TANGIBLE ACTIVE OBJECTS AND INTERACTIVE SONIFICATION AS A SCATTER PLOT ALTERNATIVE FOR THE VISUALLY IMPAIRED

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ABSTRACT

In this paper we present an approach that enables visually impaired people to explore multivariate data through scatter plots. Our approach combines Tangible Active Objects (TAOs) [1] and *Interactive Sonification* [2] into a non-visual multi-modal data exploration interface and thereby translates the visual experience of scatter plots into the audio-haptic domain. Our system and the developed sonification techniques are explained in this paper and a first user study is presented.

Index Terms— Exploratory Data Analysis, Scatter Plots, Sonification, Tangible Active Objects, Tangible Interaction

1. INTRODUCTION

Nowadays in the information age, data visualizations are omnipresent. Not only scientists use visualizations, also in everyday life visualizations become more and more important to convey complex information. A variety of visualization techniques have been developed to provide possibilities to explore and understand all kinds of data. Many of these methods address our visual modality, e.g. graphs, diagrams, and plots. Obviously, the visually impaired cannot use these visualization techniques. Therefore different methods have to be developed to allow alternative data exploration, e.g. by using auditory or haptic displays.

Visualization refers not only to visual data representations, but more generally to an abstract concept to convey information about data in different modalities or even in multi-modal manner. Thereby also haptic, auditory approaches and methods using other modalities or combinations of them are visualizations, too. Generally visualization comprehends methods that create a mental representation of the visualized data in the experiencing persons mind [3]. However "perceptionalization" is a term that makes this breadth more obvious.

Because haptic and auditory display methods require a longer time for the user to actively acquire an overview of the represented data, interaction with the data representation system is important. The possibility of actively changing the rendering parameters through interaction allows the users to get an all-embracing overview of the underlying data. Interacting with data representations allows users to explore the kind and characteristics of data. Tangible User Interfaces (TUIs) specifically use physical objects as representatives to give the user that data at hand. This allows to explore the data with our everyday manual interaction skills in a bi-manual and parallel manner. Our Tangible Desk (tDesk) (formerly known as the Gesture Desk [4]) is a typical table-top TUI. In different applications, such as AudioDB [5], TI-Son [6], Tangible Data Scanning (TDS) [7], and AmbiD [8], etc. passive Tangible User Interface Objects (TUIOs) were used. The TUIOs, used in these applications are optically tracked by a camera. By interacting with these TUIOs, the user can directly interact with the represented data.

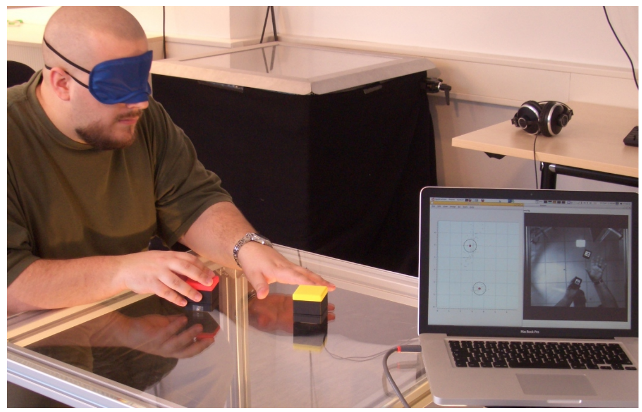

Figure 1: Blindfolded user interacting with the IAS at the tDesk. The laptop shows the computer vision module and the clustering of the data (here the Iris Dataset [21] was clustered in two clusters) with a TAO for each cluster prototype.

We here start with such a Tangible Interaction system and extend it with active feedback capabilities, allowing the objects to move actively on the table surface. In addition we use Interactive Sonification [2], defined "as the use of sound within a tightly closed human–computer interface where the auditory signal provides information about data under analysis, or about the interaction itself, which is useful for refining the activity." In our approach, we combined TAOs and Interactive Sonification to create a novel data exploration interface for the visually impaired.

Compared to the research field of visual data analysis techniques, the field of non-visual techniques for multivariate data analysis is still quite sparse. Most multivariate data are collected in tables of numbers which are often visualized using scatter plots.

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1.1. State of the art

We briefly review different non-visual methods to represent data, focusing on haptic, auditory and combined perceptionalization approaches. The Sonic Scatter Plots [9] are an approach to sonify multivariate data. Since "notes can also be plotted in time", here the data are seen as a score, where one dimension is scaled and interpreted as time. Then every data-point is interpreted as one note and the different characteristics of the notes are controlled by data values. The work of Sarah Bly [10] and John Flowers [11] on multivariate data mappings and auditory scatter plots are seminal to the topic. Another related application is the TDS [7]. "A sonification model following the Modelbased Sonification approach that allows to scan high-dimensional data distributions by means of a physical object in the hand of the user" is developed in this paper. Therefore a virtual plane is linked to one TUIO, that can be moved through the data space. A Model-Based Sonification (MBS) is triggered each time the plane crosses a data point, whereby the user can interactively explore the data distribution.

Panëels and Roberts [12] provide a comprehensive review of designs for Haptic Data Visualization (HDV). They propose a taxonomy of seven categories: Charts, Maps, Signs, Networks, Diagrams, Images and Tables. Unfortunately the authors did not find a haptic translation for scatter plots, but they present techniques, that could be used for scatter plots, as well. Interpreting scatter plots as height-fields, e.g. the Nanomanipulator [13] could be adapted. Further more image translation techniques, such as proposed in [14] can be used to transfer scatter plots into the haptic domain.

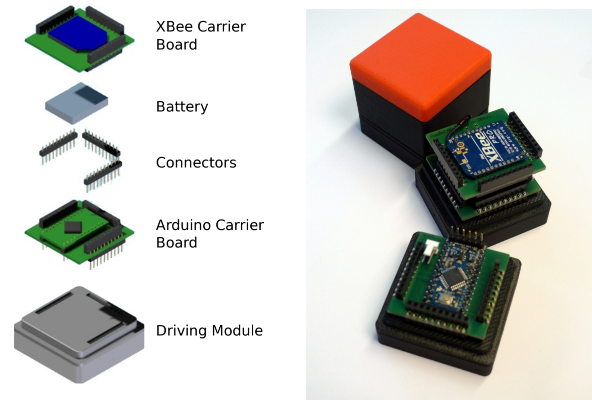
We introduce the combination of TAOs and Interactive Sonification as an alternative to visual scatter plots. The paper is organized as followed: We give an introduction to the TAOs, our novel tangible interfaces used in our system. We describe two different new sonification approaches and their implementation. Furthermore we present the system design, the hardware components and basic ways of interaction. A short study and evaluation is presented, followed by the discussion of results and our conclusion.

2. TANGIBLE ACTIVE OBJECTS

Most Tangible User Interfaces (TUIs) use passive objects that offer no active feedback. Active feedback refers to the ability to actively influence the interaction by e.g. changing the object's position or orientation, or multi-modal feedback via the haptic, auditory, or visual modality, etc. In our present work we develop a swarm of TAOs, capable of different kinds of feedbacks [1].

2.1. Hardware

The hardware assembly of our Tangible Active Objects (TAOs) is depicted in Fig. 2. The TAOs are built in different modular Printed Circuit Boards (PCBs) that fit into custom layers, compatible to TUImod [15], modular building blocks for TUIOs. These PCBs are connected over simple vertical buses to make them flexibly extensible. Our current TAOs are configured as small mobile robots, but it is also possible, to equip them with a display, buttons, or loud speakers. The mobile configuration consists of a driving module, the control module with additional connectors and batteries, and a wireless communication module. The driving module is a simple differential drive, which means that two motors drive two wheels on the same rotational axis independently. Thereby it is possible to drive the TAO continuously from in-place rotation to



(a) Exploded assembly drawing (b) Manufactured devices at different stages of assembly (without batteries)

Figure 2: Hardware architecture

straight forward or backward linear movement. The control module is the core of each TAO. It holds an Arduino pro mini [16], a community-based rapid prototyping microcontroller platform, often used for physical computing approaches. This microcontroller is programmed with the SerialControl firmware [17], which allows to receive commands over the wireless communication module and to control the connected in- and output componentes, in this case the driving module. The wireless communication module is based on an XBee module, which is configured to work in a star-network together with other modules. One XBee module is serially connected to the host computer and spreads the remote control commands into the network. Each TAO has its own ID and only reacts on commands starting with this ID. This allows to control each TAO independently. Additionally, each TAO is equipped with a visual fiducial marker, which is based on the tracking algorithm of the Reactable [18], but we use a new marker set which was especially designed for the TAOs.

2.2. Software architecture

The TAOs are remote controlled by a host computer, where a dynamically extensible software framework controls each TAO and the sonification of the IAS. Fig. 3 depicts the different cooperating modules. All modules are implemented as stand-alone processes which communicate over the XML enabled Communication Framework (XCF) [19]. The Computer Vision module (1) tracks the TAOs' position and orientation in the camera image. These data are spread into an ActiveMemory server, which is part of the XCF and runs transparently in the background. Several other modules subscribe on the content of this information stream, such as the Path Planner module (2) and the IAS application (3). The Path Planner module reacts also to XCF messages that invoke navigation tasks. Based on the position and orientation of the TAOs and the new target positions from the navigation query, the Path Planner calculates trajectories for each moving TAO, based on a potential field approach [20] and transmits control commands that make the TAOs move to the new targets. To transmit these commands, the XCF2Serial module (4) listens for these commands in the XCF stream and relays them to the serial port of the host computer where an XBee module (5) broadcasts the commands to the wireless network and to the TAOs (6).

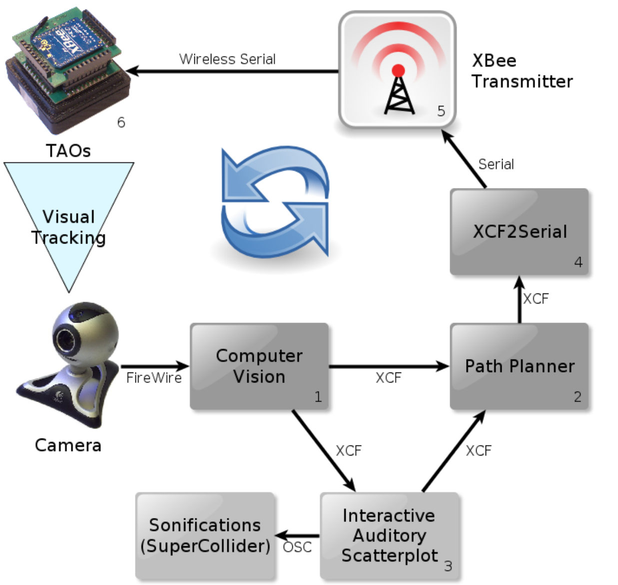


Figure 3: Software architecture. Modules (1) - (6) are explained in 2.2

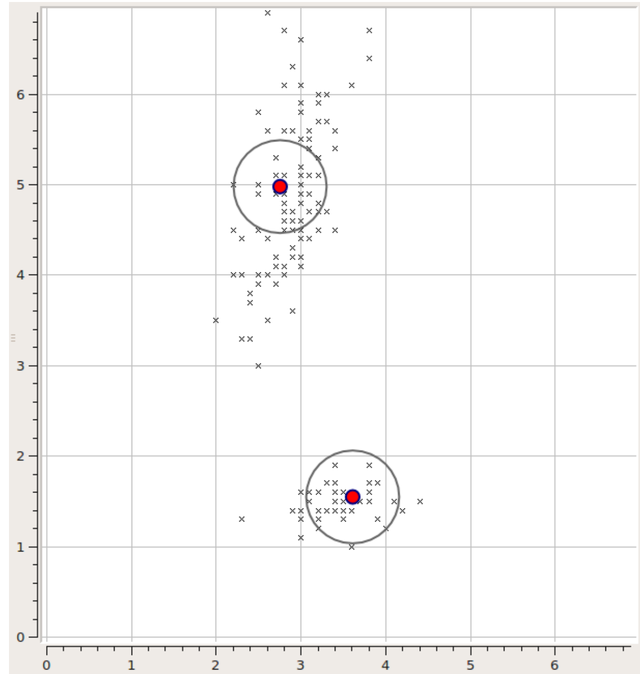


Figure 4: Two TAOs representing prototypes of clusters (detail screenshot from the application module). Here the Iris Dataset [21] was used for the visualization.

3. DESIGN: INTERACTIVE AUDITORY SCATTER PLOT

Clustering is the most basic structure of data distributions. Clusters are groupings of data at certain locations in data space as shown in Fig. 4. The TAO-based Interactive Auditory Scatter Plot (IAS) is currently designed to enable and assist the understanding of clustering structure without the need of any visual display. It is implemented as a special application module for the TAO architecture.

3.1. Ideas and concepts

We created a direct two-dimensional transformation of the spatially distributed data into the audio-haptic domain to allow visually impaired people the exploration of scatter plots. Since we have a limited number of K TAOs, which should become graspable anchors of the data, we first need a method to find K representative locations. Vector quantization with the K-Means algorithm is an appropriate starting point for this.The TAOs move autonomously on the table to the cluster centers and represent them as prototype objects. Thereby the visually impaired user is enabled to explore roughly how the data is organized. Each TAO can then be used to examine how the data are distributed in detail: By moving a TAO, a sonification is excited that perceptualizes local characteristics of the data distribution. Furthermore, releasing an object triggers a local data sonogram after which the object moves back to its anchor position, as explained in detail in Sec. 4. During interaction, the user can thereby construct a mental model of the spatial data distribution and clustering structure.

3.2. Hardware setup

The hardware basis of our system is the tDesk, which is a redesign of the Gesture Desk, introduced in [4]. On a 70 × 70 × 70 cm cube of aluminum profiles lies a glass surface. A FireWire camera which is mounted underneath this surface looks upwards to the table's surface to track the TAOs position on the table. The tracking area on the table is marked with black tape. The speakers with its sound interface and the camera are connected to the host computer together with the XBee transmitter for the wireless communication.

3.3. Interaction design

As depicted in Fig. 5, we subdivide interaction into three different parts: The first part uses the TAOs as haptic representations of data clusters. By touching the table surface and the TAOs, the user can gain a rough idea of where interesting data are located. The user can then move any TAO, which excites a sonification of the local density and can thereby continuously explore how the data is distributed in the vicinity of a cluster. The third interaction type is to release a TAO. This triggers a local data sonogram, yielding an audible spherical sweep through the data space at the location of the TAO. Afterwards the TAO moves back to its cluster center.

4. SONIFICATION METHODS

We integrated two different sonification approaches into our system using SuperCollider for the implementation [22]. The first is a parameter mapping-based approach, where the local density of the data is mapped directly to parameters of a continuous sonic stream.

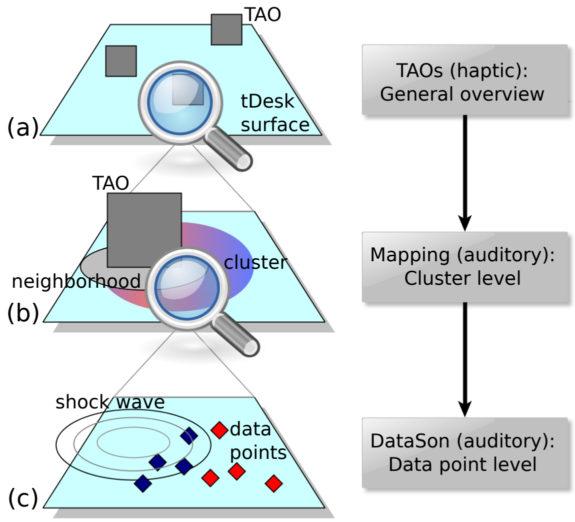


Figure 5: Levels of detail in the IAS (The stylized cluster and data points are only depicted for better understanding of the picture; They are not visible to the user of our system.)

The second approach uses a Model-Based Sonification (MBS) approach to communicate more detailed characteristics of the underlying data [23, 24, 25].

4.1. Parameter mapping-based sonification for IAS

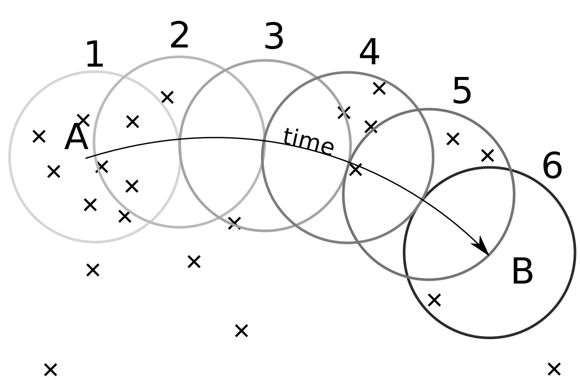


Figure 6: Mapping: The circles depict the neighborhood of TAOs. Moving a TAO from A to B results in a continuous sonification of the data density as pitch of a continuous sound stream.

In our first sonification approach, a simple mapping of the local data density controls a continuous sonic stream. When moving the TAO at position $\vec{x}$, the number of data points N in the neighborhood of an adjustable radius r around the TAO is mapped to the frequency of an additive synthesis using

$$f[Hz] = f_0 \cdot 2^{\alpha N(\vec{x},r)}. \quad (1)$$

This leads to a pitch increase of an octave if $N \rightarrow N \cdot \frac{1}{\alpha}$. Fig. 6 explains this simple mapping approach. This sonification is automatically activated whenever a TAO is moved by the user. The sound is generated at constant amplitude. At the moment of releasing the TAO, the data sonogram sonification is triggered as explained next.

4.2. Local data sonograms

Releasing a TAO after moving it around excites a local data sonogram [23] at the TAOs location to provides a detailed inspection into the spatial data distribution. For this a virtual 'shock wave' emanates from the the TAO's location to the border of the neighborhood. Whenever this wave crosses a data point, a virtual spring connected to the data point is excited to oscillate, which generates audible sound, as depicted in Fig. 7. This local data sonogram approach was introduced in [23] and generalized to Multi-touch interactions in [26]. However multi-touch enabled visual display are unfortunately unsuitable for the visually impaired so that our extension to graspable interfaces makes data sonograms for the first time usable for visually impaired users.

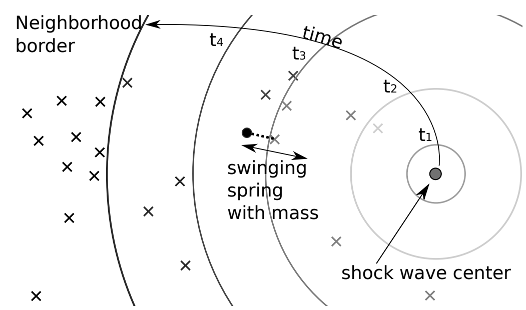


Figure 7: Data sonograms: A virtual shock wave is evoked at the location where the TAO is released and expands in circles until it reaches the border of the TAO's neighborhood. Data points are excited by the shock wave front and thereby contribute to a spacial sweep.

5. INTERACTION EXAMPLES AND FIRST EXPERIMENTS

A basic demonstration of our system is provided at our website[1]. The introduction video shows a user interacting with the system and presenting each of the three interaction stages. The video shows that the system basically works as intended. Our interpretation is that this system is well capable of allowing visually impaired or blindfolded people to understand scatter plots without seeing. In the paper we present results of a first qualitative and quantitative study.

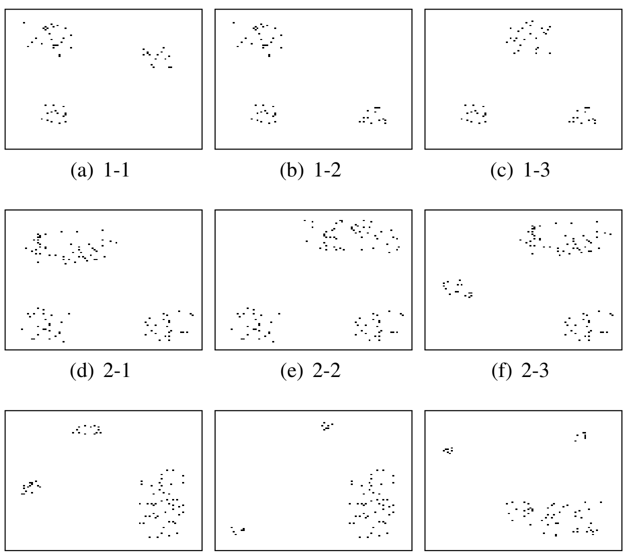
5.1. First experiment: the blind herder

In our first study we wanted to learn in how far our approach can be used as an alternative to the classical scatter plot. Basically we wanted to know if IAS users are able to recognize the same visual plot from a list of slightly different candidates. This can be tested by showing to the users the pictures of different classical scatter plots including the one, the user just explored with the IAS and asking to choose the one they think they just have explored.

[1] see http://www.techfak.uni-bielefeld.de/ags/ami/publications/RHR2010-TAO/ for the video

Because not all subjects were familiar with the concept of scatter plots and clusters, we created a metaphoric story called "the blind herder": The subjects were told to think of the tDesk's surface as the grazing land of three herds of animals. The subjects had to discover the distribution of the animals by interacting with the system.

The subjects have to complete different tasks with the system. In the first task, the sighted but blindfolded subjects have to explore a certain IAS until they subjectively have acquired an understanding of the data distribution. For this task there is no time limit, but the time needed is recorded for later evaluation. As test distributions simple synthetic datasets were created that all show three easily distinguishable clusters of data points at different positions, and of different shapes and sizes. Three sets with three datasets were generated (see Fig. 8). Every trial one row with three datasets is chosen randomly. One dataset is randomly chosen from the row and presented in the IAS. Before the subjects are asked to select the corresponding visualized classical scatter plot from a set of three different versions shown, they had to sketch their mental image of the data distribution with pen and paper.



(a) 1-1 (b) 1-2 (c) 1-3
(d) 2-1 (e) 2-2 (f) 2-3
(g) 3-1 (h) 3-2 (i) 3-3

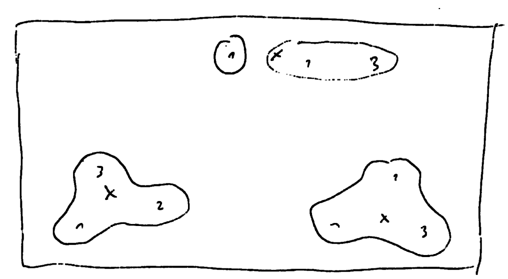
Figure 8: Synthetic datasets used in the study.

5.2. Subjects

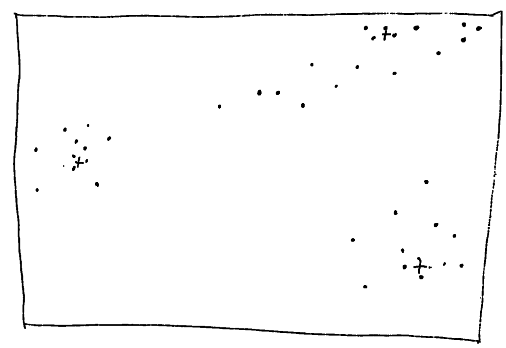
Nine untrained subjects participated in this first study and performed 13 trials. One subject conducted three trials, two conducted two trials, all other subjects were tested only once. The age of the subjects ranged from 24 to 67, but most of the subjects were younger, so that the mean age of the subjects was 33. Most of the younger subjects are students.

5.3. First results an observations

77% of the trials were successful, 23% were not. 67% of the subjects were able to successfully recognize the explored dataset, 28% were not. As depicted in Fig. 11 the subjects were allowed to explore an IAS as long as they wanted to. The duration ranges from 51 seconds to 18 minutes for a single plot. In the mean every subject used about 9 minutes. Furthermore the figure shows that even the short period of 51 seconds was enough to recognize the explored dataset in the plots. On the other hand the subjects that took much more time were able to tell quite impressively how dense the data points were distributed, including holes in the clusters (see datasets 2-1 to 2-3) and single data points at the border of the clusters. Fig.9 depicts two hand-drawn examples of what the subjects had explored. The level of detail ranged from single closed curves representing the border of the clusters to very detailed pictures with single data points and the density of their distribution.



(a) lower level of detail (data set 2-2)



(b) high level of detail (data set 2-3)

Figure 9: Examples of subject's hand drawn plots of the explored data sets. Corresponding underlying datasets are plotted in Fig. 8

Finally the subjects are asked to answer a questionnaire. All subjects stated that they can work with the system and that they think that practice can improve the understanding of IASs. Most of the subjects answered that working with the system is fun. The parameter mapping-based sonification was regarded as useful by all subjects, where as the data sonograms seemed to be much harder to understand. Only two subjects found this sonification element useful, four found it partly useful and seven subjects were not able to understand it. This may be for technical problems or inefficient explanation. A technical problem was the lag between the tracking and the sonification output and sudden jumps of the tracked markers, caused by the users hands or bright colored clothes in the camera image. Also a differing position of the subject in front of the tDesk was problematic in one case.

After filling out the questionnaire, the subjects had the opportunity to freely state what their impression of the system was and which strategy they used to orientate. One subject was surprised how easy it was to grasp the TAOs without seeing them. A good spatial imagination was regarded as very helpful. The tape bordering around the tracked area was often used to measure distances to the border of the interaction area (see Fig. 10).

After a short phase of getting used to the system, many subjects developed individual and interesting strategies to discover the borders of clusters. By scanning the cluster with the clusters TAO vertically and horizontally, a first rough idea of the clusters size and shape was gathered. some subjects also tried to trace the border of the cluster by moving the cluster's TAO over the border in zig-zag-patterns.

Figure 10: Moving a TAO with the right hand and staying in touch with the taped border with the left hand simultaneously for better orientation.

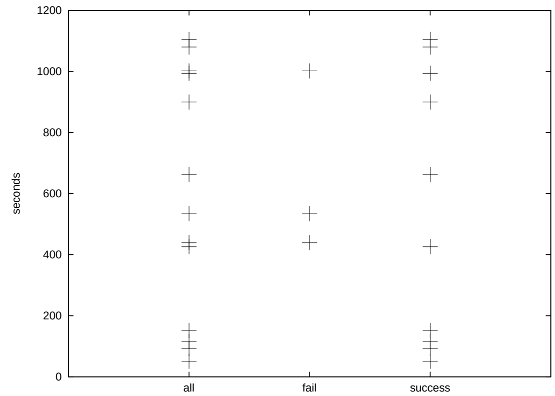


Figure 11: Results: exploration time (one cross for each single trial) in seconds for all trials (left), failed (middle) and succeded (right)

6. CONCLUSION

In this paper we presented a novel approach for combined auditory and haptic interactive rendering of scatter plots. Through Interactive Sonification and TAOs, it was possible to create a rich exploratory data analysis interface for the visually impaired. As a novel contribution we introduced a hybrid (subdivided) interaction schema where continuous density sonification and a model-based sonification using data sonograms are tightly interwoven to create a rich repertoire for exploratory interactions to create a rich multi-modal user interface. This system was evaluated in a first user study and was proved successfully to enable non-visual exploration of scatter plots.

6.1. Future developments

This application is still under active development, further additions are considered for future developments. For a multi-modal exploratory data analysis interface that can be used both by sighted and visually impaired users simultaneously, we plan to overlay the audio-haptic rendering interface with a visual projection of the scatter plot.

The next step is to extend this case study to a empirical study. Here we want to analyze how well users perform in specific tasks, such as defining different cluster characteristics, e.g. cluster size, density, and shape, etc. We also consider experiments for visually impaired people, since their spatial imagination may differ from those of sighted people. Furthermore we plan to spatialize the data sonograms to enrich the display and the interaction further and to enhance the multi-modal rendering. In summary, the IAS opens attractive new interaction steps and auditory inspection metaphors to support navigation and examination of scatter plots, particularly for visually impaired users.

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