JOINT ACTION IN 2D TRAJECTORY FORMATION
Cooperation with a Computer to Create 2D Oscillatory Trajectories

BACHELOR THESIS

JAAP VAN DE SANT
(s0309060)

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SUPERVISOR:
DR. L.G. VUURPIJL
DONDERS INSTITUTE FOR BRAIN, COGNITION AND BEHAVIOUR
2ND SUPERVISOR:
PROF. DR. R.G.J. MEULENBROEK
DONDERS INSTITUTE FOR BRAIN, COGNITION AND BEHAVIOUR

RADBOUD UNIVERSITY NIJMEGEN
FACULTY OF SOCIAL SCIENCES
ARTIFICIAL INTELLIGENCE

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Abstract

Present BCI research suggests that it is possible to control a computer by the brain on two separate dimensions. As trajectory formation as found for instance in handwriting is also a 2-dimensional control task, we try to find out if the separation between different dimensions in the 2D trajectory formation can be learned. Therefore, we constructed a platform which facilitates the research of learning effects in the production of 2-dimensional trajectories. The platforms' ability to facilitate learning this task includes a 1 person, a 2 person and a HCI setting. The 1 person and 2 person conditions have been explored in a previous study, in which the platform has proven to be very successful. The aim of the present research is to find if the ability to separate between movement dimensions can be learned in a HCI setting. We are also interested to find if the behavior of the computer influences the users' ability to learn this task when interacting with a computer. Results of these studies indicate that participants could indeed separate the movement dimensions and that there are suggestions that the behavior of the computer influences this ability. A more cooperative computer could help to create more accurate and more fluent trajectory formation. Findings in this research might transfer to the BCI domain, where the learning of a 2-dimensional task could benefit from the interaction with a computer.

Chapter 1

Introduction

1.1 Human Computer Interaction

The past decades Human Computer Interaction (HCI) has become part of everyday life for many people. Advances in interaction technology and improved processing of interaction modalities have provided new ways of interacting with a computer that go beyond the traditional use of mouse and keyboard. The keyboard and mouse controls are more and more abandoned to make way for new ways of interacting with a computer. These new interaction methods include movement, gesture and speech recognition, eye tracking and lots of other modalities [5, 15]. The "holy grail" of human computer interaction is perhaps the ability to control a computer only by thinking. Brain-Computer interfaces (BCIs) have been subject to an increasing amount of research for the past two decades. When using a BCI, the user communicates with the computer via activity patterns in the brain. These activity patterns are small electrical signals which can be picked up by an external device, such as a EEG. The measured signals are then translated into usable input signals for a computer [18]. A common method of control for a BCI device is by recording EEG signals on the scalp. Typically, BCI control is established by intentionally changing brain activity patterns via e.g. imagined movement of body parts or performing cognitive tasks[1, 12].

However exciting the use of BCIs may sound, the primary goal of BCI research at the moment is to enable users who are completely paralyzed ("locked in") to communicate with the world [20]. To be able to use such systems efficiently, a lot of training is needed, which takes a lot of time. The emphasis of current research is on developing non invasive BCIs. Invasive BCIs which use implants inside the brain to record brain activity entail obvious risks. Invasive BCIs are subject to research, but researchers use primates, rather than human subjects for these studies [2].

The problem of the long training time in (non invasive) BCIs has been addressed in numerous studies and will continue to be subject to research in the future, however most research emphasizes the use of more efficient methods for analyzing and improving the quality of the signal [6]. The training remains roughly the same. In this research we tried to find a way to improve the interaction between humans and computers by setting up a situation in which cooperation between the two is required rather than "just" processing human input using signal processing and machine learning methods.

1.2 Trajectory formation and BCI

Research in 2004 by Wolpaw and McFarland [20], shows that simultaneous control of cursor movement in two dimensions is possible when using a BCI. Simultaneous control of x and y dimensions of movement is also what makes up handwriting. It is interesting to see if this correspondence between controlling two dimensions when using a BCI and when producing handwriting can yield novel insights that may be used to enhance future BCIs. As a first step to explore this correspondence, we set out to examine whether people are capable of separating the movements involved in handwriting into horizontal and vertical components as suggested by Hollerbach [4].

The production of handwriting by humans requires a hierarchical information flow. The writer starts with the intention to write a message, this is transformed into words, then into a sequence of letters and eventually into the production of the shape of the letters. These shapes of letters are then transformed into movement patterns. These movement patterns are error free, non hesitant and fast. Furthermore the characteristics of handwriting (such as slant, character shapes, loops and between word distance) are strongly consistent for a given writer [16].

There are a lot of different theories about how humans are able to be so fast and accurate in producing handwriting[3, 10, 13, 14]. One of these theories was proposed in 1981 by Hollerbach [4]. In this theory handwriting arises from orthogonal oscillations in the horizontal and vertical direction on the plane of the writing surface. These two oscillatory motions are superimposed on a rightward horizontal sweep with a constant speed. Hollerbach bases this theory on the physical properties of the muscles and joints, the horizontal oscillation arises from wrist movement and the vertical oscillation from finger movement. Hollerbach formalizes the movement in two equations governing the oscillations in the velocity domain:

$$\begin{aligned} x &= a * \sin(w_x(t - t_0) + \phi_x) + c \\ y &= b * \sin(w_y(t - t_0) + \phi_y) \end{aligned}$$

where:

a = horizontal velocity amplitude.
b = vertical velocity amplitude.
w_x = horizontal frequency.
w_y = vertical frequency.
ϕ_x = horizontal phase.
ϕ_y = vertical phase.
t = time with respect to t_0.
t_0 = reference time.
c = magnitude of the horizontal sweep.

We will use this model to study the cooperative generation of 2D trajectories. According to the theory proposed by Hollerbach, it would be possible to detach these different oscillations and the sweeping motion from each other. This means that the oscillatory 2D trajectories resulting from the Hollerbach model, could then be created by two actors both controlling only one axis of the trajectory.

The other actor in the creation of these trajectories, does not necessarily have to be a human, this could very well be a computer. When the other actor is a computer, then creating the trajectories becomes in principle a task which is quite similar to tasks performed in current BCI research, not in the least in the fact that it will take some time to learn. The learning is mainly due to the fact that the user has to get used to the behavior of the computer and the complexity of the trajectories. This behavior of the computer can change in its way of cooperating.

When creating 2D trajectories controlling only one parameter, the computer can act independently and continuously, assuming the user is very able to adapt to the situation created by the computer. However, the computer can also try to be more cooperative. It can use features found in human 2D trajectory formation to act in a way a human would expect these patterns to be created [7, 8, 9]. Besides that, the computer could try to adapt to human errors, for instance wait for a human to catch up if it notices the human input is too slow. In short the degree in which the computer cooperates can be changed.

The result of the extended cooperation between the human and the computer could be a joint action system in which a human joins action with a computer. For this to happen, the human and the computer need to share representations (such as speed, direction and planned trajectory) according to the task, be able to predict each others' actions and to integrate predicted effects of their own and the others' actions [17].

1.3 Our research

1.3.1 Creating the platform

We created a generic research platform on which multiple tasks can be executed to examine the capability of human subjects to separate the different parameters involved in 2D trajectory formation. This platform accommodates several different setups for examining 2D trajectory formation. The exact specifications of the platform are described in section 2, it comprises three parts.

- The first part is a setup where one human subject controls movement along both axes independently from each other.
- In the second part, two human subjects each control movement along one axis to create trajectories cooperatively.
- The third part allows a human subject to cooperate with the computer to create the trajectories.

Our research will focus on this third part: the production of 2D trajectories by cooperation between a computer and a human using a pen on a writing tablet.

1.3.2 Using the platform

The first two 2D cooperative movement control setups have been explored in a joint research project between the author and van Wingerden [19]. The goals of this project were to design, implement and evaluate a research platform which allows for research as described in section 1.3.1. The platform was then used to start the three parts of this research.

The first two setups of the platform as described above were first evaluated in research. The main goal of this research was to "find out whether people can learn to write by separate manipulation of two dimensions and if so, if it is best done alone or in cooperation with another actor" [19]. The task was to dissociate the horizontal and vertical components of trajectory formation, and study the learning effects in a 1 and 2 person condition.

1.3.3 1 person and 2 person conditions

Setup

A group of participants was divided between the 1 and 2 person conditions of the research platform. The participants had to recreate the letters *e*, *n* and *d*. These stimuli were generated by the researchers. The participants in the 1 person condition held 2 pens with which they had simultaneous control over the horizontal and vertical movement, each of the pens controlling one of the two.

In each session there were three blocks of 21 trials. The trials were made increasingly difficult during a session. The three blocks had a decreasing amount of guidance for the participants. The first block showed the Shape and Viapoints (see section 2.2.4 for explanation about Shape and Viapoints). The second block showed only the Viapoints. The last block showed only the begin and endpoint.

Results

Performance on the ability to generate trajectories was expressed via two main categories, Speed and Accuracy. The ability of participants to separate the movement dimensions was assessed by looking at the width height ratio of the drawn trajectories

It was shown that people have the ability to separate a 2-dimensional movement into separate dimensions. This was shown for a single person controlling both axes, as well as for two persons in cooperation. However there were some interesting differences between the 1 and 2 person conditions.

Most of the results indicated an advantage for the 2 person condition. In this condition, the created pattern was more fluent, the mean velocity of the pen was higher and the duration of the trials was shorter (all indicators for Speed). The accuracy was higher in the 1 person condition, except for the correlation measure (which was a indication of the quality of cooperation between the two pens). The correlation showed a remarkable advantage for the 2 person over the 1 person condition. This indicates that the 2 person condition results in a better coordination of the movements in terms of accuracy.

Important findings for our research

The findings in this earlier research lead to some interesting questions, some of which will be addressed in this research. The first of these questions is whether the findings shown in the 1 person and 2 person conditions can be recreated in the HCI condition. Also very interesting is the advantage for the 2 person condition, where cooperation, shared representations and predictions of behavior are very important. Does this advantage only occur in a 2 person condition or also in the HCI condition?

It was also suggested that if the speed domain is the most important aspect in a BCI, there is a significant beneficial effect of a second actor. It is even concluded that "When speed is most important, the help of an artificial partner is wanted"[19]. This artificial partner mentioned by van Wingerden will be the subject of this research.

1.4 Our goals

In this research we try to evaluate the third part of the research platform. Thereby also researching the capability of a human actor to create 2D trajectories in combination with a computer. Another aim for this research is to find if the behavior of the computer influences the users' ability to learn how to use the system. However, bearing in mind the possibilities for further research in the field of 2D trajectory formation and the combination with BCI, the research platform was extended to be able to use it outside the field of human computer interaction. This system was made generic such that it supports different inputs and different user settings, these are discussed in section 2. What we try to find in this study is the relation between different behavior of the computer system and different learning effects of the user. These learning effects will be explored by assessing accuracy and the ability to separate the horizontal and vertical movement.

The findings of van Wingerden show that in both the 1 person and 2 person condition, 2D trajectory generation can be decomposed in two separate movement dimensions. In the 2 person condition, persons have to cooperate with each other to reproduce a certain pattern. This indicates that it should be possible for a person to cooperate with an artificial partner as well.

The current research will explore whether this hypothesis is true. Furthermore, different behaviors of the artificial partner will be assessed on accuracy, temporal aspects and on learning. The research questions pursued in this bachelor project read:

- Can a person cooperate with an artificial partner when controlling one separate dimension of a 2D trajectory?
- Do different behaviors of the artificial partner influence accuracy or velocity?
- Do these different behaviors influence learning?

1.5 Thesis order

The remaining chapters of this thesis are organized as follows. In the second chapter we will explain the research platform we created. It will explain the main idea behind the platform 2.1 as well as the technical setup and possibilities of the platform 2.2.

In section 3.1 the actual setup of our experiment will be discussed. In section 3.2 we will explain the stimuli we gave the participants and in section 3.3 the task they had to perform. We discuss the settings for the computer behavior in section 3.4 and in section 3.5 we discuss the way in which we analyzed the data.

The results we got from our experiment will be discussed in chapter 4. Here we will discuss the computations we did to make the data manageable 4.1 and the statistical analysis 4.2.

Finally chapter 5 will contain the conclusions 5.1 and discussion 5.2. This chapter will also include a section about possibilities for future research 5.2.4.

Chapter 2

Research platform

2.1 General idea

The research platform on which all experiments are done, is a generic platform accommodating further research on the creation of 2D trajectories in joint action either with a computer or with another person. It consists of two input tablets linked to a computer, this way it will be possible to get input for the horizontal axis from one table and input for the vertical movement from the other. The users can interact with the computer via these tablets, using a pressure sensitive pen to which the tablets respond. The use of a pressure sensitive pen is consistent with the usual modality when creating 2D trajectories.

On the physical research platform, a Delphi-pascal program will run in a windows environment, using the wintab tablet interface. This program will enable the researcher to change settings in order to do different kinds of research. The program is able to get input patterns in various ways. It is able to generate its own oscillatory patterns with various parameters that can be changed to create lots of different patterns. These parameters include speed, size and parameters discussed in section 3.2.2. The program is also able to receive input patterns from files rendered by researchers, this could be actual handwriting patterns. These patterns can be resized to the same size so there is no need for similar sized input patterns.

Besides the input, there are also a lot of possibilities in controlling the appearance of the program on the screen and experimental setup. These possibilities are discussed in section 2.2

2.2 Platform possibilities

The program accommodates three settings for different kinds of research, these settings will be discussed in sections 2.2.1-2.2.3. The first setting is when a user does the task alone. The second is the interaction between two human actors. The third setting, used in this study is the interaction of a human with the computer.

2.2.1 Single person

This part of the program accommodates research in human control over 2D trajectory production. The platform needs two tablets to generate the input because it is not possible to get input from two pens on one tablet. In this case, the input pattern shifts to the side of one panel so that the input patterns are closer to the edge of the screen where the horizontal axis is controlled. By doing this it gets closer to the place where the vertical axis is controlled. Everything the user needs to see is put close together so this does not interfere with the results of these tests. Figures 2.1 and 2.2 shows what the screen in this setting looks like. The black line indicates the gap between the two screens.

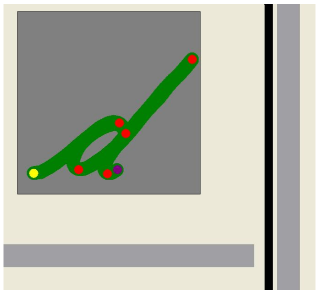


Figure 2.1: Screen of a 1 person trial before it started

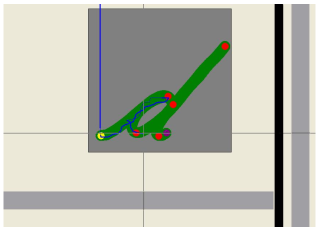


Figure 2.2: Screen of a 1 person trial during trial

2.2.2 Human-human interaction

This part of the program accommodates research in joint action and 2D trajectory production. The platform can show the same input pattern on both tablets and divide the control over the axes between the two, so that on one tablet the vertical movement can be controlled and on the other tablet the horizontal movement. Figures 2.3 and 2.4 shows what a screen in this setting looks like.

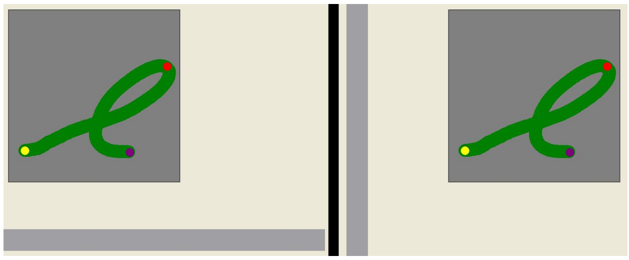


Figure 2.3: Screen of a 2 person trial before it started

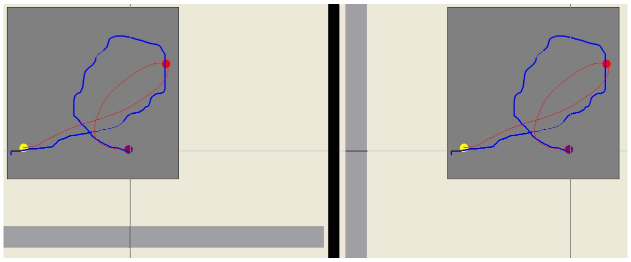


Figure 2.4: Screen of a 2 person trial right after trial

2.2.3 Computer assisted

This part of the program is discussed extensively in section 3 of this thesis. The computer assisted setting can be used for research in human computer interactions. The researcher has a lot of control over the behavior of the computer. Settings that change the behavior of the computer, like speed and cooperation settings can be changed. These particular possibilities are discussed in section 3.4. Figure 2.5 represents what a screen in this setting looks like.

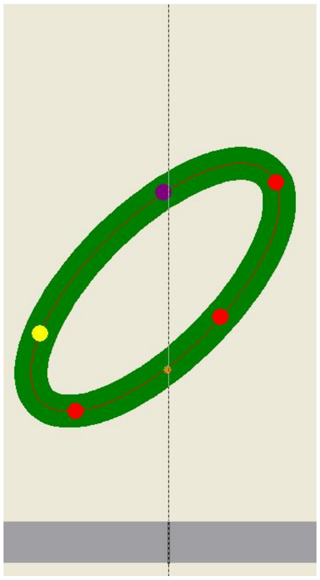


Figure 2.5: Screen of a HCI trial during trial

2.2.4 Control possibilities

Besides the choice between the three main settings discussed above, there is extensive control over different settings that are important to different research setups. These settings will be discussed in the following sections.

Shape

The Shape is the representation of the input pattern on the screen. This is a line that shows the user what figure is intended to be reproduced. The Shape can either be a representation of a input pattern from a file or a computer generated oscillatory pattern. The researcher is in control over the width of the line that makes up the figure and of its color. The Shape is usually normalized as to create an equal sized output even with different sized inputs, but the normalization can be disabled when needed. The drawing of the Shape can also be turned off in which case the Shape is not rendered. The Shape can be seen as a red line in figures 2.4 and 2.5. In figure 2.4 the Shape is displayed after the trial to indicate the original form as a direct feedback to the user.

Autobahn

The Autobahn is an area around the Shape with a different color than the Shape. The Autobahn can be used as an area around the shape in which the performance of the user is considered correct. In the case of a computer assisted task, the behavior of the computer could change when the user gets outside the Autobahn. As with the Shape, the researcher is in control over the width, color and presence of the Autobahn. The autobahn is depicted as a green zone in figures 2.1-2.3 and figure 2.5. In figure 2.3 and 2.4 the user first sees the Autobahn but when the trial starts, the Autobahn disappears. After the trial, the Shape is shown.

Viapoints

The Viapoints are colored circles on the shape. These points are indicators of a few important points on the Shape, they indicate its start and finish point, they can indicate important points in a figure (e.g. top, bottom, turns) but they can also indicate the direction of a Shape. The start point is usually a unique color, as well as the finish point, the points in between are all the same color. The Viapoints can either be rendered by the program, in which case the Viapoints are evenly distributed over the Shape. But in the case of input patterns read from files, the location of the Viapoints can also be indicated in the file. Like the Shape and Autobahn, the size, color and presence of the Viapoints can be controlled as well as the number of Viapoints. The Viapoints can be seen as colorful circles in all figures of this Chapter. In figure 2.4, the Viapoints are the only guidance the users have to recreate the Shape correctly.

Bounding box

The Bounding box is a box surrounding the Shape and Autobahn. This can be shown as a box in which all figures appear. If a Bounding box is presented, the Shapes and Autobahn are always normalized to fit within the Bounding box. The researcher is in control over the width, height and color of the Bounding box. The Bounding box can be seen in figures 2.1-2.4, where the input patterns are normalized to fit inside this Bounding box, when necessary even taking into account the width of the Autobahn.

Gutters

The Gutters are small bands along either the X or Y axis depending which axis the user is supposed to control. These Gutters are the actual drawing boards of the user, outside these Gutters, the program changes behavior (e.g. changing the width or color of the line or taking away control over the movement), depending on what the researcher would prefer. In order to investigate the ability to separate the use of the different axis of handwriting, the width of the Gutters can be changed. The distance between the side of the panel and the Gutters can also be changed as it is possible to rest the pen against the edge of the screen when drawing. If the Gutters would be placed against, or too close to the edge of the screen, the movement along that axis would become very stable as the user uses the edge as a guide in that direction. The color of the Gutters can also be changed. The gutters can be seen in all figures of this chapter as gray squares in the bottom or on the left side of a screen.

Line or Penpoint

The Line or Penpoint is the indication on the screen of where the combined X and Y inputs are located. A choice can be made to either display a Line or a Penpoint. The Line follows the movement and leaves a figure on the screen, this is more similar to what people are used to when creating handwriting, and can be evaluated instantly by the user. The Penpoint is more useful when using oscillatory patterns that have to be created repetitively. A Line that is drawn several times over the same Shape could become confusing. In both cases the size (width in case of a Line) and color can be controlled. A line can be seen in figure 2.2, this line becomes smaller when one of the pens is outside the Gutter. A Penpoint can be seen on figure 2.5 as a little orange dot.

Chapter 3

Methods

3.1 Experimental setup

Participants

In this research 24 right-handed subjects participated, including 16 male and 8 female participants (divided 9:3 in one condition, 7:5 in the other). The age ranged from 18 - 62 with a mean of 28.83 (28.75 in one condition and 28.92 in the other). None of the participants had any previous experience with the use of tablets to interact with a computer. All participants were volunteers and they received no reward.

Interaction modality

The interaction with the computer happened through the use of a 15 inch Wacom Cintiq 15X(PL550) tablet. The LCD tablet had a pixel resolution of 1024∗768 pixels. The spatial resolution of the tablet was set at 805dpi. The sample rate of the tablet was set at 100Hz. On these tablets the software program discussed in section 2 was running.

Design

Participants were randomly assigned to the between-subject conditions: 12 participants in the synchronous condition and 12 participants in the system driven condition. Each session started with a little explanation about the task after which a short training session began.

3.2 Stimuli

3.2.1 The platform

Al the experiments will take place using a research platform as described in section 2. This study uses only the part of the platform set up to facilitate the creation of 2D trajectory patterns with a human subject controlling one axis and the computer controlling the other axis.

3.2.2 Trajectory patterns

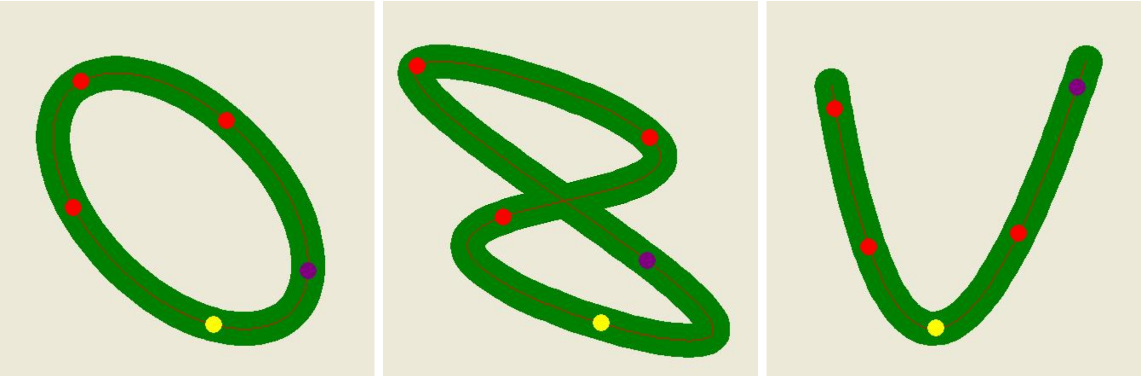
For this research the program creates three kinds of 2D trajectory patterns. These patterns are oscillatory patterns with some random variables and some variables set. The oscillations are calculated according to the model of Hollerbach [4] as follows:

$$\begin{aligned} x &= a * \cos(w_x * \theta) + c \\ y &= b * \sin(w_y * \gamma) \end{aligned}$$

where:

x = horizontal coordinate.
y = vertical coordinate.
w_x = horizontal frequency, indicating the velocity of horizontal movement.
w_y = vertical frequency, indicating the velocity of vertical movement.
θ = horizontal phase, changing the horizontal form of the shape.
γ = vertical phase, changing the vertical form of the shape.
c = horizontal sweep.

By changing θ and γ either to 1 or 2, the three patterns are created. If the phases are the same, the same kind of pattern is created, so there are three different kinds of patterns, they can be seen in figure 3.1. The first is both θ and γ being 1. This creates an oval as seen in figure 3.1(a). If $\theta = 1$ and $\gamma = 2$, then an eight is created as seen in figure 3.1(b). If $\theta = 2$ and $\gamma = 1$, then a U-shape is created as seen in figure 3.1(c). In the original model of Hollerbach [4], the horizontal sweep was changed to change the velocity of the horizontal sweeping motion. In this research it is set to 0, indicating no horizontal sweeping motion. As mentioned by Hollerbach, this results in a cycloid.



(a) Oval shape (b) Eight shape (c) U-shape

Figure 3.1: Three different patterns

To have more diversity in the figures, all these figures are randomly rotated around their center point with a maximum rotation of 180 degrees. For instance a U-shape can be rotated to a C-shape or even a ∩-shape

3.2.3 Display settings

The created Shapes as seen in the figures 3.1(a)-3.1(c), have a colorful appearance. These colors do have a meaning in the task. The various objects that appear on the screen are the same objects as discussed in section 2.2.4. We will discuss these shortly. The actual Shape is presented by a thin red line, if the user stays exactly on this line, the produced output will be exactly correct. Surrounding this red line there is a green Autobahn, which is 9 mm wide. If the user keeps the drawing inside the Autobahn, the output will be roughly correct. In the Synchronous setting of the program discussed in section 3.4.2, the computers' behavior will depend on the users' ability to remain within the boundaries of the autobahn. The Viapoints are placed evenly over the shapes and are 7 mm wide. The yellow Viapoint indicates the start and a purple one indicates the last Viapoint that has to be crossed. Because all Shapes have to be reproduced 5 times directly after each other, the yellow Viapoint also acts as the endpoint.

Not shown on the pictures is the Penpoint and the Gutter. The Penpoint is 3,5 mm wide and is orange if it is inside the green Autobahn. It turns blue when outside of the Autobahn. There is only one Gutter in this task, as only the horizontal axis is controlled by a human. This Gutter is 15 mm wide and is placed 15 mm from the bottom of the screen. This to prevent the user from using the side of the screen as a guide to stay within the Gutter.

3.3 Task

The task that has to be performed by the user is to make the Penpoint follow the red line as closely as possible while cooperating with a computer that controls one axis. The previous research by van Wingerden showed no significant difference in performance between the x and y axes other than a slightly better separation between the two movement dimensions for the x axis. Therefore, and because it fits better within the scope of this bachelor thesis, the choice has been made to only let users control the horizontal axis, the computer always controls the vertical axis.

Each trial starts with a little countdown sequence in which the user can focus attention. After this sequence, the computer will start drawing his part of the figure and it is the task of the user to adapt his behavior in such a way that the Penpoint stays as close as possible to the red line. Each figure has to be drawn 5 times directly after each other. When the figure is drawn 5 times, a sound signal will indicate that the trial is over. Also control over the movement of the Penpoint is no longer present and the computer will stop its movement.

As already said, the aim of this research is to find learning effects in the users' behavior given different behavior of the computer. These learning effects can best be researched by instructing a subject to repeat the same task and assess performance on e.g. improvement in task completion times, accuracy and number of errors [11]. Therefore the patterns mentioned above are presented to the user in two sets of an equal number of trials. Each of the three Shapes is presented 5 times, first five times the Oval, then five times the Eight and then five times the U-shape. There is no counterbalancing or randomization because the different parts of these tests (the different shapes) are not compared, only the difference between the two tests.

Before the task, the user is given a short trial run in which each of the varieties is presented two times, in the same order as the actual task. Including the training trials, the user performs 36 trials. Each pattern is created 12 times, of which 2 are training.

3.4 Computer behavior

The behavior of the computer is of course an important part of this research. However, it is not our intention to find out what exact settings are most beneficial for humans to cooperate with. It is our intention to find out if the behavior of the computer has an effect on the learning of such a task. The platform will have two modes of cooperation. In the first mode, the user has to adapt to the computer, this is the system driven mode. The second mode is aimed at working together with the user. In the second mode, the computer adapts its behavior to the input of the user, this is the synchronous mode.

3.4.1 System driven

In the system driven mode, the computer fills in its part independently of what the user is doing. It does however show some human like skill in the way it fills this in. This means that the computer will slow down a little in corners and on turns and will increase its speed on straight sections. It does this roughly the same way as a human would according to Morasso and Mussa Ivaldi (1989) [10], using the stroke length and curvature within a shape to determine velocity and using bell shaped velocity profiles for strokes. By doing this it should be easier for the user to adapt to the behavior of the computer. Furthermore, in this setting when the user goes off the drawing bar, the Penpoint remains at the same place on the horizontal axis (controlled by the user), it no longer follows the user on that axis, but continues to move along the vertical axis (controlled by the computer).

3.4.2 Synchronous

In the synchronous mode, the computer adapts its behavior to the input of the user. The computer will behave in the same human like way as in the system driven mode, but with some extra consideration of the generated input. The speed in which the computer moves, does not only depend on the shape of the figure and where there are corners or straight sections, but is also linearly related to the distance between the place of the user on the horizontal axis, and the place he is supposed to be on that same axis in order to let the Penpoint be at the correct location on the red line. This only applies when the difference is more than the distance between the red line and the border of the green zone.

In synchronous mode when the user goes off the drawing bar, the computer slows down significantly, increasingly going slower with a maximum of waiting half a second before taking the next step. This should be a very clear sign that the user is off the drawing bar. The Penpoint also no longer follows the user on the horizontal axis, but will (very slowly) keep moving along the, computer controlled, vertical axis.

3.5 Data analysis

During the experiment we recorded the following variables:

- Trajectory of the pen (x and y coordinates)
- Trajectory of the Penpoint (x and y coordinates)
- Elapsed time since the beginning of the trial
- Markers of several events: completed oscillation, off gutter events, start and finish, and drawing before the start or after the finish.

These variables were analyzed and several aspects of performance were calculated afterwards. These can be roughly divided into the categories Speed, Accuracy and Ability to separate movement dimensions. Results of these analysis can be found in section 4

3.5.1 Speed

The actual speed or duration of the trial could not be taken into account as the settings of the computer behavior effect the duration and speed of a trial. All trials in the system driven setting have the same duration. The trials in the synchronous setting differ in duration depending on the accuracy of the participant. The two variables we used were Velocity and ZeroCrossings.

Velocity

The velocity is actually the difference in velocity pattern between the intended figure and the actual input from the user. A velocity pattern is computed as the derivative of the coordination pattern. The velocity pattern of the shape is computed as the derivative of the supposed shape. The mean difference between the two is what could be called ΔVelocity, however, it will be called Velocity in the rest of this thesis.

ZeroCrossings

The number of ZeroCrossings is a measure of the fluency on the writing. As with Velocity, ZeroCrossings are actually the difference in number of ZeroCrossings between the user created input and the intended figure. The number of ZeroCrossings was computed by counting the number of times the velocity pattern changed from positive to negative or otherwise. This was computed for the shape and for the input by the user. There are some ZeroCrossings inherent to the creation of the shapes and this differs per shape, therefore the difference between the two was computed and this difference was called ZeroCrossings. A higher number of ZeroCrossings is an indication of less fluent writing.

3.5.2 Accuracy

The accuracy is a measure of resemblance between the shape and the input generated by the user. The closer the input resembles the shape, the better the accuracy. This is measured by the distance between the input and the shape.

Distance

The distance is calculated as the euclidean distance between the actual position of the user and the position where the user is supposed to be on the shape at that moment. Because of the interaction with a computer which performs the task over time, the accuracy of the user always depends on the time since the start of the trial. Even though the computer can speed up or slow down in the Synchronous Control mode, the amount by which it can slow down is limited. Because of these limitations and because the user only controls the X axis, the calculation of the distance becomes very simple.

$$\begin{aligned} D &= \sqrt{(U_x(t) - H_x(t))^2 + (C_y(t) - H_y(t))^2} \\ &= \sqrt{(U_x(t) - H_x(t))^2 + 0} \\ &= abs(U_x(t) - H_x(t)) \end{aligned}$$

U(t) = User input on time t (x and y coordinates).
C(t) = Computer generated input on time t (x and y coordinates).
H(t) = Position on the figure at time t according to Hollerbach model.

As the Y axis is filled in by the computer, this is always correct, therefore the difference on the Y axis is always 0. The distance between the Shape and the User on the X axis over time is the only difference that is not 0. This distance is a measure of deviation from the ideal trajectory, so could be seen as the inverse of the Accuracy.

3.5.3 Separation of movement dimensions

Part of the task was to learn to separate the dimensions involved in 2D trajectory formation into separate movement dimensions. The ability to do so was measured by the Width/Hight Ratio (WHR) and the number of Off Gutter Events (OGE).

Width/Hight Ratio

For the computation of the WHR we used the following formula:

$$WHR = (max(X) - min(X))/((max(Y) - min(Y))$$

When a participant is able to completely separate the horizontal and vertical movement, the pen will only move in the horizontal direction. Consequently, for a better separation between the movement dimensions, the WHR becomes bigger.

Off Gutter Events

The number of OGE is an indication of the participants ability to separate movement dimensions. The more the user is able to remain within the gutter, the more the separation is present. There was a difference in reaction of the computer to OGEs, as explained in section 3.4.

3.5.4 Factors

The variables mentioned above are the five dependent variables in this research. There are three independent variables or factors in the design of this research. There is the between-subject factor Control mode, which has categories Synchronous and System driven. There are two within-subject factors, Block and Shape. Block is the distinction between the first time the test was done and the second time. Shape is the distinction between the three possible shapes discussed in section 3.2.2.

Chapter 4

Results

4.1 Data preparation

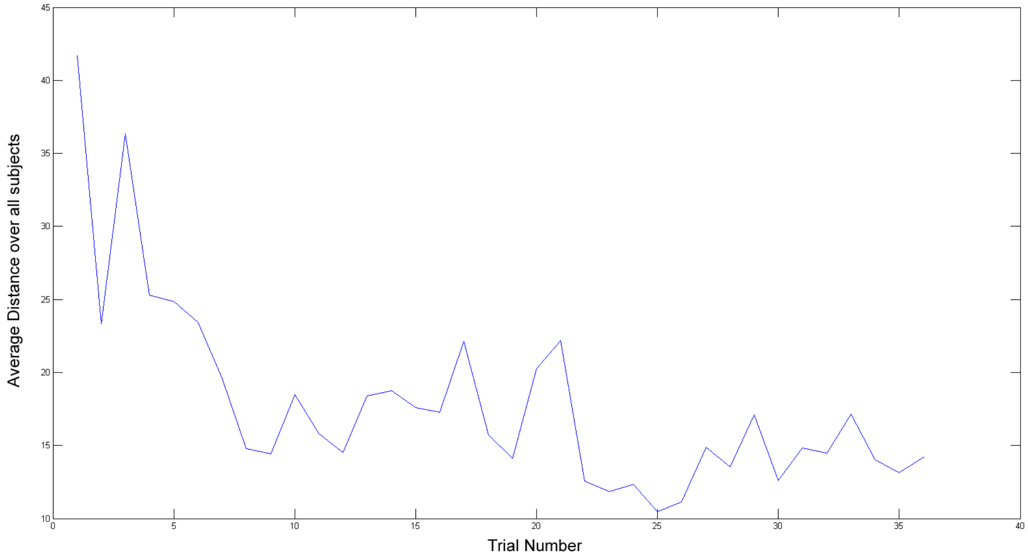


Figure 4.1: The average distance for the trials over all subjects

Before analysis all data was filtered using a low-pass filter with a cut-off frequency of 1 Hz. After calculating the Velocity, the data was filtered again, with the same filter. This smoothed both the actual input and velocity curve. This also gave better results on the ZeroCrossings, which were sensitive to small hitches in the fluency of the writing. This is similar to what was done in the 1 person and 2 person settings.

The results for each participant were calculated for the different trials and all data for the dependent variables was sorted by block and control mode. A repeated measures ANOVA was conducted with Control mode as between-subject factor and Shape and Block as within-subject factors.

The effects of Block and Shape are discussed here. Block gives an indication of the overall learning effects by the participants. Shape indicates the difference in difficulty between the three shapes. Furthermore, the effects of Control mode are discussed, this indicates the overall difference between performance in the two different Control modes. Finally, The interaction effect between Control mode and Block is discussed. This is the indication if the Control mode had an effect on learning by the user.

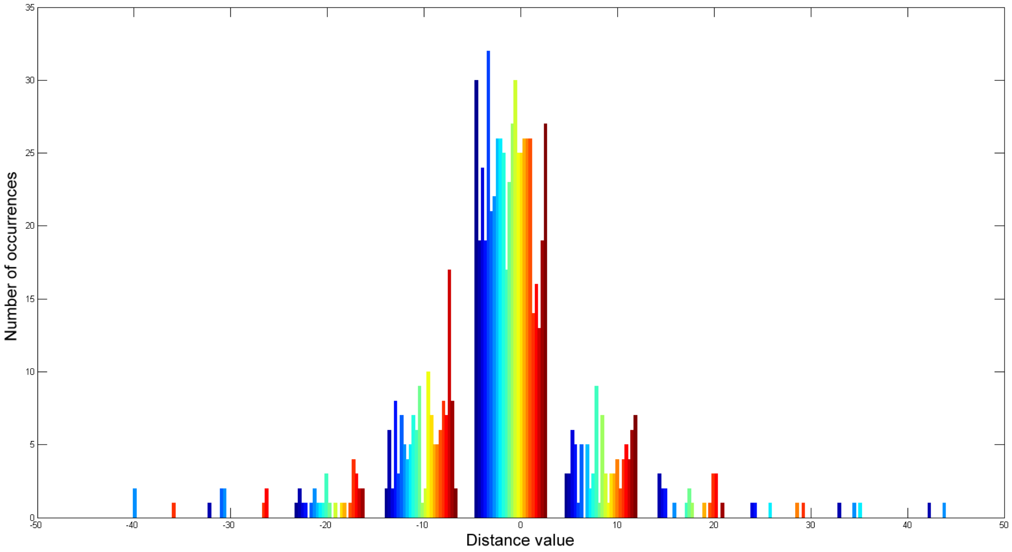


Figure 4.2: Average distance distribution (the colors indicate the distribution within the groups created to make a histogram of the continuous Distance score)

4.2 ANOVA results

For all variables there was no reason to assume the normal distribution was violated. The distribution of the Distance measure is shown in figure 4.2. For the analysis of the Control mode, a between subject test was used. Block and Shape were subject to a Univariate test. The interaction between Block and Control mode was tested using a Multivariate test.

4.2.1 Speed

Block

Significant effects of Block were found for Velocity (F(1,46)=708.247, p=.000, partial η^2=.939) and ZeroCrossings (F(1,46)=48.837, p=.000, partial η^2=.515). In all cases, the effect indicates a significant better performance on Speed between the first and second Block of the experiment. This can be seen in figure 4.3.

Shape

A significant effect of Shape was found for Velocity (F(2,8.029)=103.95, p=.000, partial η^2=.693). This effect indicates a significantly better performance on Velocity for the Eight and the U-shape than for the Oval. This can also be seen in figure 4.3.

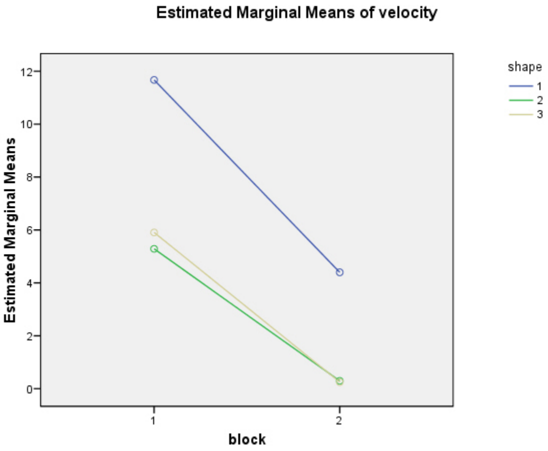


Figure 4.3: Velocity of different Shapes different Blocks

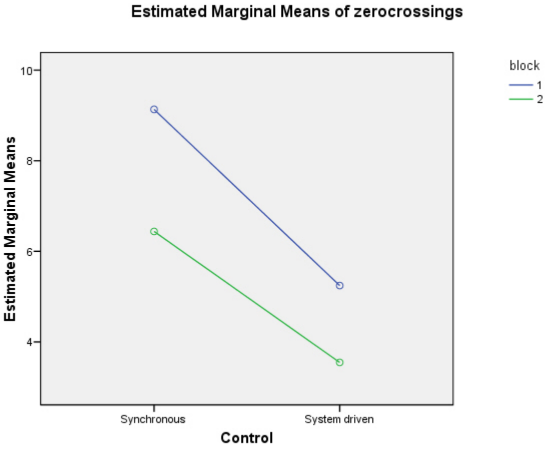


Figure 4.4: ZeroCrossings for different Blocks in different Control modes

Control mode

A significant effect of Control mode was found for ZeroCrossings (F(1,46)=11.593, p=.001, partial η^2=.201). This effect shows a significantly higher number of ZeroCrossings for the System driven setting than for the Synchronous setting. This is shown in figure 4.4.

4.2.2 Accuracy

The overall accuracy found over the course of all trials and averaged over all participants, shows a learning effect on this task. This is visualized in figure 4.1. The learning effect in the first part of the trial is very obvious after which the learning curve flattens out increasingly over the trials.

Block

A significant effect of Block was found for Distance (F(1,46)=266.861, p=.000, partial η^2=.853). This effect shows a a significant increase in Accuracy between the first and second Block of the experiment.

Shape

A significant effect of Shape was found for Distance (F(2,19.838)=99.434, p=.000, partial η^2=.684). This effect indicates that the U-shape was created significantly more Accurate than the Oval and the Eight.

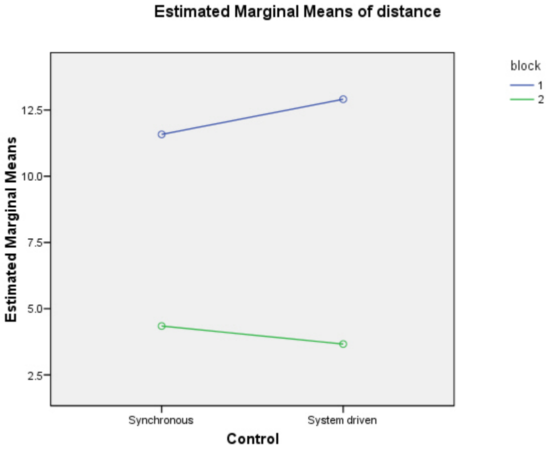


Figure 4.5: Distance of the two Blocks in the different Control modes

Interaction Control mode * Block

A marginally significant interaction effect between Control mode and Block was found for Distance(F(1,46)=3.958, p=.053, η^2 =.079). The effects indicate that the difference in Accuracy between the two Blocks in the Synchronous Control mode is larger than the difference between the two Blocks in the System driven Control mode. In the first Block the System driven Control mode is more accurate, while in the second Block the Synchronous Control mode is more accurate. This is shown in figure 4.5.

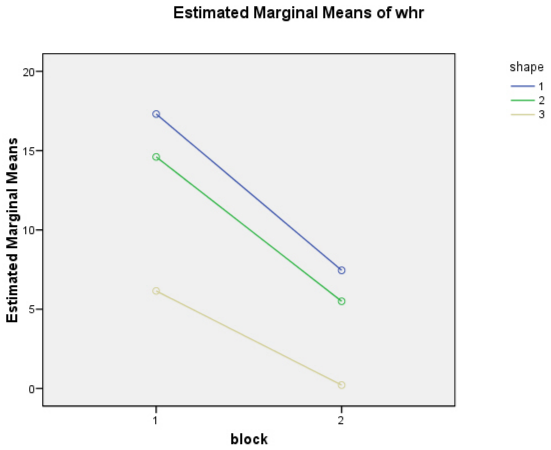


Figure 4.6: WHR of Shapes in different Blocks

4.2.3 Separation of movement dimensions

Block

Significant effects of Block were found for WHR (F(1,46)=255.115, p=.000, partial η^2=.847) and OGE (F(1,46)=329.107, p=.000, partial η^2=.877). The effects indicate that the Separation of movement dimensions in the second Block was better than the Separation in the first Block. This is shown in figures 4.6 and 4.7.

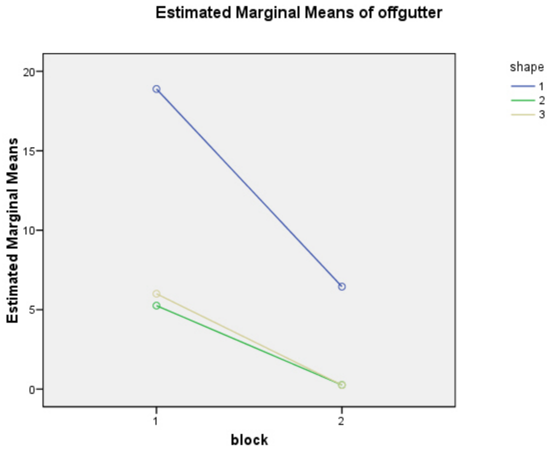


Figure 4.7: OGE of Shapes in different Blocks

Shape

Significant effects of Shape were found for WHR (F(2,24.413)=89.912, p=.000, partial η^2=.662) and OGE (F(2,45.366)=127.277, p=.000, partial η^2=.735). The separation of movement dimensions was significantly better for the Eight and U-Shape than for the Oval on both WHR and OGE. The separation of movement dimensions was significantly better for the U-shape than the Eight on WHR. This can also be seen in figures 4.6 and 4.7.

Chapter 5

Conclusions and discussion

5.1 Conclusions

The experiment was set up to find out whether the behavior of the computer influences the users ability to learn to produce handwriting in cooperation with a computer. The results we found indicate that the behavior of the computer indeed influences the users ability to learn to use such a system. Accuracy in creating the handwriting patterns is learned better when working together with a computer which adapts to the behavior of the user.

Furthermore, there are also indications that the system in which the computer adapts its behavior to that of the user, result in a more fluent way of writing. This could indicate that the speed in which the patterns are created also benefits from the adaptive behavior of the computer.

Besides this we also found that the overall performance on the task is increasing during the experiment, indicating that people learn to cooperate with the computer. This effect is shown on all measures we used. People learn to anticipate the behavior of the computer and adapt their own behavior accordingly.

5.2 Discussion

5.2.1 Results

The results we have found were good indicators for our research questions. However, we did not find a lot of evidence to support our main hypothesis. This could be because of the small number of participants or simply because the effect was not significantly large.

Other results we found was the support for findings in the research by van Wingerden [19]. People are indeed able to learn to separate the dimensions involved in handwriting production.

We also found a significant effect of shape on all but one of our dependent variables. This could be because some shapes are more easily produced than others, but because of the lack of counterbalancing or randomization, the effect is probably caused by learning effects of the user. In most cases where we found an effect, we found that for the first shape (the Oval) performance was significantly worse than for the second (Eight) and third (U-shape) shape. In some cases we found that performance on the third shape was significantly better than on the first and second shape. In the case of WHR we even found a significant improvement between the first and second shape as well as between the second and third shape.

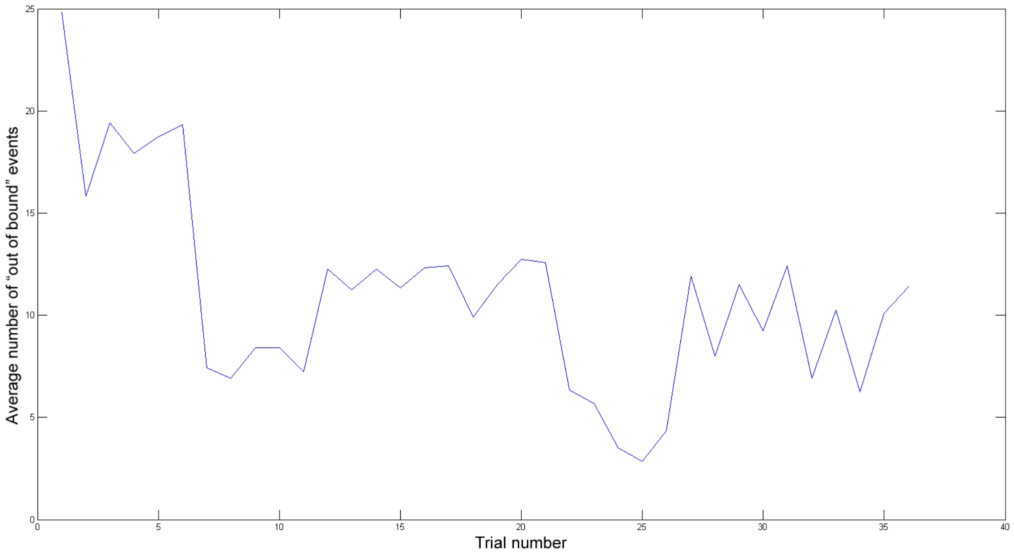


Figure 5.1: Average number of "out of bound" events

The question could rise whether or not the computer program actually had to adapt to the user, it could be that the users just did not come into contact with the behavior of the computer, because it only behaves differently if the performance of user is bad enough to cross a threshold. This was not the case for OGEs as we saw in section 4.2.3. As shown in figure the number of "out of bound" events shows a nice decrease over time.

As shown in figure 4.1 there is a very strong learning effect in the early part of this experiment. This learning happens during the training session. This effect has not been subject to research here, but we found strong increases in performance on all measures. It would be very interesting to have a closer look at the early stages of such a task.

5.2.2 Validity

A concern about the validity of this research is the relatively small amount of subjects. This was caused by the limitations put on the project by the fact that it had to fit within the scope of a bachelor thesis. Because a lot of time and effort went into creating the research platform which has already been used outside of this research, this constrained the time left for the experiment.

Another concern about the validity is the ability to separate between movement dimensions. The results show evidence that the participants are increasingly able to separate between dimensions over the course of the experiment. Figure 5.2 shows the input of the user normalized for the height of the Gutter. This shows that even though the output becomes better, the images the participants draw still resemble the Shapes very closely although they are more stretched over the horizontal axis. This could suggest that the separation between the movement dimensions observed was not complete by the end of the research. Fact remains that there is an increase in the performance on all variables measuring the separation, so the separation is learned over the course of the experiment.

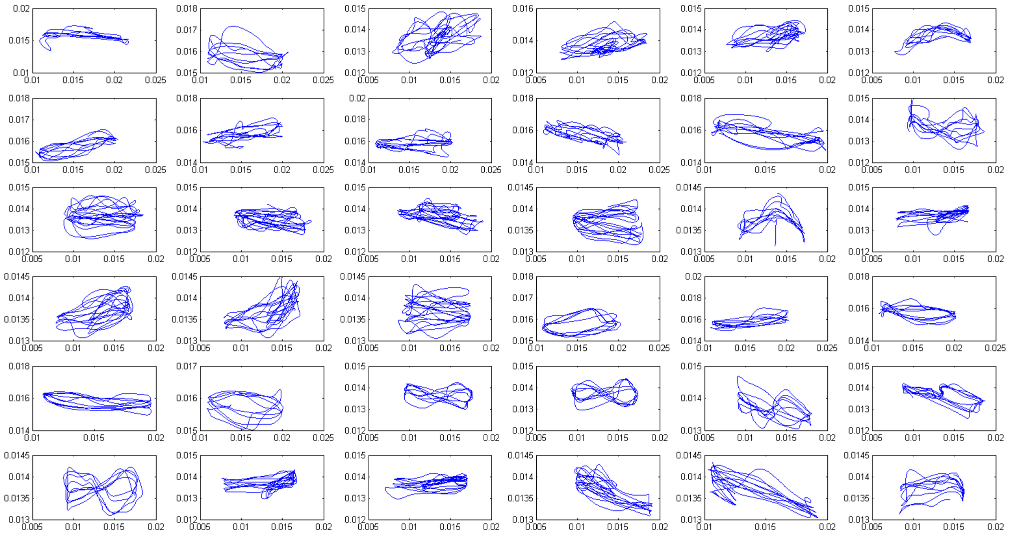


Figure 5.2: Normalized WHR of one participant over all trials

5.2.3 Relations to BCI

The findings in this study support the theory that the separate manipulation of movement dimensions is possible. It also shows that the user can benefit from the right behavior of the computer. These findings could be used in BCI research to create systems in which the computer behaves in a way that is helpful in learning to use the system. But what is helpful for the user should be examined more thoroughly.

5.2.4 Future research

This study shows that there is some influence of the behavior of the computer on the users ability to learn to produce handwriting in cooperation with a computer. Several questions however, are still to be answered. Some of these questions are about the setup of this experiment. There has been no counterbalancing or randomization in the presentation of the trial, therefore we can not answer questions about the difficulty of the different Shapes. From a questionnaire we found that most participants found the Eight shape most difficult to recreate. Which figures are indeed the most difficult and if the feeling the participants had relates to the actual performance could be subject to further research.

In this research we only looked at the performance of the user on the x axis. The performance on the y axis is not discussed, but it could be subject to future research. The difference in performance between the two axes would also be worth taking a closer look at.

Shortly mentioned in section 5.2.1 the learning effects during training are very strong, it would be very interesting to look at the early stages of learning to perform such a task. This could provide some useful insights in the field of HCI but also in learning motor control.

The behavior of the computer had just two settings in this research. This could be more of a slowly increasing amount of cooperation in future research. From no cooperation at all to adapting its behavior completely to the user is a big gap with a lot of possibilities for changes in the system. This way a more complete view of what settings are beneficial for the user is created. This could also lead to some understanding in the learning process in other more common areas.

Another suggestion for future research could be the use of changes in behavior of a computer system in an actual BCI setting. The setting used here was one where the user could easily adapt his behavior to that of the computer. In an actual BCI setting, this adaptation could prove much more difficult than suggested here.

The research platform for exploring joint action principles or the production of 2D trajectories has been quite successful. The results presented in this bachelor thesis show that the research platform can be used to assess cooperative interactions between a human user and an artificial partner. Furthermore, the research performed by van Wingerden has been made possible through the same research platform, providing ways to examine two-hand cooperation by a single person and by two different persons. Both van Wingerden and the author of the current thesis have pointed at various future research issues in the area of joint 2D trajectory generation. This research platform may serve as a very useful environment for further exploring these issues.

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