.

5 Social navigation

Social navigation most commonly refers to shared navigation through digital spaces [23]. Here, though, we consider social navigation applied to *physical* spaces. While maps can offer potential routes and pathways through a location, geolocated social data indicate positions where people have physically been, with quantity as a simple measure of location popularity.

We considered options for taking advantage of the huge quantities of public geolocated social media that are generated and publicly shared each day, worldwide. With the increasing exposure of everyday experiences online, many of the most popular social networking services are adding functionality to allow participants to pair location data with their updates. These location-based updates range in detail from approximate city-level information to precise latitude-longitude co-ordinates, depending on the level of privacy chosen by the poster. Crucially, a large number of the most popular services provide public APIs that allow filtering and retrieval of these social updates by precise location. By retrieving these located posts around a navigating user, we are able to build on our previous social navigation work to construct a social representation of a pedestrian's surroundings: *social navigation*.

While our previous work has used navigation data from co-located users moving in cooperation, our approach here incorporates the location of people external to the navigation process in both location and, likely, time. In a similar way to [15], the thoughts and opinions of strangers who have been (or are currently) in the same location are used to inform the user's behaviour. However, as in our dynamic feedback approach earlier, these shared updates are not presented directly to the user, but instead used to inform them of the variety and diversity in their surroundings.

Naturally, the distribution of social media updates is irregular and unpredictable, often concentrated heavily around popular or built-up places. However, this dispersion gives the approach its value—by constructing several unique views of publicly shared geolocated content, we are able to offer the possibility of custom social tours through public spaces. Choosing pictures might help the user explore the most scenic parts of a park or nature reserve, while the use of social network status updates could hint at the most popular places during a live music festival. Although clearly inferior in absolute accuracy to location maps, we believe that this approach offers particular benefits in those scenarios where maps struggle to keep up with changes in scenery (such as live events) or when context is important and, for example, a person walking alone might take a different route than when walking with friends.

In the following sections, we demonstrate the use of content shared on Twitter and Panoramio[1] for ad hoc estimation of the route variability in a particular location, using both the extent and distribution of social network updates as a proxy for detailed map data. As demonstrated in our previous work [39] and in field trials of the two prototypes described earlier in this article, using simulations for the design and evaluation of interactive mobile systems can be both accurate and reliable. Accordingly, rather than implement physical social media navigation prototypes, we designed simulations of several methods, allowing evaluation of their potential effectiveness without the need for extensive user testing at this early stage.

5.1 System designs

In keeping with the theme of our previous dynamic navigation design, the positions of social media (instead of route possibilities) were used to predict potential paths between the user's current position and the goal (see Fig. 5). Paths that added more than 25% to the direct distance between the navigator and the goal were again discarded. The number of 'routes' from the user's location through each permutation of social media items was used to expand and contract the feedback area, using the same minimum (60°) and maximum (120°) angular widths as previously. In addition, we also took into consideration the distance of the user to the geotagged content in order to prevent, for example, content items clustered around the goal from affecting the apparent path choices throughout the entire journey.

We designed three separate approaches, creating interfaces for each in our simulator. The designs were chosen in order to investigate how different sources and interpretations of dynamic social content might influence the behaviour of pedestrian navigators, helping them explore particular views of their surroundings. Our three designs were as follows:

Nearby social media: Our first design uses the public Twitter API to retrieve status updates posted in the area between the user and their goal. Due to a lack of sufficient real-time social network data in the study area, however, we collected an aggregated record of Twitter posts over a two-week period to give a more accurate picture of the spread of social updates in the area.

Social media hotspots: For the second design, we take the same aggregated Twitter data to estimate route possibilities ahead of the user. However, in this design, we group results into hotspots based on the quantity of updates in a single location. Areas with at least three updates within 100m are considered a cluster; those with fewer are ignored. Using clustered results, rather than every update available, allows us to investigate how the features of the navigation area—in this case, popularity—might be used to aid navigation.

Geolocated images: Our third design uses the Panoramio API to retrieve images in the user's vicinity, rather than social updates, using these in the same way to adjust the width of the feedback area. As geolocated images shared on Panoramio are less time dependent than Twitter updates, there is no need to collect images over a longer period of time; instead, we retrieve images when needed, simulating the possible operation mode of a real-world system.

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[1] http://twitter.com, http://panoramio.com.

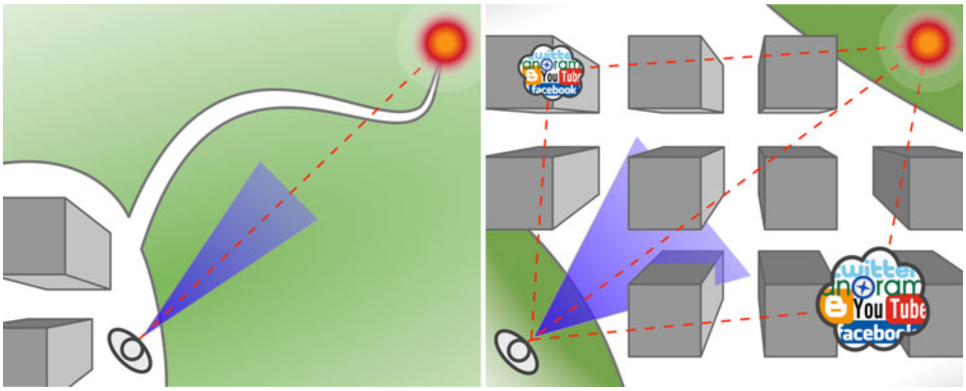

Fig. 5 Our social navigation approach links shared geotagged data to potential route options. When little or no content is available (*left*), the feedback area (shown in *blue*) is small, aiming directly at the goal as in our earlier prototypes. When more content is available (*right*), the feedback area expands to indicate the choice available

5.2 Simulation results and analysis

Five hundred iterations of each of our designs were simulated using the same parameters as used for our initial prototypes (see Sect. 3.2). Although previous results suggested that the simulated walking speed chosen was slightly lower than pedestrians' actual speed (when compared to real-world walking data from the trial), we chose to keep the same 1.0 metre per second (±0.2) to allow comparison between results from both simulations.

Table 1 shows the resulting times taken and distances walked for each of our designs. When comparing with the simulations of our initial prototypes, it is clear that behaviours are similar, indicating that this simple use of geolocated social media updates might be a viable source of 'map' data, especially when location models are not available.

Differences in navigation behaviours are evident when we look in detail at the routes taken by simulated users. Figure 6 shows the paths taken by simulated agents for each social navigation method. When comparing routes in the built-up area, there are few variations between the three designs. However, routes taken in open parkland are clearly more widely distributed. While both clustered and unclustered social media updates have prompted agents to take largely similar routes, the large quantity of images in the open area (resulting in a larger feedback width) seems to have encouraged more variety in navigation.

Table 1 Simulated results for times taken and distances walked for each of the social navigation designs

System	Mean time taken (min)	Distance walked (km)
Nearby social media	21:22 (SD 9:11)	1.36 (SD 0.54)
Social media hotspots	20:09 (SD 7:01)	1.29 (SD 0.40)
Geolocated images	20:48 (SD 7:38)	1.34 (SD 0.45)

5.3 Discussion

The use of public social media updates and shared images shows potential for allowing social navigation of pedestrianised areas, as demonstrated in multiple simulations. The results from simulations of socially influenced dynamic navigation are comparable with those for route-based dynamic navigation, which themselves are comparable to the results from a real-world field study.

Looking more closely at the simulation results, interesting behaviours are evident when considering the source of the geolocated data. In the trial area chosen for our simulation, Twitter postings are most common around built-up areas, while Panoramio images are more widespread in the surrounding parkland. The spread of content, particularly in the open area, seems to have led to more diverse routes. Although this is perhaps a predictable result, it also hints at the potential for automatic off-the-beaten-track tours of both urban and rural areas, augmented with appropriate social media service data, but with no need for manual route generation. Indeed, while our socially influenced navigation designs are, of course, simplistic methods for the estimation of route variation and location popularity, it is relatively easy to create custom views of this content, closely tailored to particular user or organisational needs.

Although in these simulations we used aggregated data, real-time social media retrieval is possible in many of the most widely shared locations, such as busy cities or live events. Indeed, where our approach offers most benefits is in its direct transfer of the social popularity of an area to the device of a pedestrian navigating through it, regardless of the quantity of updates that are being posted. Simple modifications to our methods could use the area maximum to calibrate the local quantity of social updates, providing an instant picture of currently evolving events and helping to alert users to the possibilities around them.

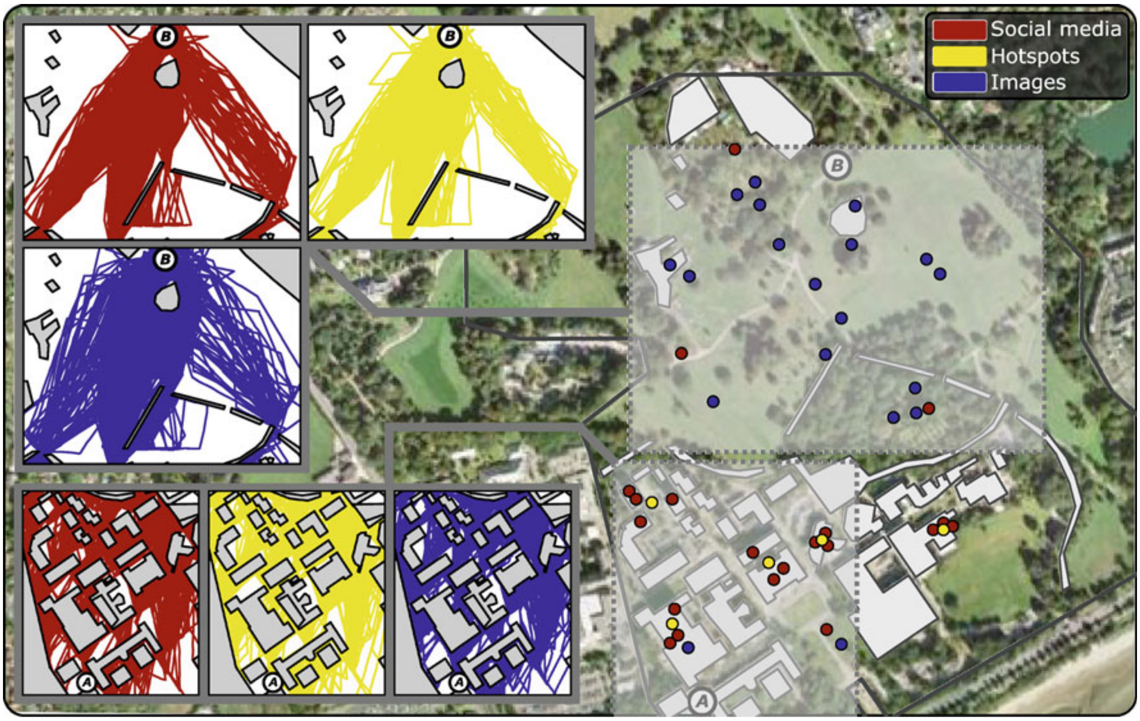

Fig. 6 Simulated social navigation. *Right*: the model of the study area used for simulation, with social media positions *highlighted*. *Inset*: routes taken by 500 simulated agents for each social navigation method. When using the position of images to adjust the feedback, more diverse paths result (*upper left*)

6 Conclusions

In this article, we began by exploring and evaluating the application of active, bearing-based, low-resolution haptic feedback to real-world navigation. The promising results show potential for this type of system in the wild. In our trials, pedestrians using a minimal directional vibrotactile cue successfully navigated to an unknown target while dealing with the complexities inherent in pedestrian navigation. Users were able to maintain a steady walking pace throughout the trial, with negligible affects on their normal behaviour.

Results from our static prototype using fixed-size vibrotactile feedback support those of a similar system [39], and those from a more advanced prototype show the benefits of providing users with alternative path awareness via simple changes to angular feedback. Extending this by simulating the use of geolocated public and social network data as a proxy for route and obstacle models, we have begun to investigate how the use of publicly shared content could allow dynamic navigation personalised to particular needs via a constantly evolving social map.

Future extensions of this work could look more closely at how these social 'maps' might be created, evaluating on a larger scale using real-time social data. Extending this further, incorporation of social data into a real prototype, in conjunction with the dynamic route techniques used in our initial designs, could form the basis for a class of navigation device offering users a choice between the most appropriate navigation methods, allowing exploration if desirable, or waypoint-based shortest-path navigation where necessary.

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