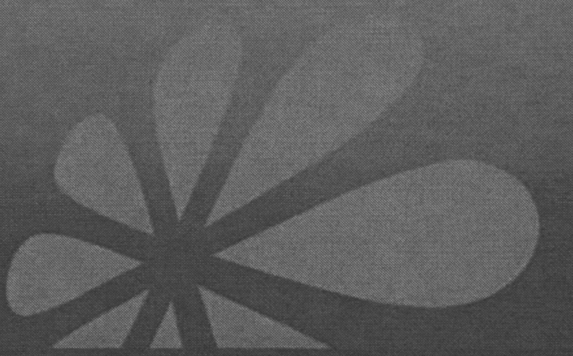

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A laboratory evaluation framework for pedestrian navigation devices

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A laboratory evaluation framework for pedestrian navigation devices

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ABSTRACT

The design of personal mobile navigation devices needs to take into account the context of use, including different types of input in order to react to changing cognitive as well as to haptic constraints. In this work we propose a laboratory evaluation framework for pedestrian navigation devices that aims to maximize the significance of results obtained in a virtual environment for later field usage. In order to increase the degree of physical motion of test users, we have designed a Virtual Environment (VE) with a treadmill-based walking interface. In order to validate our approach we present preliminary results from a study comparing over-ground walking with treadmill walking, which shows the applicability of the treadmill VE. With this work we would like to combine methodologies coming from cognitive psychology with field-study methods often used in user-interface design.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]: Ergonomics, Evaluation/methodology.

General Terms

Human Factors, Experimentation.

Keywords

Evaluation, navigation, mobile devices.

1. BACKGROUND AND MOTIVATION

Usability testing of mobile navigation devices is essential because these services have to be strongly adapted to the needs and abilities of the users. But the dependence of such devices on the context of use creates extra challenges for the effective usability testing. From the psychological point of view recent endeavours have used desktop virtual environment (VE) paradigms to study the essentials of navigation in complex environments (e.g., investigating the question how humans build up representations over time through active exploration, as well as through detailed and multiple perceptual cues) while maintaining control of the environment. Furthermore, interindividual differences in navigation performance (e.g., [14]; [15]; [19]) and the neurological processes of navigation behaviour (e.g., [1]; [4]; [5]; [6]; [12]) have been studied in such paradigms. For example, Moffat et al., [15] administered a VE maze-learning task and confirmed pronounced adult age differences in navigation performance.

However, the question arises as to what extent navigation in VEs simulates real world navigation and supports natural behaviour of the user. Most relevant studies suggest that spatial knowledge acquired in a VE transfers rather well to subsequent navigation in the real world (e.g., [18]; [22]), at least for navigation in spatially simpler environments [17], but there are also important limitations with VE paradigms (see [16] for overview). Clearly, one of the greatest drawbacks of desktop VE paradigms is that they do not require actual movement through space. In fact, self-motion is an important component of navigational place finding (see Lövdén et al. [11]). Additionally, several studies have indicated that cognitive processes and motor functions (e.g. walking) may compete for shared mental resources ([9]; [24]) and thus need to be studies together.

This line of reasoning suggests that field experiments can form a useful alternative when studying novel, variable and less understood situations, such as those involved in mobile devices. There are also various reasons for preferring field situations to laboratory settings. Principally, the difference between use in a laboratory setting and use in the real world can be quite startling, especially for navigation devices that rely heavily on the surrounding environment. Aspects such as lighting levels, weather, the effects of walking, the appearance of landmarks in real life and the effectiveness of location-sensing systems can have unpredictable effects on the usability and effectiveness of a device [3]. But the benefits of field-testing can be offset by limited experimental control: the surrounding environment with dozens of confounding factors may blur the concrete reasons for the findings. Obviously, it is impossible to test several individuals in the same condition.

In the proposed approach to usability testing of pedestrian navigation aids, we want to benefit from both field experiments and laboratory studies that maintain the participants in their everyday situations as close as possible to the real world and at the same time keeping control on experimental and measurement domains, to allow for replication and clean data collection. Our main idea is to use a treadmill combined with a large screen, which provides an immersive VE for the user. In general, this setup allows examination of spatial navigation and the interaction

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with mobile devices while walking. Moreover, the set up can be used to specify and implement psychological criteria for the design of effective assistive technology, with a special focus on different user groups, e.g. younger and older adults.

2. RELATED WORK

A prototype of the treadmill VE was originally designed for a single study [11] in which age-differences in spatial navigation was investigated. Sixteen 20- to 30-year-old and sixteen 60- to 70-year old men were asked to perform a way-finding task in each of several of virtual museums until they reached perfect performance. These virtual museums were generated as an example of an indoor scenario and the map was stored in a matrix format, so that each entry represented a specific type of a corridor part. The way structure was based on the idea of mazes, which means there was only one correct path from the start to the goal. To visualize such kind of virtual museums we implemented a parser to read this map and a tool which extruded it to a 3D-indoor-environment filled with pictures and inventory and saved the generated information in an xml-formatted file. The experimental program written in C was configured to read this xml files and used OpenGL functions to generate the visualization projected in front of the treadmill. Additionally, the program adjusted the speed of the treadmill and synchronized this information with the movement in the virtual environment. Operating two buttons controlled navigation in the virtual environment. The custom-designed button-boxes were either handheld or attached to the handrail. Posture during walking was recorded with a ZEBRIS ultrasound system[1]. The experimental system could send triggers to the capture device to match the posture data afterwards with the captured routes and decisions made by the user.

Another example for a motion-supported test-environment is the lab at the Max Planck Institute in Tuebingen [21]. It features a large curved projection screen. A very fast graphical supercomputer is used to compute highly detailed images that are then front-projected onto the curved projection screen, in stereo if required. For an observer seated in the centre of the cylinder, this image covers a visual angle of 180" horizontal by 50" vertical. Alternatively, experiments can be conducted using a head mounted display or high-resolution computer monitors. Depending on the type of experiment they make use of several interface devices. In driving studies they use a force-feedback steering wheel and simple controls to give the subject a natural interface for driving. The torque exerted at the steering wheel is computer-controlled and is based on a car dynamics simulation. In several of the navigation studies they use a bicycle simulator consisting of a modified exercise bicycle originally. The bike allows one to actively steer and pedal through the virtual city. The bicycle tilts as you steer through the world, just as a real bicycle would do. The design of the bike allows for a realistic simulation of the physical aspects of bicycle riding. For instance, the inertia of the bicycle is simulated by two fly-wheels connected to the pedals. The pedal resistance is computer-controlled and can be used to simulate going uphill or downhill, or driving on roads with different friction coefficients. Finally, for the grasping experiments they make use of a pair of Phantom force-feedback devices. These devices allow them to control the forces present at thumb and index finger when grasping a virtual object. The example shows a relevant approach for experimental testing of navigational tasks, but cannot transfer the needs of a navigation aid supported pedestrian.

Singh et al. [20] propose the use of immersive video, to overcome limitations of applying traditional prototyping and early evaluation approaches to mobile systems, and to capture the sensory experiences that we expect users to be exposed to at locations of deployment of location-based services. By capturing video (imagery and sound) at the site of the intended deployment of a location-based service and simulating the sensor infrastructure, system developers can have ready access (i.e. in their development office) to a high fidelity recreation of a user's experience of using a prototype mobile system on location. The new approach points in an encouraging development to transfer a real scenario into the laboratory setting.

Finally, we will have a look at some examples of field experiments ([2]; [3]; [7]) to evaluate pedestrian navigation devices. They have shown the benefits of tests in real environments, because they can outline the practical problems or limits in the use of mobile devices, e.g. an oral navigational help could be worst in a noisy city. But the significance of measurements is clearly restricted. For example, navigation performance is just based on the time subjects needed to complete a navigation task. At this level of detail it is difficult to assess the navigation performance, because completion time is only an indirect measure for a good navigation performance. Of course, reaching the goal faster is better then walking for hours in an environment. But there could be still differences in the behaviour of users with similar completion times. To compare two users in more detail it is necessary to know what the user did with the navigation device. The design of the navigation aid can force users to stop during the navigation, which in turn could lead to a faster navigation performance after the interaction. We are particularly interested in these trade-offs that are hard to investigate in a field-study.

To recapitulate, an approach for a laboratory framework has to simulate, as good as possible, the real worlds important conditions for a specific task. It is especially important for the evaluation of pedestrian navigation in a lab setting to simulate natural walking behaviour.

3. TEST FRAMEWORK

The concept of the proposed test framework (see Figure 3) consists of:

1. the controller, the core of the experimental program,
2. the visualization engine,
3. the VICON motion capture system.
4. the walking interface,
5. the input interface,
6. the navigation interface, and

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[1] ZEBRIS Medizintechnik GmbH, Isny, Germany

3.1 The controller

The controller (see Figure 3, frame 1) is the main program of the test framework written in Java. It is implemented for the experimental tasks and controls capturing data, mode of integrated navigational help and navigational task. It also holds a map representation of the scene to control and update the interaction and movement of the user. In the running process the controller repeatedly communicates with the visualization engine to update position and view in the visual scene. The implemented interfaces allow the communication with the physical devices integrated in the framework. Additionally the controller stored the captured decisions and walked routes of each user in a database. The synchronization to the gait parameters captured by the separate VICON system is enabled through a trigger process that allows sending start- and stop-commands to the camera system.

3.2 The visualization engine

The virtual environment is now back-projected by means of one or two projectors on a 270 x 200 cm power-wall in front of the treadmill. Usage of two projectors allows for 3D projection.

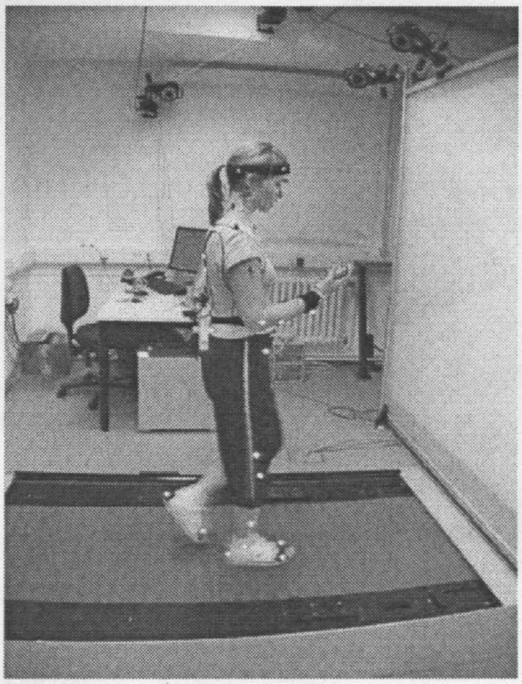

Figure 1. The virtual reality motion lab at the Max Planck Institute for Human Development, Berlin.

The visualization engine (see Figure 3, frame 2) runs on a different computer and communicates with the controller via a network connection. The systems exchange data concerning the changes of the user position and the line of vision. At the beginning of the task the controller loads the desired map and commands the graphical engine to show the corresponding environment on the wall. Afterwards the engine runs in a passive mode controlled through the core of the framework. This is realized as in multi-player game engines which also allow showing the perspective of another player. For recent experiments we are using VEs running on a modified quake engine[2] or other graphical engines[3]. As navigation scenes we are using indoor and outdoor scenarios to represent large buildings like museums or virtual cities or zoos/parks. For future work we are able to use different visualization engines, e.g. video based systems, or to switch to a CAVE environment. The new techniques only needs to adapt to the network interface of the experimental system that controls the movement of the visual flow or rather the virtual position and walking direction of the user in the VE.

3.3 The VICON motion capture system

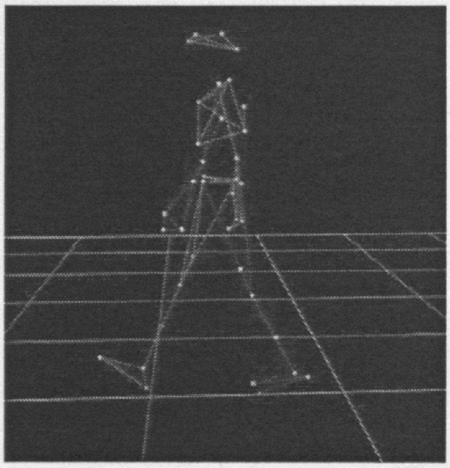

Figure 2. The biomechanical model of the user

The current configuration of the VICON motion capture system[4] consists of 12 infrared cameras that detect up to 41 reflective markers attached to the body of users (see Figure 2). The system is fully functional and allows for whole body motion capturing, advanced biomechanical modeling, and millisecond synchronization with a portable 8-channel EEG/EMG system. The biomechanical model provides a full interpretation of the user's movements, so that the common spatial temporal gait parameters, e.g. step length, step width, velocity, knee angles, cadence, can be analyzed. Furthermore, principle component analysis to characterize the gait in terms of variability, stability or flexibility can be performed.

During testing of navigational devices the motion capture system delivers information how strongly the interaction with the device interferes with walking. Additionally, we can capture numbers and time of user's stops while handling the aid. The camera system also allows personalizing the framework to the user's habits by supporting the adaptive walking speed and capturing gestures for user interaction.

3.4 The walking interface

The walking area of the treadmill (200 x 70 cm) is integrated into the floor (see Figure 1). The treadmill is connected via a serial port to the experimental computer and offers a full functional protocol, e.g. to send and receive speed and acceleration changes. A drawback of the treadmill interface is the limitation in physical turns. To catch this problem we implemented smooth visual turns

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[2] http://www.idsoftware.com/

[3] http://www.ogre3d.org

[4] http://www.vicon.com

to reduce the break between physical and visual feedback. The walking interface (see Figure 3, frame 4) is implemented with the treadmill protocol allowing the controller to synchronize the virtual movement with the speed of the treadmill. So far the participants have shown a good accommodation to the compromise. Despite recent improvements in Virtual Reality technology, there is currently no satisfactory solution available that enables users omni-directional walking.

Before starting an experiment, users needs to go through a familiarization phase in the lab, to identify an individual walking speed that will be used to control the speed of the treadmill and the movement throughout the experiment. To increase the freedom of walking we implemented a first version of an *adaptive* walking interface. This is coupled to the treadmill control and can send or receive among other things speed or acceleration of the treadmill. On the other side it communicates with the real-time module of the VICON system. The real-time module reroutes the captured data online to a network port. The interface reads this port permanently and filters the coordinates of the hip markers. These four markers are good predictors for the global position of the walker. In this approach we are adjusting the speed of the treadmill out of distance to the self-selected walking area. In the initialization phase the user can select a comfortable walking position on the treadmill that will be captured by the cameras and the experimental system defines this position as the new user's origin. To adjust the speed while walking the walking control use a linear function to change the speed and a quadratic function to adjust the acceleration. The implemented mechanism is able to control the treadmill smoothly so that the user is not irritated by a bumpy ground.

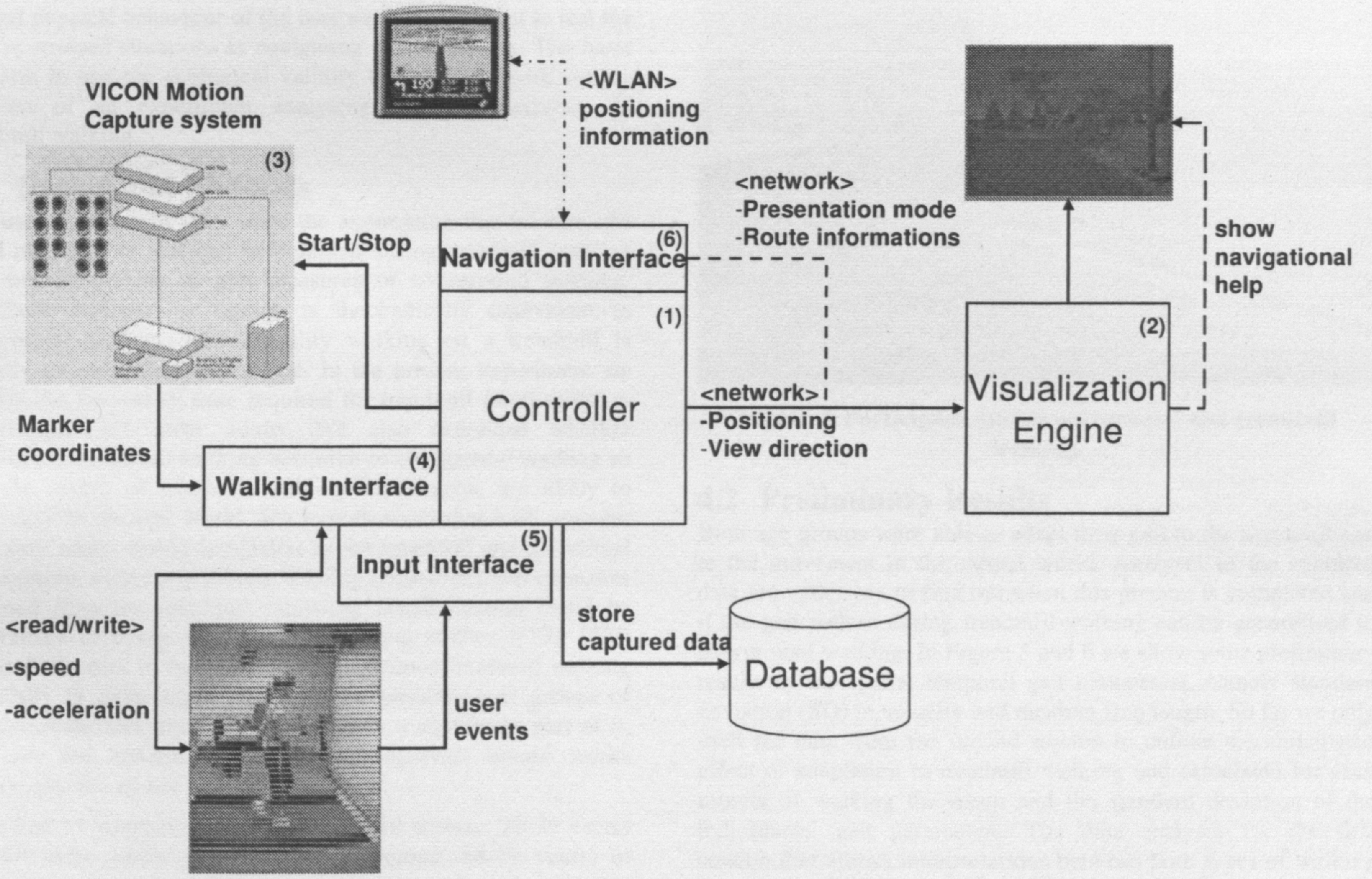

Figure 3. The concept of the test framework

3.5 The input interface

The input interface (see Figure 3, frame 5) processes all kind of usual user inputs, namely key and mouse events. The user interacts with wireless handheld buttons, e.g. to induce a virtual turn in the scene. These buttons based on wireless computer mouse to simplify the interaction with the experimental system. But the input interface is also open to read and analyze events from other input domains like the VICON real-time module or measurement cards.

3.6 The navigation interface

A core feature of the test framework is the integration of navigational aids (see Figure 3, frame 6). Assisting the user in his navigational task can be realized in two different features. For rapid prototyping of navigational help and experiments abstracting from the physical design of assisting device the support is integrated in the virtual environments. In this case the experimental system sends the required information to the visualization engine. The engine can show an additional window with an overview map or integrate arrows or direction lines directly in the scene. The other possible feature loads a network process to communicate with a mobile device, e.g. a PDA, via wireless LAN. Therefore we wrote a simulation program running at the mobile device that builds up a network connection to the navigation interface of the experimental system and presents visual or oral navigational help via the PDA.

4. VALIDATION STUDY

The focus of the laboratory evaluation framework is to support natural physical behaviour of the user and we also want to test the user in stressed situations as navigating while walking. The basic scenario to test the ecological validity of the framework simply consists of an experiment analysing the familiarization to treadmill walking.

4.1 Design and Methods

The use of treadmills rests upon the assumption that reliable and valid measures of gait can be obtained during treadmill walking and are comparable to gait measures of overground walking. Treadmill walking, in theory, is mechanically equivalent to overground walking, but in reality walking on a treadmill is initially an unfamiliar experience. In the present experiment we studied the amount of time required for treadmill familiarisation in younger and older adults. We also examined whether familiarised treadmill walking is similar to overground walking so that the results of treadmill walking experiments are likely to generalize to the real world. We hypothesised that both younger and older adults would familiarise to the treadmill and the virtual environment within one 20-min training session and that measures obtained from the treadmill following familiarization could be generalised to overground walking. Recent studies ([13]; [22]) report difficulties in familiarization to common treadmill walking especially in older adults. Thinking on possible user groups of navigation devices older adults will show a significant part of it, therefore the laboratory evaluation framework should works realistically for all age groups.

We asked 17 younger adults (7 men and 10 women; 20-29 years) and 18 older adults (10 men and 8 women; 68-79 years) to perform an overground walking exercise as well as a treadmill-walking session. Participants had little or no previous exposure to treadmills and were reasonably healthy and fit. In a first session participants walked at self-selected speeds on the 30-m walkway 30 times with whole body motion captured each time over 7,5 m. After each 10 trials there were short breaks. The average preferred speed for each participant across six walking trials was calculated with the captured data. In the second session the treadmill speed was set at the preferred walking speed calculated for each participant. Participants walked freely on the treadmill for 20 min with a virtual environment projected in front of them. Data were captured during the whole trial after the treadmill reached the designated speed.

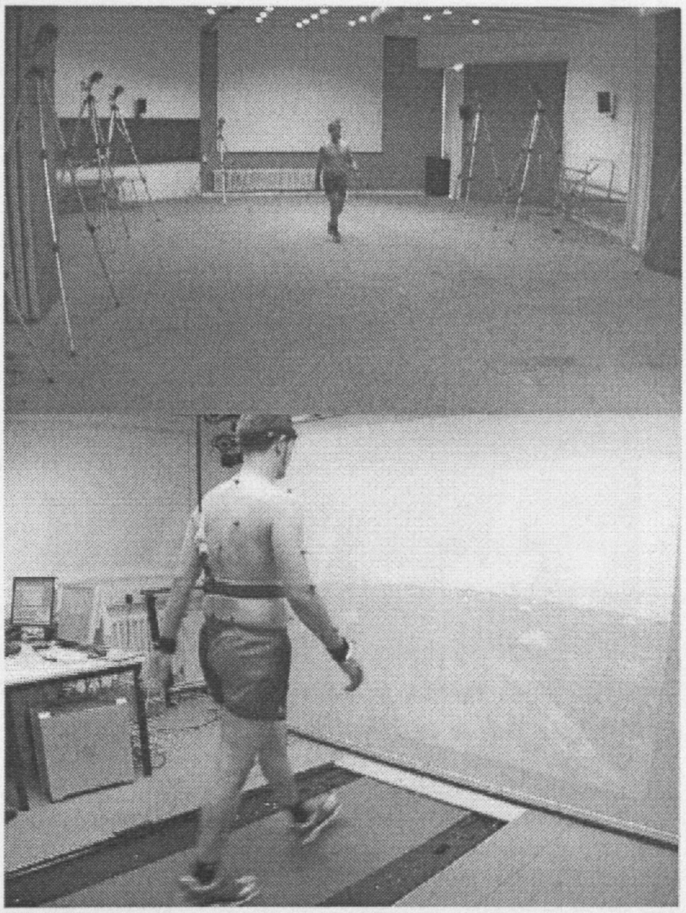

Figure 4. Participant during overground and treadmill walking.

4.2 Preliminary Results

Both age groups were able to adapt their gait to the treadmill and to the movement in the virtual world. Analyses of the captured data are underway to find out when this process is completed and if the gait pattern during treadmill walking can be generalised to overground walking. In Figure 5 and 6 we show some preliminary results of the spatial temporal gait parameters, namely standard deviation (SD) in velocity and mean in step length. So far we only used the data from the second session to outline the anticipated effect of adaptation to treadmill walking and calculated for each minute of walking the mean and the standard deviation of the individuals' gait parameters. The data analyses for the first session that allows interpretations between both types of walking are under their way.

In the figures you can see the averaged values across age group and sex. These data revealed that the participants in each age and sex group produced constant values in the parameters and could reduce the variability after approximately 6 minutes. We can also see a higher variability for the older participants. Especially in the results in velocity, which is strongly connected to the speed of the treadmill, we can directly interpret the standard deviation of the velocity as the individuals' success to adjust the actual walking speed to the given speed of the treadmill. Thus, a decrease in the variability represents an increase in the synchronisation to treadmill walking. For the generalisation to overground walking we can suggest out of the observations that the participants will not show necessarily identical gait measures, e.g. exactly the same step length in both condition, but there exists a trend that the gait characteristics, e.g. the variability or stability in walking, and afterwards the effects of additional tasks as using a navigational aid in gait pattern are comparable to real world walking. Thus, the study confirms the ecological validity of the test framework concerning walking.

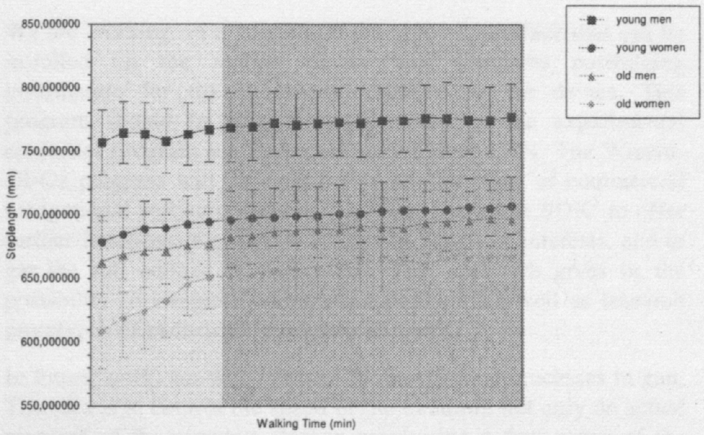

Figure 5. Characteristics of steplength during treadmill walking.

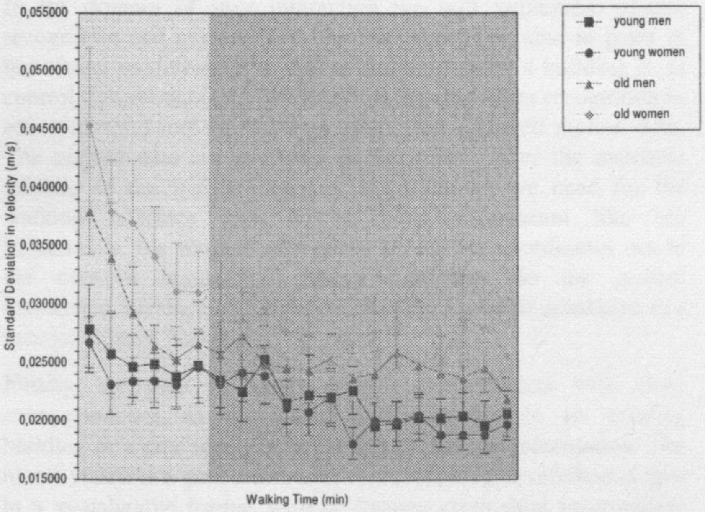

Figure 6. Characteristics of the SD in velocity during treadmill walking.

5. A CASE STUDY

In order to provide an idea how an evaluation of a mobile guide could be realised with the treadmill VE, we will now describe a concrete case study. The goal of the case study is to investigate user behaviour while using a mobile device as a guide in a museum. The scenario can be generated as a fictive gallery or as clone of existing museum that is afterwards the field of application for the guide. The nature of the visitors can vary a lot but we can over-simplify and group participants by sex, age and the level of familiarity to the museum. To start experiments we have to import the map of the museum in the "controller" of the experimental system with additional knowledge of points of interests and of open areas in which the user are allowed to go through. In this scenario the mobile guide can reduced to the original user interface. The information about the different exhibits will support by the controller and send to the mobile device using the wizard process. The simulation program will present the information or navigational help in the future phase (see Figure 7).

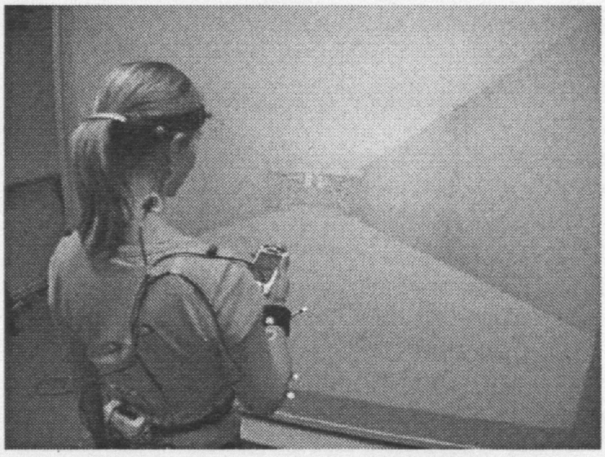

Figure 7. Participant with a mobile guide in a virtual gallery.

Now the experimenter is able to configure the test framework for different tasks for each group, for example: Have a walk through the museum in your preferred speed and look at all paintings of van Gogh. The user starts the test by slowly begin to walk, so that the walking interface can adjust the preferred speed. The turns within the VE are actually induced by wireless buttons, but during the use of the PDA, we would simulate the interaction in the way that the experimenter will decide based on speech commands of the participant. During testing the system can track the routes that the participants took. By means of the motion capture system we will capture not only the walking behaviour but also other movements while interacting with the mobile guide. Concerning the gait data, we are able to analyse the effects of the system in gait pattern, e.g. if the user always pauses while looking at the device to brief himself on the direction, we could assume that this user is overtaxed by the device and we have to refine the guide. Other movements such as the coordination between head and arm to use the guide can also outline problems in the design, e.g. if signs are not distinguishable or text information are too small, the user will hold the device closer to the field of view and will retain the focus for a longer time. After this pre-testing we will run some testing within the real museum using the developed mobile guide and go back if something happens what we couldn't track in the real world.

6. FUTURE WORK

In an upcoming experiment we will require both young men and older men to find a goal in several environments with different navigational help (no support, virtual guide and map support) and capture their gait pattern by the motion capture system to show positive as well as negative effects on their gait. The resulting knowledge about the interaction between walking stability and cognitive load in old age may serve to improve the adaptive capacities of mobile systems.

Furthermore we will extend the features of the test framework concerning:

- the integration of mobile devices to commercial navigation assistant devices,
- the adaptive walking interface,
- the user interaction, and
- video based representation of the environment

We are working on a Wizard-Of-Oz type of interface that can be installed on the mobile device and simulates positioning information for the application running on the device. This program should be able to communicate to the experimental controller program via Bluetooth or Wireless LAN. The Wizard-Of-Oz program will be extended to the interface of commercial navigational software like the TomTom Navigator SDK[5] to offer further functions, e.g. define Routes or points of interests, and to get the full control of the device. This approach gives us the possibility to integrate commercial products as well as research prototypes of pedestrian navigation devices.

In future work, we will evaluate biomechanical processes in gait. The idea is to control the speed of the treadmill not only on actual postures of the user but also on monitoring a time range of the user's gait. In this case we will be able to predict the actual speed based on gait parameters like gait cadence and movements in knees and feet.

In the domain of user interaction we will implement speech recognition and gesture. E.g. the user should be able to point in the virtual environment to get information about a building or to control turn movements. We are working on pattern recognition in arm and hand movements concerning the captured motion data. The needed data are available during testing over the real-time module of the VICON system. Even though we need for the walking interface only lower body information like hip movements, the module is writing all marker coordinates out to the network connection during capturing. So the gesture interaction interface and walking interface could be combined to a general gesture interface.

Finally, we plan to design virtual environments with close correspondence to real-world environments, as an existing building or a city scenario, including contextual information. The nicest vision is a generation tool to transform geo-referenced data in a visualizable format without loosing contextual information. But as it is mentioned in Singh et al. [20] all these techniques are very work and time consuming, therefore we will also follow the idea of a video based representation of the scene and try to combine this visual input with the proposed motion and interaction devices.

7. CONCLUSION

In this paper, we proposed the approach using virtual environments equipped with a walking interface and a motion capture system to transfer a real navigation scenario in a controlled setting. We described the technical features and the potential of the framework to evaluate pedestrian navigation devices in the benefit of navigation performance and effects of the user's motion. Finally, we have shown in the validation study that this test framework allows persons to walk as common.

8. REFERENCES

[1] Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A.,Newman, E. L., & Fried, I. (2003). *Cellular networks underlying human spatial navigation.* Nature, 425, 184–187.

[2] Goodman, J., Gray, P., Khammampad, K. and Brewster, S. (2004). *Using landmarks to support older people in navigation.* In Proceedings of Mobile HCI 2004, Springer, LNCS 3160, 38-48.

[3] Goodman, J., Brewster, S. and Gray, P. (2004). *Using field experiments to evaluate mobile guides.* In K. Cheverst and B. Schmidt-Belz (eds), Proceedings of Mobile Guides, Workshop at Mobile HCI 2004.

[4] Grön, G., Wunderlich, A. P., Spitzer, M., Tomczak, R., & Riepe, M. W. (2000). *Brain activation during human navigation: Gender differential neural networks as substrates of performance.* Nature Neuroscience, 3,404–408.

[5] Hartley, T., Maguire, E. A., Spiers, H. J., Burgess, N. (2003). *The well-worn route and the path less traveled: Distinct neural bases of route following and wayfinding in humans.* Neuron, 37, 877–888.

[6] Janzen, G., & van Turennout, M. (2004). *Selective neural representation of objects relevant for navigation.* Nature Neuroscience, 7, 673–677.

[7] Krüger, A., Ilhan, A., & Zimmer, H. D. (2004). *The Effects of Mobile Pedestrian Navigation Systems on the Concurrent Acquisition of Route and Survey Knowledge.* In Proceedings of Mobile HCI 2004, Springer, LNCS 3160, 446-450.

[8] Laurance, H. E., Thomas, K. G. F., Newman, M. C., Kaszniak, A. W., Nadel, L., & Jacobs, W. J. (2002). *Older adults map novel environments but do not place learn: Findings from a computerized spatial task.* Aging, Neuropsychology, and Cognition, 9, 85–97.

[9] Li, K. H. Z., & Lindenberger, U. (2002). *Relation between aging sensory/ sensorimotor and cognitive functions.* Neuroscience and Biobehavioral Reviews, 26, 777–783.

[10] Lindenberger, U., & Lövdén, M. (2006). *Co-constructing human engineering technologies in old age: Lifespan psychology as a conceptual foundation.* In P. B. Baltes, P. Reuter-Lorenz, & F. Rösler (Eds.), Lifespan development and the brain: The perspective of biocultural co-constructivism (pp. 350-375). New York: Cambridge University Press.

[11] Lövdén, M., Schellenbach, M., Grossmann-Hutter, B., Krüger, A., & Lindenberger, U. (2005). *Environmental topography and postural control demands shape aging-associated decrements in spatial navigation performance.* Psychology and Aging, 20, 683-694.

[12] Maguire, E. A., Burgess, N., Donnett, J. G., Frackowiak, R. S., Frith, C. D., & O'Keefe, J. (1998). *Knowing where and getting there. A human navigation network.* Science, 280, 921–924.

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[5] http://www.tomtom.com/pro

[13] Matsas, A., Taylor, N., & McBurney, H. (2000). *Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects.* Gait & Posture, 11, 46-53.

[14] Moffat, S. D., Hampson, E., & Hatzipantelis, M. (1998). *Navigation in a "virtual" maze: Sex differences and correlation with psychometric measures of spatial ability in humans.* Evolution and Human Behavior, 19, 73–87.

[15] Moffat, S. D., Zonderman, A. B., & Resnick, S. M. (2001). *Age differences in spatial memory in a virtual environment navigation task.* Neurobiology of Aging, 22, 787–796.

[16] Peruch, P., & Gaunet, F. (1998). *Virtual environments as a promising tool for investigating human spatial cognition.* Current Psychology of Cognition, 17, 881–899.

[17] Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). *Spatial knowledge acquisition from maps and from navigation in real and virtual environments.* Memory & Cognition, 27, 741–750.

[18] Ruddle, R. A., Payne, S. J., & Jones, D. M. (1997). *Navigating buildings in "desk-top" virtual environments: Experimental investigations using extended navigation experience.* Journal of Experimental Psychology: Applied, 3, 143–159.

[19] Sandstrom, N. J., & Kaufman, J., & Huettel, S. A. (1998). *Males and females use different distal cues in a virtual environment navigation task.* Cognitive Brain Research, 6, 351–360.

[20] Singh, P., Ha, H.N., Kwang, Z., Olivier, P., Kray, C., Blythe, P. & James, P. (2006). *Immersive Video as a Rapid Prototyping and Evaluation Tool for Mobile and Ambient Applications.* In Proceedings of MobileHCI' 06, Espoo, Finland, September 2006.

[21] van Veen, H., Distler, H., Braun, S., & Bülthoff, H. (1998). *Navigating through a virtual city: Using virtual reality technology to study human action and perception.* Future Generation Computer Systems, 14, 231–242.

[22] Wass, E., Taylor, N., Matsas, A. (2005). *Familiarisation to treadmill walking in unimpaired older people.* Gait & Posture, 21, 72-79.

[23] Witmer, B. G., Bailey, J. H., Knerr, B. W., Parsons, K. C. (1996). *Virtual spaces and real world places: Transfer of route knowledge.* International Journal of Human-Computer Studies, 45, 413–428.

[24] Woollacott, M., & Shumway-Cook, A. (2002). *Attention and the control of posture and gait: A review of an emerging area of research.* Gait and Posture, 16, 1–14.