Journal of Assistive Technologies

Presentation of spatial information in navigation aids for the visually impaired

Daniel Innala Ahlmark Kalevi Hyyppä

Peer-reviewed paper

Presentation of spatial information in navigation aids for the visually impaired

Daniel Innala Ahlmark and Kalevi Hyyppä

Daniel Innala Ahlmark is PhD Student and Kalevi Hyyppä is Professor Emeritus, both at the Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Luleå, Sweden.

Abstract

Purpose – *The purpose of this paper is to present some guidelines on how different means of information presentation can be used when conveying spatial information non-visually. The aim is to further the understanding of the qualities navigation aids for visually impaired individuals should possess.*

Design/methodology/approach – *A background in non-visual spatial perception is provided, and existing commercial and non-commercial navigation aids are examined from a user interaction perspective, based on how individuals with a visual impairment perceive and understand space.*

Findings – *The discussions on non-visual spatial perception and navigation aids lead to some user interaction design suggestions.*

Originality/value – *This paper examines navigation aids from the perspective of non-visual spatial perception. The presented design suggestions can serve as basic guidelines for the design of such solutions.*

Keywords *Audio, Haptics, Human-computer interaction, Navigation aids, Spatial perception, Visual impairment*

Paper type *Research paper*

1. Introduction

Assistive technology has made it possible for people with a visual impairment to navigate the web, but negotiating unfamiliar physical environments independently is often a major challenge. Much of the information that provides a sense of location (e.g. signs, maps, buildings and other landmarks) are visual in nature, and thus are not available to many visually impaired individuals. Often, a white cane is used to avoid obstacles, and to aid in finding and following the kinds of landmarks that are useful to the visually impaired. Examples of these include kerbs, lampposts, walls and changes in ground material. Additionally, environmental sounds provide a sense of context, and the taps from the cane can be useful as the short sound pulses emitted enable limited acoustic echolocation. The cane is easy to use and trust due to its simplicity, but it is only able to convey information about ground-level obstacles at close proximity. This restricted reach does not significantly aid navigation, as that task is more dependent on knowledge about things farther away, such as doors in a hallway or buildings and roads. One of the authors has long personal experience of the navigation problem as he has been visually impaired (Leber's congenital amaurosis) since birth.

Many technological navigation aids – also known as electronic travel aids (ETAs) – have been developed and produced, but they have not been widely adopted by the visually impaired community. In order for a product to succeed, the benefit it provides must outweigh the effort and risks involved in using it. The latter factor is of critical importance in a system whose job it is to guide the user reliably through a world filled with potentially dangerous hazards.

Received 24 October 2014
Revised 10 April 2015
Accepted 10 April 2015

This work was supported by Centrum för medicinsk teknik och fysik (CMTF) at Umeå University and Luleå University of Technology – both in Sweden – and by the European Union Objective 2 North Sweden structural fund.

A major challenge faced when designing a navigation aid is how to present spatial information by non-visual means. Positioning systems and range sensors can provide the needed information, but care must be taken in presenting it to the user. First, there is no easy sensory translation from the highly spatial visual sense; and second, the interaction should be as intuitive as possible. This not only minimises training times and risks, but also increases comfort and security.

The purpose of this paper is to review the literature on navigation aids, focusing on the issues of user interaction. The goal is to further the understanding of the qualities navigation aids should possess, and possibly shed light on the reasons for the weak adoption of past and present solutions. To accomplish this, several solutions are presented and discussed based on the interaction modes. There are many solutions not mentioned herein; solutions that employ similar means of interaction to the ones presented were excluded. To aid in the discussion, some background information on how space is perceived non-visually is also presented. The focus for this paper is on the technological aspects, but for technology adoption the socio-economical and cultural aspects are equally important. While the visually impaired are the main target users, non-visual navigation and obstacle avoidance solutions can be of use to sighted individuals, for instance to firefighters operating in smoke-filled buildings.

Section 2 describes the literature selection process. Section 3 contains some background information on non-visual spatial perception. This, together with Section 4 which examines some commercial and prototype navigation aids serve as background to the discussion in Section 5. Lastly, Section 6 concludes the paper with some guidelines on how different modes of interaction could be utilised.

2. Methods

Database searches were made to find relevant literature. Scopus, Google Scholar and Web of Science were primarily used, with keywords such as navigation aids, visually impaired, assistive technology, haptic, audio, speech, blind and user interaction. Articles were then selected based on user interaction. The goal was to have articles representing novel uses of different interaction modes, thus many articles presenting similar solutions were excluded. The purpose was to have literature supporting the later discussion, rather than presenting a comprehensive overview.

As an example, the search string "navigation aid" AND "visually impaired" yielded 41 unique articles in Scopus. Of those, 39 per cent were about algorithms and models and were thus not focusing on user interaction. An equal share (39 per cent) described navigation aids based on audio and 22 per cent used haptics in some form.

3. Non-visual spatial perception

The interaction design of a navigation aid should be based on how individuals with a visual impairment perceive and understand the space around them. A reasonable question to ask is whether spatial ability is diminished in people with severe vision loss. It is not illogical to assume that the lack of eyesight would have a negative impact on spatial ability, as neither sounds nor touch can mimic the reach and accuracy of vision. It is therefore noteworthy that a recent review by Morash *et al.* (2012) on this subject concluded that, on the contrary, the spatial ability of visually impaired individuals is not inferior to that of sighted persons, although it works differently. Another recent study by Schmidt *et al.* (2013), concluded that the mental imagery created from spatial descriptions can convey an equally well-working spatial model for visually impaired individuals. A particularly interesting insight this study provides is that while many blind participants performed worse at the task, those whose performance were equal to that of sighted persons were more independent, and were thus more used to encountering spatial challenges. This suggests that sight loss *per se* does not hamper spatial ability; that in fact this ability can be trained to the level of sighted individuals.

Even though spatial understanding does not seem to pose a problem, a fundamental issue is how to effectively convey such understanding using other senses than sight. The review by Morash *et al.* (2012) concentrates on haptic (touch) spatial perception, presenting several historical arguments on the inferiority of this modality. It has been argued that a prominent problem with haptic spatial perception is the fact that it is an inherently sequential process. When exploring a room by touch, one has to focus on each object in turn. The conclusion was that touch cannot accurately convey the spatial relationships among objects, compared to vision where a single glance encompasses a larger scene with multiple objects. The problems with this argument, as noted in the review, are evident if considering the vastly different "fields of view" provided by touch and vision. When a braille letter (composed of multiple raised dots) is read, it is not a sequential process. There is no need to consciously feel each dot and then elaborately map out the relative positions of those in the mind. Touch is only sequential when considering objects that are too large for its "field of view", just as vision is sequential when the scene is too large for a single glance to contain. In fact, at the higher level of unconscious sensory processing, vision has been shown to be sequential even for a single scene. When looking at a scene, the eyes focus on each object in turn, albeit very rapidly and unconsciously (Martinez-Conde *et al.*, 2004). With vision, the scene is constructed in a "top down" manner, whereas a haptic explorer must build the scene "bottom up" by relating each object to others as they are discovered.

Besides touch, spatial audio is used extensively by visually impaired individuals. The sounds from the environment help with getting the big picture, and can also aid in localisation (Middlebrooks and Green, 1991). Audio is perhaps the closest substitute to vision in that it provides both an understanding of what is making the sound, and where it is emanating from. Unfortunately, the localisation aspect is not that accurate, and a navigation system employing spatial sounds to represent obstacles has to overcome the challenge of user fatigue. Multiple sound sources making noise all the time can be both distracting and tiring. Also, the real environmental sounds should not be blocked out or distorted (Strothotte *et al.*, 1996).

The way visually impaired people perceive and understand the space around them should be taken into account when designing navigation aids. The next section describes some commercial and non-commercial navigation aids that utilise haptics and/or audio.

4. Navigation aids

ETAs come in numerous shapes and sizes ranging from small wearable and hand-held devices designed to accomplish a very specific thing, to complex multi-sensor and multi-interface devices. For the purpose of this paper, the devices presented below are grouped based on how they communicate with the user. An important distinction to keep in mind is that some devices use positioning (such as GPS) while others are obstacle avoidance devices sensing the environment. These two kinds of devices complement each other perfectly, as obstacle avoidance devices do not give travel directions, and positioning devices (typically based on GPS) rely on stored map data that can provide travel instructions, but need to be kept up to date. Further, the GPS system does not work indoors and cannot by itself give precise movement directions relative to the user's current orientation. GPS devices can overcome the latter limitation by incorporating a magnetometer or through utilising the user's direction of motion.

4.1 Haptic feedback

Haptics, being the primary way to explore ones surroundings non-visually, has been difficult to incorporate into navigation aids. The typical manifestation of haptics is in the form of vibration feedback, which is primarily used to convey simple alerts. Examples of navigation aids utilising this kind of feedback include the UltraCane (www.ultracane.com/) and the Miniguide (www.gdp-research.com.au/minig_1.htm). These two devices work on the same principle, but the UltraCane is an extension of a regular white cane, whereas the Miniguide is a complementary unit. Both employ ultrasound to measure the distance to obstacles, and both present this information through vibrating in bursts. The time between these bursts increases as the distance to the measured obstacle increases. This kind of feedback has also been used for route guidance. Ertan *et al.* (1998) used a grid of four-by-four vibration motors embedded in a vest to signal directions. This was accomplished by turning the motors on and off in specific patterns to signal a given direction.

Vibration feedback is limited when it comes to presenting more detailed information. Another option for haptic feedback is to use a haptic interface. These interfaces have been used primarily for surgical simulations, but are more and more used for virtual reality applications and gaming. The Virtual White Cane (Innala Ahlmark *et al.*, 2013) used such a haptic interface to convey spatial information. The system was mounted on a wheelchair and used a laser rangefinder to obtain range data in a horizontal plane of 270° centred in the forward direction. A three-dimensional model was constructed from these data, and the haptic interface was used to explore this model by touch. A field trial concluded that this kind of interaction resembling a white cane was feasible and easy to learn for visually impaired users familiar with the regular white cane.

4.2 Auditory feedback

The most widely used method of conveying complex information non-visually is through audio. Of these, devices based on GPS are the most common ones. Most GPS apps and devices designed for sighted users present information by displaying a map on a screen, and can provide eyes-free access by announcing turn-by-turn directions with synthetic or recorded phrases of speech. Devices specifically tailored to the visually impaired usually rely solely on speech synthesis as output, and buttons and/or speech recognition as input. Efforts have been made to improve the usefulness of this mode of interaction. For example, the Trekker Breeze (http://store.humanware.com/hus/trekker-breeze-handheld-talking-gps.html) offers a "Where am I?" function that describes the current position based on close-by landmarks. Additionally, a retrace feature is provided, allowing someone who has gone astray to retrace their steps back to the intended route. These days much of this functionality can be provided through apps, as evidenced by Ariadne GPS for the iPhone (www.ariadnegps.eu/) and Loadstone GPS for S60 Nokia handsets (www.loadstone-gps.com/). An alternative to speech for route guidance can be found in the System for Wearable Navigation (SWAN) (http://sonify.psych.gatech.edu/research/swan/). The SWAN system uses stereo headphones equipped with a device (magnetometer) that keeps track of the orientation of the head. Based on the relation between the next waypoint and the direction the user is facing, virtual auditory "beacons" are positioned in stereo space.

For obstacle avoidance, Jameson and Manduchi (2010) developed a wearable device that alerts the user of obstacles at head-height. An acoustic warning signal is emitted when an obstacle is sensed (by ultrasound) to be inside a predetermined range. While simple auditory cues are often used, there are exceptions such as The vOICe for Android (www.artificialvision.com/android.htm), which converts images it continually captures from the camera into short snippets of sound. These sound snippets contain multiple frequencies corresponding to pixels in the image.

5. Discussion

Some of the solutions mentioned in the previous section are commercially available, the least expensive being the smartphone apps (provided the user already has a smartphone). Despite this, the adoption of this kind of assistive technology has not been great. Compare this to the smartphones themselves, which are used by many non-sighted individuals. Even touch-screen devices can be and are used by the blind, thanks to screen reader software.

The reason for the weak adoption of navigation aids appears not to have been scientifically investigated. More generally, there seems to be a lack of scientifically sound studies on the impact of assistive technology for the visually impaired. In a 2011 synthesis article by Kelly and Smith (2011) on the impact of assistive technology in education, 256 studies were examined, but only a few articles were deemed to follow proper evidence-based research practices. Going even further in the generalisation, one can find a lot written about technology acceptance in a general sense. Models such as the Technology Acceptance Model (Davis, 1989) are well established, but it is not clear how these apply to persons with disabilities.

Despite the lack of studies on adoption in this specific case, some things can be said based on how individuals with a visual impairment perceive space, and the solutions they presently employ. It should no longer be questionable that non-sighted people have a working world model. It is, however, important to note that this model is constructed differently than that of a sighted individual. It is important to keep this in mind when planning user interaction. For example, consider the "where am I?" function mentioned in the previous section. This function can be more or less useful depending on how the surrounding points of interest are presented. A non-sighted individual would be more likely to benefit from a presentation that reads like a step-by-step trip, as this favours the "bottom up" way of learning about ones surroundings.

Some things can be learnt by comparing the technological solutions to a sighted human being who knows a specific route. This person is able to give the same instructions as a GPS device, but can adapt the verbosity of these instructions based on current needs and preferences. Additionally, this person can actively see what is going on in the environment, and can assist if, for example, the planned route is blocked or if some unexpected obstacle has to be negotiated. All of this is possible with vision alone, but is difficult to replicate with the other senses. Ideally, a navigation aid should have the ability to adapt its instructions in the same way a human guide can.

Most of the available solutions use speech output. This interaction works well on a high level, providing general directions and address information. There are, however, fundamental limitations that speech interfaces possess. Interpreting speech is a slow process that requires much mental effort (Pitt and Edwards, 1996), and accurately describing an environment in detail is difficult to do with a sensible amount of speech (Franklin, 1996). Non-speech auditory cues have the advantage that they can convey complex information much faster, but they still require much mental effort to process in addition to more training. Headphones are typically used to receive this kind of feedback, but they generate their own problems as they (at least partially) block out sounds from the environment that are useful to a visually impaired person. Strothotte *et al.* (1996) noted that many potential users of their system (MoBIC) expressed worries about using headphones for precisely this reason. Complex auditory representations such as used in The vOICe for Android require much training and long-time use is questionable.

Haptic feedback is a promising option as humans have evolved to instinctively know how to avoid obstacles by touch. While the typical vibration feedback widely employed today does not easily convey complex information, it works well in conveying alerts of various kinds. Tactile displays of various kinds are being developed (Rantala *et al.*, 2011; Yamamoto *et al.*, 2006) that could be very useful for navigation purposes. For instance, nearby walls could be displayed in real-time on a tactile display. This would be very similar to looking at a close-up map on a smartphone or GPS device. The usefulness of tactile maps on paper has been studied, with mostly positive outcomes (Espinosa *et al.*, 1998). Even so, the efficiency of real-time tactile maps is not guaranteed.

Interaction issues aside, there are many practical problems that need to be solved to minimise the effort involved in using the technology. In these regards, much can be learnt from the white cane. The cane is very natural to use; it behaves like an extended arm. It is easy to know the benefits and limitations of the cane, and it is obvious if the cane suddenly stops working, i.e., it breaks. This can be compared to a navigation aid, where although it might provide more information than the cane, it requires more training to use efficiently. Additionally, there is an issue of security. It is not easy to tell if the information given by the system is accurate or even true. Devices that aim to replace the white cane face a much tougher challenge than those wishing to complement the cane.

When conducting scientific evaluations, care should be taken when drawing conclusions based on sighted (usually blindfolded) individuals' experiences. While such studies are certainly useful, one should be careful when applying these to non-sighted persons. For example, studies have shown that visually impaired individuals perform better at exploring objects by touch (Vinter *et al.*, 2012) and are better at using spatial audio (Massof, 2003). As a result, one should expect conclusions based on sighted participants' performances to be worse than that of visually impaired persons. Care must also be taken when comparing the experience provided by a certain navigation aid to that of a sighted person's unaided experience. This comparison is of limited value as it rests on the assumption that one should try to mimic the experience of sight, rather than what is provided by sight. This assumption is valid if the user in question has the experience of sighted navigation to draw upon, but does not hold for people who have been blind since birth. The benefits and issues of navigation aids need to be understood from a non-visual perspective. One should not try to impose a visual world model on someone who already has a perfectly working, albeit different, spatial model.

6. Conclusions

The purpose of this paper was to look into the means present solutions employ to present spatial information non-visually. The goal was to suggest some design guidelines based on the present solutions and on how non-visual spatial perception works. A secondary goal was to shed light on the reasons for the weak adoption of navigation aids. While technology adoption has been studied in general, there is a research gap to be filled when it comes to navigation aids for the visually impaired. Though the previous discussion mentioned several issues regarding information presentation, it is not clear if or how these contribute to the weak adoption. Further, there are a multitude of non-technological aspects that affect adoption as well. Looking back only a couple of decades, a central technological issue was how to make a system employing sensors practically feasible. Components were bulky and needed to be powered by large batteries. Today, this is less of an issue, as sensors are getting so small they can be woven into clothes. Even though spatial information can now easily be collected and processed in real-time, the problem of how to convey this information non-visually remains. Many solutions have been tried, with mixed results, but there are no clear guidelines on how this interaction should be done. There are guidelines on how different kinds of information should be displayed in a graphical user interface on a computer screen. Similarly, there should be standardised guidelines on how to convey different types of spatial information non-visually. The primary means of doing this are through audio and touch. Audio technology is quite mature today, whereas solutions based on haptics still have a lot of room for improvement. As audio and touch both have their unique advantages, it is likely they both will play an important role in future navigation aids, but it is not clear yet what kind of feedback is best suited to one modality or the other. A further issue for investigation is how to code the information such that it is easily understood and efficient to use.

Design choices should stem from an understanding of how visually impaired individuals perceive and understand the space around them. From a visual point of view, it is easy to make assumptions that are invalid from the perspective of non-visual spatial understanding. It is encouraging to see studies conclude that lack of vision *per se* does not affect spatial ability negatively. This stresses the importance of training visually impaired individuals to navigate independently.

Below are some important points summarised from the previous discussion:

- Use speech with caution: speech can convey complex information but requires much concentration and is time-consuming. It should therefore not be used in critical situations that require quick actions.
- Headphones block environmental sounds: if using audio, headphones should be used with caution as they block useful sounds from the environment. Bone conduction headphones that do not cover the ears can help when the system is silent, but any audio it emits will compete with environmental sounds for the user's attention.
- Non-speech audio is effective, but requires training: complex pieces of information can be rapidly delivered through non-speech audio, at the cost of more needed training.
- Be careful with continuous audio: continuous auditory feedback can be both distracting and annoying.
- Consider vibrations for alerts: vibration feedback is a viable alternative to non-speech audio as alert signals. More complex information can be conveyed at the cost of more needed training.
- Real-time tactile maps will be possible: tactile displays have the potential to provide real-time tactile maps, but using such maps effectively likely requires much training for individuals who are not used to this kind of spatial view.
- Strive for an intuitive interaction: regardless of the means used to present spatial information, one should strive for an intuitive interaction. This not only minimises needed training, but also the risks involved in using the system. For obstacle avoidance, one should try to exploit the natural ways humans have evolved to avoid obstacles.

- Systems should adapt: ideally, systems should have the ability to adapt their instructions based on preferences and situational needs. The difference in preferences is likely large, as there are many types and degrees of visual impairment, and thus users will have very different navigation experiences.
- Be careful when drawing conclusions from sighted individuals' experiences: when conducting evaluations with sighted participants, one must be careful when drawing general conclusions. Non-sighted individuals have more experience of using other senses besides vision for spatial tasks. Additionally, one must not forget that the prior navigation experiences of non-sighted compared to sighted individuals can categorically differ. In other words, assumptions made from a sighted point of view do not necessarily hold for non-sighted individuals. For these reasons it is important to conduct evaluations with the target users, or when not possible to do so, carefully limit the applicability of conclusions drawn based on sighted (including blindfolded) individuals' experiences.

References

Davis, F.D. (1989), "Perceived usefulness, perceived ease of use, and user acceptance of information technology", *MIS Quarterly*, Vol. 13 No. 3, pp. 319-40.

Ertan, S., Lee, C., Willets, A., Tan, H. and Pentland, A. (1998), "A wearable haptic navigation guidance system", *Second International Symposium on Wearable Computers, 1998. Digest of Papers*, pp. 164-5.

Espinosa, M.A., Ungar, S., Ochaíta, E., Blades, M. and Spencer, C. (1998), "Comparing methods for introducing blind and visually impaired people to unfamiliar urban environments", *Journal of Environmental Psychology*, Vol. 18 No. 3, pp. 277-87.

Franklin, N. (1996), "Language as a means of constructing and conveying cognitive maps", in Portugali, J. (Ed.), *The Construction of Cognitive Maps*, Kluwer Academic Publishers, pp. 275-95.

Innala Ahlmark, D., Fredriksson, H. and Hyyppä, K. (2013), "Obstacle avoidance using haptics and a laser rangefinder", IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), pp. 76-81.

Jameson, B. and Manduchi, R. (2010), "Watch your head: a wearable collision warning system for the blind", *IEEE Sensors*, 1-4 November, Waikoloa, HI, pp. 1922-7.

Kelly, S.M. and Smith, W.D. (2011), "The impact of assistive technology on the educational performance of students with visual impairments: a synthesis of the research", *Journal of Visual Impairment & Blindness*, Vol. 105 No. 2, pp. 73-83.

Martinez-Conde, S., Macknik, S.L. and Hubel, D.H. (2004), "The role of fixational eye movements in visual perception", *Nat. Rev. Neurosci.*, Vol. 5, No. 3 pp. 229-40.

Massof, R.W. (2003), "Auditory assistive devices for the blind", *Proc. Int. Conf. Auditory Display*, pp. 271-5.

Middlebrooks, J.C. and Green, D.M. (1991), "Sound localization by human listeners", *Annual Review of Psychology*, Vol. 42 No. 1, pp. 135-59.

Morash, V., Connell Pensky, A.E., Urqueta Alfaro, A. and McKerracher, A. (2012), "A review of haptic spatial abilities in the blind", *Spatial Cognition and Computation*, Vol. 12 Nos 2-3, pp. 83-95.

Pitt, I.J. and Edwards, A.D.N. (1996), "Improving the usability of speech-based interfaces for blind users", *Int. ACM Conf. Assistive Technologies*, pp. 124-30.

Rantala, J., Myllymaa, K., Raisamo, R., Lylykangas, J., Surakka, V., Shull, P. and Cutkosky, M. (2011), "Presenting spatial tactile messages with a hand-held device", *IEEE World Haptics Conf. (WHC)*, pp. 101-6.

Schmidt, S., Tinti, C., Fantino, M., Mammarella, I.C. and Cornoldi, C. (2013), "Spatial representations in blind people: the role of strategies and mobility skills", *Acta Psychologica*, Vol. 142 No. 1, pp. 43-50.

Strothotte, T., Fritz, S., Michel, R., Raab, A., Petrie, H., Johnson, V., Reichert, L. and Schalt, A. (1996), "Development of dialogue systems for a mobility aid for blind people: initial design and usability testing", *Proc. 2nd Annu ACM Conf. Assistive Technologies*, pp. 139-44.

Vinter, A., Fernandes, V., Orlandi, O. and Morgan, P. (2012), "Exploratory procedures of tactile images in visually impaired and blindfolded sighted children: how they relate to their consequent performance in drawing", *Research in Developmental Disabilities*, Vol. 33 No. 6, pp. 1819-31.

Yamamoto, A., Nagasawa, S., Yamamoto, H. and Higuchi, T. (2006), "Electrostatic tactile display with thin film slider and its application to tactile telepresentation systems", *IEEE Trans. Visualization and Computer Graphics*, Vol. 12 No. 2, pp. 168-77.

About the authors

Daniel Innala Ahlmark graduated from the Master of Science in Computer Science and Engineering Programme at the Luleå University of Technology, Sweden in 2011. He is currently pursuing a PhD degree on the topic of navigation aids for the visually impaired. Daniel Innala Ahlmark is the corresponding author and can be contacted at: daniel.innala@ltu.se

Professor Kalevi Hyyppä received his MSEE from the Royal Institute of Technology in Stockholm, Sweden in 1967. After moving to the Luleå University of Technology in 1975 he developed optoelectronic measurement equipment for industrial use. He received his PhD from the Luleå University of Technology in 1993. He held a position as Professor in Industrial Electronics at the Luleå University of Technology during 2006-2013. His research interests are optoelectronics, power electronics and mobile robots.