HeartPlotter: Visualizing Bio-data by Drawing on Paper

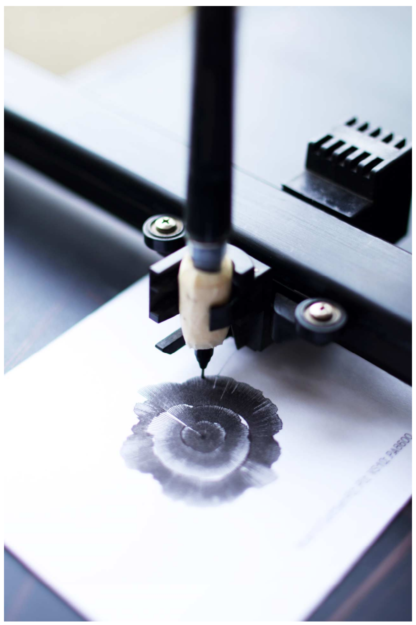

Figure 1: Heart Plotter

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Abstract
This paper reintroduces pen plotting to interaction and visualization design through the project of HeartPlotter. The HeartPlotter collects the user's heartbeat data, maps the data into the pen movements, then presents the real-time variations in heart rate through its mechanical movements and sounds, and finally delivers the overall HRV information in a compact form as one drawing on paper. In this pilot study, we experimented with three basic mappings between data and visualizations by controlling the pen movement in speed, path and pen-down timing. The results show that the pen's speed could present changing heart rate data in real-time and the pen's path mainly affects the data visualization and the aesthetic of the plotted drawings. Finally, we discuss the possibility and limitations of the pen plotter used in information display and interaction design.

Author Keywords
Biofeedback; Physical visualization; Digital fabrication; Bio-data

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

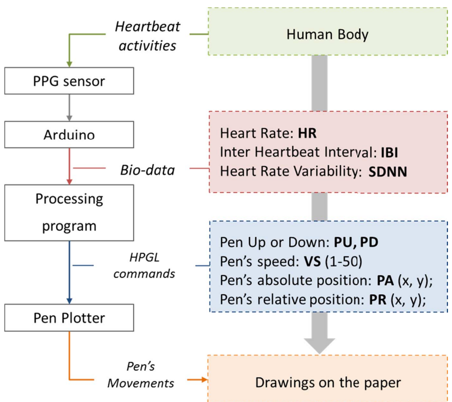

Figure 2: System of Heart Plotter

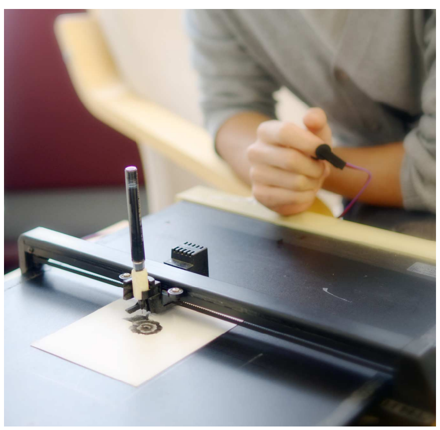

Figure 3: visualization process of Heart Plotter

Introduction

In the 1980s, pen plotters were popular vector-graphics printing devices. They were beloved because of the fine continuous lines they could draw. Unlike inkjet printers, pen plotters use an actual pen to draw, instead of spraying little drops of ink over the paper. As such, even today, many artists and graphic designers are still attracted by pen plotters for the effect of actual ink touching paper. Typically, pen plotters draw slowly by stepping through every command in a vector graphics file and translate the commands into a series of pen movements. Pen plotters can be controlled by for example HPGL (Hewlett-Packard Graphics Language) commands from a serial port in real time, achieving a separate movement such as "pen up", "pen down", or "move from point A to point B". Seen in this light, a pen plotter can be used as an interactive drawing machine, responding to a user's live input.

This work expands the view of visualizing bio-data beyond the screen by drawing the data on paper with a pen plotter. In many previous studies, heart rate data has been visualized in various novel ways. For instance, Hoinkis [1] visualizes the heartbeat through vibration patterns in the water surface. Lee et al. [2] visualizes users' accumulated activity logs by engraving patina-like patterns on the wristband of activity trackers. In [3], the authors developed a drawing machine named *Metaphone*, transforming the user's bio-data into an abstract painting. Furthermore, Khot et al. [4] designed a system called *SweatAtoms* that transforms the heart rate data into 3D printed material artifacts. More interestingly, they also proposed a new way of visualizing heart rate data through a public interactive water fountain installation, which creates a personalized sports drink [5].

Recently, pen plotters have been rediscovered as quirky, customizable interactive devices. For instance, Wilshen and Quinn [6] developed an electro-mechanical sound device based on a pen plotter (Roland-DXY). Winterberg et.al [7] designed an interactive installation based on a plotter, which draws graphics responding to an audience's facial expression. Except for applications in art installations, we found that very few studies had explored the feasibility of pen plotter as an interface for information display and purpose-directed interaction.

HeartPlotter: a Visualization Tool of Bio-data

In this study, we use a pen plotter instead of an on-screen graphic display to visualize the heart rate variability. HeartPlotter measures the user's pulse signal, calculates the heart rate variability data, and then presents the data by the pen movements and its drawings on paper.

System

The system structure of HeartPlotter is shown in figure 2. The pulse signal is measured by a PPG sensor with an Arduino board. We developed a Processing sketch that receives the pulse signal from the amplifier and processes the signal to extract Heart Rate Variability (HRV) data. In the program, HRV parameters are mapped to the parameters of the pen movements in HPGL format commands. Then through a serial (RS-232C) port, the commands are passed to the pen plotter, controlling the pen acting on the surface of the paper.

Bio-data acquisition and processing

The pulse signal is acquired with an optic PPG sensor at a sampling rate of 256 Hz. In an effort to simplify the calculations, the signal is down-sampled to 128Hz. Then the pulse signal is filtered by a 3th order

Butterworth low pass filter with a cut-off frequency of 2Hz, so the peaks of the signal (pulse peak) can be detected accurately. Each time the system detects the pulse peak value it saves the time accordingly. The Inter Beat Interval (IBI) is the time difference between two heartbeats. For better control of HeartPlotter, we smoothen the IBI data by averaging the IBI data with an exponentially weighted moving average filter of 16 heartbeats. The formula is: $IBI_{avg} = (15 \times IBI_{avg} + IBI)/16$. The initial value of IBI_{avg} is 600 ms. The real-time HR_{avg} (Heart Rate) value will be 60000ms divided by the value of IBI_{avg}. In the time-domain representation of the HRV time series, we calculated statistic feature, the standard deviation of IBI in a moving window of 16 heartbeats, namely $SDNN_{16}$. In this way, we obtained three clearly defined parameters from the measured pulse signal, HR_{avg}, IBI_{avg} and $SDNN_{16}$, which will be mapped to pen movements for visualization.

Mapping between different parameter spaces
Different from the design of screen-based visual feedback, the data is not used to create visualization directly. In HeartPlotter, the data is mapped to the pen's movements and the 'interaction' between pen and paper allows deviations from the visualization designed in the program, which gives rise to aesthetics beyond human control. The mapping process in HeartPlotter can be divided into two stages between three parameters spaces: bio-data space, physical movement space and visualization space, see figure 4. In data space, three parameters (HR_{avg}, IBI_{avg} and $SDNN_{16}$) are prepared as above mentioned. Then, the data is mapped to the movement space in three different ways, namely speed of movement, path of movement and time of pen-down. The physical movements of the pen determine the drawing output on the paper but also affect the user experience. For instance, the speed of movement influences the thickness of the lines on the paper, but also the tone of machine sound.

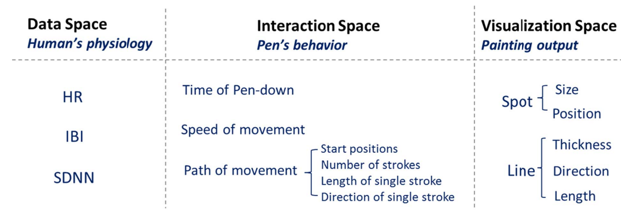

Figure 4: Division of mappings between parameter spaces

HeartPlotter is designed to present the variation of heartbeat data. To make the interaction immediate and transparent, we implement a heartbeat-triggered interactive mode for HeartPlotter, where the pen will act upon each individual heartbeat, but one or more of the extracted parameters 'modulate' the pen movements. This also requires that each movement should be finished within the shortest heartbeat interval, which is about 500ms [8]. The drawing process of a circle, arc, or polygon shape would be too slow to be finished within one heartbeat interval, hence we use 'dot' and 'line' as the basic forms in the visualization design. Through the pen movements, the data can be visualized on paper with a sequence of dots and lines of different size, thickness, length and position.

Design Exploration

We conducted a pilot study to explore the visualization of HRV with the plotter. Three basic aspects of the pen movement were experimented, namely speed and path and time of pen-down. Through the following three

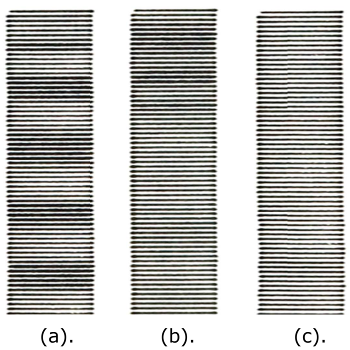

Figure5: The speed-mapping HeartPlotter drawings. (a) during deep breathing exercise (b) during normal relaxation, (c) after physical exercise

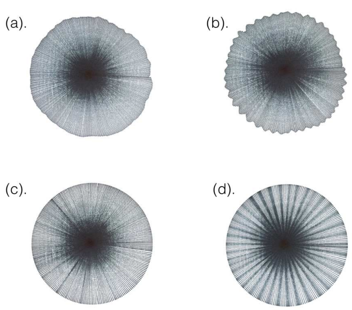

Figure 6: The path-mapping HeartPlotter drawings. (a) (c) during normal relaxation, (b) (d) during deep breathing exercise

explorations, we would like to see the dynamic qualities and constraints of the plotter from the perspectives of visualization and interaction.

Visualization 1: Based on speed-mapping

The speed of the pen movement not only affects the thickness of the lines, but also varies the tone of the machine sound. The speed parameter ranges from 0 to 40, where 0 is the slowest speed of 13.8 mm/second, and 40 is the fastest speed of 468.7 mm/second. In a pilot user test, we found that the pitch of the machine sound changes linearly with the speed, but can only be perceived by users in a limited range from speed 0-speed 20.

In the speed-mapping visualization process, the plotter draws straight lines of same length (10 mm). The pen's speed is modulated by the user's heart rate. A high speed indicates a fast heart rate. To ensure the user can perceive the variations of heart rate during the interaction, the HR_{avg} value ranging from 50 to 120 bmp (beat per minute) is mapped to a hearing-distinguishable speed (0-20). We selected the normal white print paper of 80 g/m^2 and a black felt pen of 0.3mm tip size for the user test. Figure 5 shows one example of drawings produced with heartbeat data measured from the same participant under different conditions: (a) during deep breathing exercise (b). in relaxation (c). after physical exercise. From the drawings, the lines generated with a fast speed look pale and the ones with a slower speed tend to be thicker and darker. Drawing (a) shows an obvious oscillation in heart rate caused by deep breathing. In drawing (c), the relatively pale lines show an increased heart rate after exercise. Drawing (b) reflects a normal heart rate, but with a low variation.

Visualization 2: Based on path-mapping

In HeartPlotter, each heartbeat triggers one movement that might consist of several moves. The basic form of a move is a straight-line motion. Four factors determine the path of a movement: start position, number of moves, direction of each move, and length of each move. Based on the number of moves, the path of a movement could be a simple line or a complex shape. In this study, we do not intend to explore the complexity of graphic design; instead, the plotter draws a simple straight line at one heartbeat, where the direction and length of the lines are modulated with IBI data.

We started out with the simple visualization design of a circular bar chart. Again, a single straight line is used as the basic element. As HeartPlotter is designed based on a flatbed plotter, to keep the continuity of the interactive process, we made the bar chat in a circle radiating outwards, and each line starts from the center. We tried two mapping methods: mapping IBIavg to the length of the line or to the space between two adjacent lines. Figure 6 shows path-mapping drawings produced by heartbeats data during the relaxation and deep breathing exercise. We can perceive the overall HRV information of the entire session directly from the shape and the texture of drawings. Compared to subtle changes in drawings (a) (c), drawing (b) and (d) show an obvious heart rate rhythm by the regular fluctuations on the outline of the shape and the denseness of the texture.

Visualization 3: Based on time of pen-down

Besides the continuous lines, the pen plotter can also draw discrete dots by a consecutive movement of Pen-Down-Pen-Up. The position of a dot is determined by the path of movement; unlike line drawings, the pen

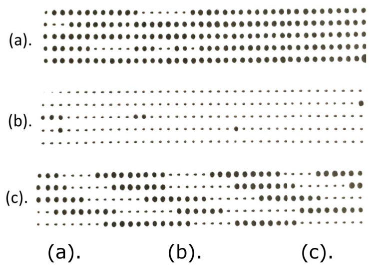

Figure7: The dot drawings of HeartPlotter. (a) during relaxation, (b) after physical exercise, (c) during deep breathing exercise

does not touch the paper during the moves until it reaches the specific position. Typically, the pen-down-up movement is quite fast (less than 100ms), leaving a dot nearly as small as the pen tip. And the longer the pen is touching the paper, the more ink will spread into a larger dot on the paper. Therefore, the time of pen down without movement on the paper determines the size of the dot, which becomes another parameter available for data visualization.

Firstly, we tested the effect of the pen-down duration on the dot's size. The duration is controlled in the program from 100ms to 1800ms. The result shows that, based on the darkness and size of the dot, the dots can only be identified into three types: small (shorter than 500ms), medium (500ms-1000ms) and large (longer than 1000ms). Then, we map the heartbeat intervals (IBI_{avg}) to the duration of pen-down. The typical human IBI data ranges from 500ms to 1200ms during deep breathing. And during normal state, fluctuations of IBI are maintained within the small range of 700ms-1000ms. Here, to achieve an immediate and natural mapping, we use a simple method. When HeartPlotter detects a new heartbeat, it moves the pen to a new position and puts the pen down on the paper. When IBI_{avg} is less than 700ms, the pen is lifted immediately with the default speed. Otherwise, the pen keeps in touch with the paper until a new heartbeat is detected. The results of the user test are shown in figure 7. Drawing (a) shows a normal heart rate level with a set of similar medium-sized dots. In drawing (b), after the exercise, the fast heart rate produces a set of small dots by a very short pen-down time. As we expected, during a deep breathing exercise, the enhanced heart rate rhythm is reflected by varied dots, see figure 6(c).

Discussion

The pilot study explored three basic parameters of the pen movement and their effects on drawings. Speed of movement can be an effective way of presenting heart rate data based on the varied tones of machine sound. This gives users an immediate audio feedback. But our hearing system can only distinguish a limited range of pitch changes caused by speed modulation. In the visualization, the speed mainly influences the thickness and darkness of lines. Generally, the lines on paper can be divided into three groups based on thicknesses and the bold line can only be generated with a very slow movement. The speed also determines the duration of one movement, which should be within one heartbeat interval. For example, if the speed were set to the slowest (speed value = 0), the pen would only move 7mm in a straight line within the shortest heartbeat interval (500ms). Therefore, the pen's speed is an important factor to be considered in the interaction design, because it limits the length and the complexity of the movement path. The path of movement has a greater flexibility in visualization and a good capacity of information display. The changes of lines, such as the direction and length, can be easily perceived visually. The time of pen-down mainly affects the dot size in the visualization. The capacity of presentation of dots is limited; only three 'levels' of data can be expressed by small, medium and large dots.

Compared with on-screen visual displays, we found the plotter has the following valuable characteristics as an interactive output. Firstly, a pen plotter is a multi-modal (physical-visual-auditory) output interface through the mechanical movements of the pen, sound of the machine, and the drawings on the paper. Secondly, the working of a plotter is a two-stage

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transformation process: from data to pen movements and from pen movements to the effect of ink on the paper. This gives plotters a good controllability of data representation but also flexibility and versatility in rendering the output artistically. Thirdly, plotters not only display the output data in real time, but also present the overall information with a whole painting after the interaction. We believe there is a great, untapped potential of pen plotters in the HCI field. The pen plotter can be used for purpose-directed interaction, presenting various types of data in a physical-audio-visual modality. It could act upon various inputs that are live and interactive, providing the users with a rich interactive experience. Just as one user said: "It brings back memories of me sitting in my father's office looking at and listening to this 'magical' machine!" As we can see, there are still some weaknesses with the plotters, such as the limited drawing speed, special requirements on pen and paper, and inevitable machine sounds. But we think these difficulties can be understood and used well, can turn out to be valuable factors in interaction design.

Conclusion and future work

This paper presents HeartPlotter, a device to visualize heart related information through integration with a pen-plotter device. HeartPlotter presents heart rate variability in a dynamic drawing process, where the pen moves with different paths and touches paper with ink gradually generating visualization. We hope the findings of this study could breathe new life into "obsolete" plotters for their interactive aspects and attract more interest from researchers in the field of HCI. Future research on HeartPlotter will explore more interactive modes and visualization designs based on the findings from this pilot study.

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