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Creating Digital Traces of Ideas

Evaluation of Computer Input Methods in Creative and Non-Creative Drawing

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Abstract

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Ideas are formed in a process of idea generation that includes creation, development, and communication of new ideas. Drawing has been used as a support for ideation for centuries. Today, computerized tools are commonly used for drawing. Such tools form a user interface between the human and the resulting drawing presented on the screen. The interface may come between the user and the drawing in a disruptive way also affecting the ideation process.

Using controlled laboratory studies, this thesis investigates the consequences of drawing with different user interfaces in two types of tasks: creative drawing tasks (based on a standardized test of creativity) and non-creative drawing tasks (i.e. shape-tracing tasks where no new idea is created). The goal was to identify and evaluate the consequences of the several issues originating from the use of different input devices, the functionality of the graphical user interfaces, the formulation of the drawing task, and the user's previous experience.

The results showed that drawing tasks are oriented toward quality of outcomes and that higher input accuracy led to higher quality of outcomes of both creative and non-creative drawing tasks. This came with a trade-off between the quantity and quality. In ideation, less accurate input devices facilitated significantly more ideas but these were of lower quality. In non-creative tracing, higher speeds caused lower quality of outcomes.

The users subjectively preferred higher accuracy, also when an inaccurate user interface offered an eraser function. However, using the eraser allowed avoiding reinterpretations of ideas and led to ideation strategies characterized by laborious drawing that negatively affected the quality and quantity of the ideas produced. For non-creative drawing, the more difficult the shapes were, the lower the tracing accuracy.

In the thesis a new framework for interaction analysis is introduced that improves the theoretical and practical understanding of computerized drawing tasks and the phenomena resulting from different aspects of the user interface design of computerized drawing tools.

This thesis demonstrates that the inaccuracy of computerized tools cannot only make our drawings less aesthetically pleasing but also negatively affect ideas that are created in the process.

Keywords: evaluation, user performance, input methods, mouse, stylus, touch, tracing, ideation

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I keep six honest serving-men:
(They taught me all I knew)
Their names are What and Where and When
And How and Why and Who.
I send them over land and sea,
I send them east and west;
But after they have worked for me,
I give them all a rest.

Rudyard Kipling
from *The Elephant's Child*

Słoneczku i Słodziaczkom

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Zabramski S., Stuerzlinger W. (2013) Activity or Product? - Drawing and HCI. *Proceedings of the Conference on Multimedia, Interaction, Design and Innovation (MIDI '13)*, ACM, 29-38

II Zabramski S. (2011) Careless touch: A comparative evaluation of mouse, pen, and touch input in shape tracing task. *Proceedings of the 23rd Australian Computer-Human Interaction Conference (OzCHI '11)*, ACM, 329-332

III Zabramski S., Stuerzlinger W. (2012) The Effect of Shape Properties on Ad-hoc Shape Replication with Mouse, Pen, and Touch Input. *Proceedings of the 16th International Academic MindTrek Conference (MindTrek '12)*, ACM, 275-278

IV Zabramski S., Shrestha S., Stuerzlinger W. (2013) Easy vs. Tricky: The Shape Effect in Tracing, Selecting, and Steering With Mouse, Stylus, and Touch. *Proceedings of the 17th International Academic MindTrek Conference (MindTrek '13)*, ACM, 99-103

V Zabramski S. (2014) A Hindrance or an Aid? The Impact of User Interface on Ideation in Computer-Mediated Drawing. *Submitted manuscript*

VI Zabramski S., Stuerzlinger W. (2013) Did We Miss Something? Correspondence Analysis of Usability Data. *Proceeding of the Interact 2013 Conference*, Springer, 272-279

All the conference papers were peer-reviewed, presented orally, and published in the respective conference proceedings. Reprints were made with permission from the respective publishers.

The order of authors reflects their contributions to the papers. I have personally written all the papers and performed the planning, data extraction, and analyses. In all papers co-authors contributed intellectually in the design phase of the studies. Additionally, Suman Shrestha collected the data for Paper IV, and Wolfgang Stuerzlinger had a strong impact on the final form of the presentation of the manuscripts.

Other Contributions

I was invited to present my research work at the doctoral consortium of CHI 2012 conference where I had the opportunity to discuss the research goals, methods, and preliminary results with a senior faculty panel consisting of Erik Stolterman, Stephen Brewster, Per Ola Kristensson, Youn-kyung Lim, Mikael Wiberg, and Katie Siek.

Zabramski S. (2012) Creative drawing with computers. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12 Extended Abstracts*, ACM, 963-966

Publications Not Included in This Thesis

Zabramski S., Ivanova V., Yang G., Gadima N., Leepraphantkul R. (2013) The Effects of GUI on Users' Creative Performance in Computerized Drawing. *Proceedings of the Conference on Multimedia, Interaction, Design and Innovation (MIDI '13)*, ACM, 142-151

Zabramski S., Neelakannan S. (2011) Paper equals screen; A comparison of a pen-based figural creativity test in computerized and paper form. *Proceedings of the Creativity and Innovation in Design Conference (DESIRE '11)*, ACM, 47-50

Zabramski S., Gkouskos D., Lind M. (2011) A comparative evaluation of mouse, pen- and touch-input in computerized version of the Torrance tests of creative thinking. *Proceedings of the Creativity and Innovation in Design Conference (DESIRE '11)*, ACM, 383-386

Zabramski S. (2011) Quickly touched: Shape replication with use of mouse, pen- and touch-input. *Proceedings of the 6th Seminar User Interface - Kansei in Practice*, PJWSTK, 134-141

Zabramski S., Gkouskos D., Lind M. (2011) A comparative evaluation of mouse, stylus and finger input in shape tracing. *Proceedings of the 1st European Workshop on HCI Design and Evaluation (EHCIDE '11)*, IRIT Press, 57-61

Contents

Abbreviations

ANOVA	Analysis of Variance
CA	Correspondence Analysis
CAD	Computer-Aided Design
CI	Creativity Index
CLC	Curves, Lines and Corners Model
EMR®	Electro-Magnetic Resonance
GUI	Graphical User Interface
HCI	Human Computer Interaction
ISO	International Organization for Standardization
LCD	Liquid-Crystal Display
M	Mean (or Average)
NLS	oN-Line System
PC	Personal Computer
RQ	Research Question
RRFC™	Reversing Ramped Electro-Static Field Capacitive
SATO	Speed-Accuracy Trade-Off
SD	Standard Deviation
SL	Steering Law
TTCT	Torrance Tests of Creative Thinking
UI	User Interface
WKCT	Wallach–Kogan Creativity Tests

Introduction

"A picture is worth a thousand words" *(Adagium)*

In mid-July of 1837 Charles Darwin started his "B" notebook of hand-written notes on Transmutation of Species. On page 36, he wrote, "I think" and below he drew a sketch of branching lines (Figure 1) representing his idea that very different species could share a common ancestor. That sketch expressed Darwin's concept of the branching divergence of varieties and relationships between species in a process of common descent from ancestors and has later been metaphorically called the "tree of life".

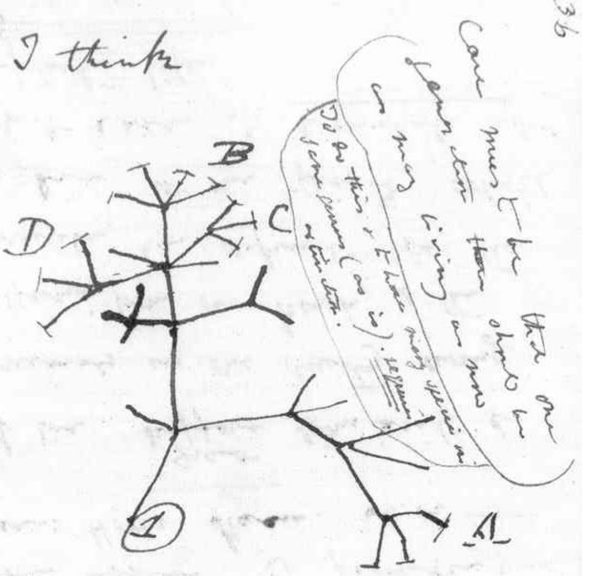

Figure 1. Page from Darwin's "B" Notebook on Transmutation of Species (July 1837) showing his first sketch of an evolutionary tree. Adopted from Wikimedia Commons (public domain).
Interpretation of handwriting: "I think case must be that one generation should have as many living as now. To do this and to have as many species in same genus (as is) requires extinction ." *(further on the same page)* "Thus between A + B the immense gap of relation. C + B the finest gradation. B + D rather greater distinction. Thus genera would be formed. Bearing relation" *(next page begins)* "to ancient types with several extinct forms".

Charles Darwin used the concept of a tree of life in the context of his theory of evolution and in 1859 the improved version of his sketch appeared in Chapter IV of Darwin's "On the Origin of Species by Natural Selection" and was the only illustration on 502 pages of that book (Darwin, 1872).

Nowadays, scientists cannot imagine creating scientific texts or notes without the use of a computer. Mouse-operated text editing software running on a desktop, laptop or tablet computer connected to the Internet is a standard workplace environment where ideas are created, stored, and shared. Yet, a question arises as to whether Darwin's conceptualization process would be affected if he were to use such a modern computerized tool, especially in a context of graphical representation of a complex idea. Does the technology enable its users to perform better in sketching ideas? Or, is it still easier, faster, and more effective to use a pen to draw on a piece of paper than perform a multitude of mouse-clicks to *insert*, *arrange,* and *modify* shapes *selected* from a *palette* offered e.g. by a *toolbar* (Figure 2) in *Microsoft Word* program? Can that process even be called *drawing*?

This thesis addresses the issues related to the use of a computer as a tool for sketching during the idea generation process.

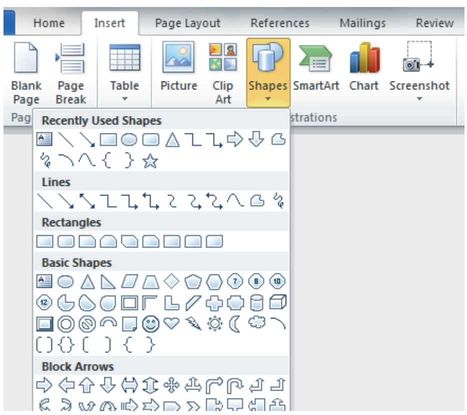

Figure 2. A fragment of the Ribbon toolbar menu with a set of shape drawing tools available in Microsoft Word 2010.

Ideation

The example of the Tree of Life illustrates how important drawing is in supporting the process of nurturing an idea. Ideas are formed in the process of idea generation (or ideation) that includes creating, developing, and communicating a new idea (Briggs & Reinig, 2007; Jonson, 2005). The ultimate purpose of ideation is to produce good and relevant ideas, not only large amounts of them (Briggs & Reinig, 2007; Reinig & Briggs, 2008). The relevance of the ideas produced is usually evaluated based on suitability for the purpose that the ideas were meant to fulfill (e.g., a relevant design solution for a particular design domain), (Shah, Smith, & Vargas-Hernandez, 2003).

Using a modern desktop computer as a tool supporting the act of ideation is generally related to using a mouse to navigate and control the software and a keyboard to write down textual notes. This procedure has been proven to be unsuitable for expressing spatial information (Oviatt, Cohen, Miller, Hodge, & Mann, 2012), supporting the view of a spatial foundation of human cognitive abilities where:

> "The evidence indeed suggests that human reasoners use functionally spatial models to think about space, but they also appear to use such models in order to think in general." (Johnson-Laird, 1999, p. 460)

Paper-based sketching has been proven to be more effective in producing larger amounts of solutions than computer-aided sketching (Stones & Cassidy, 2007). Computer-aided design (CAD) tools are unsuitable for conceptualization (Lawson & Loke, 1997; Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998).

Therefore, the role of sketching in graphical ideation and the influence of properties of computerized tools used in the process are under constant investigation (Dorta, Pérez, & Lesage, 2008).

Drawing as Sketching or Tracing

Scratched carvings or charcoal markings on a cave's wall allowed for storing ideas on a durable medium, share them, and preserve these ideas for a long time. The process of making traces on a surface that constitutes a progressive record of movement has been called the fundamental graphic act (Gibson, 1978). Its outcome in the form of a permanent track of the movement on a medium's surface forms its trace. Each individual trace has a set of properties (e.g., start, end, and curvature) and when accumulated in larger amounts, additional features of traces emerge (e.g., closure, intersections, and connections).

Whereas drawing typically has the role of a communication between individuals or their memory over time, sketching plays a role in shaping the immediate thought process. Sketching is a rapidly executed freehand form of drawing made on any drawing medium and usually involves a creative approach. The process of sketching forms a dialogue between the creator and the sketch itself, creating space for reflection (Goldschmidt, 1991; Suwa & Tversky, 1997). This form of communication adds an additional dimension to sketching that has been defined as

> "the production of untidy images to assist in the development of visual ideas." (Fish & Scrivener, 1990)

Such a constant "reflective conversation" with the material is a basis of a design process (Schon & Wiggins, 1992). Therefore, the role of sketching has been extensively studied in the context of engineering and architectural design (Purcell & Gero, 1998).

Using sketches enables us to think in a different way – "thinking visually". This kind of thinking has been found to be an important part of the thinking of great mathematicians (Hadamard, 1996). Charles Darwin's "tree of life" or Richard Feynman's diagrams from his works on quantum-electrodynamics (Feynman, 1986) are good examples of how great thinkers think in pictures, but they also suggest that using mental imagery helps to solve problems by active idea sketching.

In the creative design process sketching delivers intermediate products that enable the designer to evaluate alternatives and decide which direction to follow in relation to the design criteria (Suwa & Tversky, 1997; Verstijnen et al., 1998; Verstijnen, van Leeuwen, Hamel, & Hennessey, 2000). Freehand sketching has traditionally been considered a fundamental conceptual tool in design (Bilda & Demirkan, 2003; Plimmer & Apperley, 2002; Suwa & Tversky, 1997). Therefore, it became also an integral part of modern software design and is used to create graph-based diagrams to visualize programming organization, interdependencies, and requirements (Cherubini, Venolia, DeLine, & Ko, 2007; Socha & Tenenberg, 2013).

A sketch is rarely considered as a finished work and therefore it cannot be called a copy (Gibson, 1978). Further, not all drawings represent the outcome of creative idea generation. The goal of non-creative drawing might be to copy an existing graphic idea by tracing over the original drawing (e.g., with the use of translucent tracing paper).

This shows the existence of a spectrum of drawing tasks ranging from creative drawing tasks (where a new idea is created) to non-creative ones (where no new idea is created). Ideation takes place during creative drawing but sometimes it would be hard to say to what extent the drawn idea is copied or created. Therefore, to evaluate the potential influence of a computerized drawing tool on ideation taking place during *creative* drawing it is necessary to contrast and compare it to *non-creative* drawing, which is performed in the same situational context but where no new idea is created. This procedure constitutes the primary focus of this thesis.

Statement of the Problem

The evolution of tools used to externalize and store ideas affected the ways the ideas were presented, communicated, and distributed. Drawing on papyrus and later on paper eased storing and distribution of ideas but at the cost of the vulnerability of the medium. The printing press made replication and distribution of ideas even more widespread and affordable, and modern IT technologies transfer written information and drawings, making them ready for use in an instance.

Still, the most convenient way to perform a computer-mediated drawing is to create and modify lines on the computer's screen with some form of a manual computer input device digitizing the user's drawing movements in real-time. However, using particular computer hardware and software in combination with human biological capabilities must influence the outcome of the visual ideation tasks in numerous ways.

The users' skills and the varying experience they have in drawing also put some limits to their performance in drawing-like tasks. Depending on the type of task, this might result in a smaller or higher number of ideas generated in case of a creative drawing task, or smaller or higher accuracy in case of a shape copying non-creative task. This highlights the importance of the task formulation and the use of an appropriate measure of the user's performance.

This thesis aims to identify the elements involved in the process of shape tracing and idea sketching mediated by popular personal computer setups and to assess their respective impact on the outcomes of those processes. These elements comprise multiple properties of computer hardware and software, including the type of input device used (mouse, stylus, touch input) and software functions available on desktops and tablet Personal Computer (PC). The varying usefulness of these elements for drawing must be investigated in the context of creative and non-creative drawing tasks to evaluate how these modern ideation tools should be designed to amplify the positive and minimize the negative effects. This is done to support and help people effectively create, explore, transfer, and successfully store ideas for a future use or for sharing with others.

This research is based on the assumption that computerized tools used in the idea-sketching process affect to different degrees the outcomes of the sketching process (in terms of users' performance metrics, i.e. speed and accuracy) and, as a consequence, the ideas being created and visualized are also affected (in terms of their quantity and quality).

The main goal this thesis is to empirically determine and evaluate how particular software solutions together with popular computer input devices (i.e. mouse, stylus, and touch input) affect the outcomes of non-creative drawing (shape tracing) and creative drawing (idea sketching) that take place on the computer's screen. Therefore, the main research question is:

How does the user interface affect the outcome of computerized non-creative (shape tracing) and creative drawing (idea sketching)?

The interdisciplinary research field of Human Computer Interaction (HCI) has been the point of departure of this research. A series of explorative laboratory-based usability studies have been performed to address the research problem. Their results are presented and suggestions for future work are discussed.

Thesis outline

This thesis has the form of an extended summary that puts the attached papers in context by providing a detailed picture of the works performed and describes the relations between them. The thesis consists of:

- the first part that introduces, outlines, positions, and motivates the work performed in this thesis
- the second part that discusses the research context and theoretical background
- the third part that presents the research questions
- the forth part that discusses the tools and methods used for research, data collection and analysis
- the fifth part that summarizes the work done (Papers I–VI)
- the sixth part that presents the results of this research in the respective areas
- the seventh part discusses these results and answers the Research Questions
- the eighth part contains the conclusions of the thesis, reflections, limitations, contributions, and suggestions for future work.

Eventually, this thesis also contains a brief summary in Swedish as well as acknowledgements.

Theoretical Background

Multiple contributing theoretical frameworks have been adopted and used to address the research problem posed in this thesis. They constitute the foundation for empirical work that includes a selection of theories adopted by the HCI research community, later supplemented with evaluation activities.

Human-Computer Interaction

Probably, the closest to an intuitive understanding of the interaction between humans and computers is the *execution-evaluation cycle* (Norman, 1990). This model describes the interaction in terms of user's goals and actions executed by the user at the computer interface and evaluated to determine further actions. The issues surrounding that cycle constitute the scope of the field of HCI. This is a multidisciplinary field of research spanning a scientific community with a broad spectrum of backgrounds and research traditions. HCI is often regarded as the intersection of sociology with influences from anthropology and ethnology (that qualitatively analyzes and interprets the complexities of social settings), design (that focuses on activities leading to creating both the design objects and design processes in an aesthetic and functional way), hardware and software engineering, and applied sciences together with cognitive psychology (accentuating objectivity and precision of quantitative measurements) (Dix, Finlay, Abowd, & Beale, 2004).

HCI examines the complexity of the relation between humans and computers and has been defined and illustrated (Figure 3) in the Curricula for Human-Computer Interaction assembled by the Special Interest Group on Computer-Human Interaction of Association for Computing Machinery:

> "Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them." (Hewett, Baecker, Card, Carey, Gasen, Mantei, Perlman, Strong & Verplank, 1992)

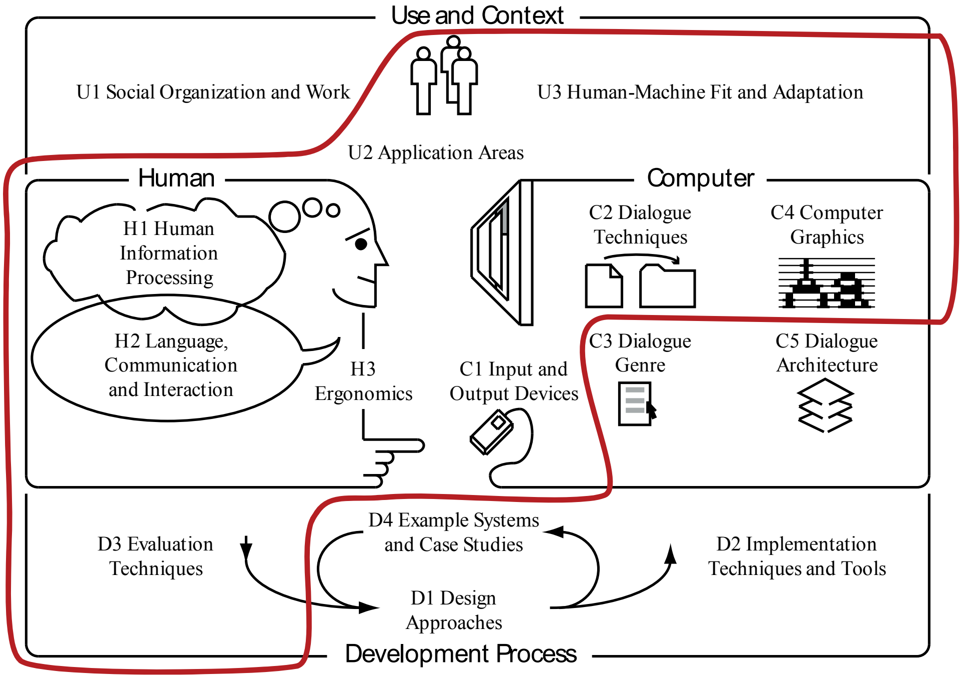

Figure 3. The area of Human-Computer Interaction according to the Curricula for Human-Computer Interaction assembled by ACM's SIG-CHI, with the red line marking the scope of this thesis. Adapted from (Hewett et al., 1992)

Figure 3 shows the broad range of aspects of the context in which the technology is designed, built, and used. It also illustrates how many elements of that context that need to be defined and analyzed because of their potential influence on the interaction process and its outcomes. This includes multiple cognitive mechanisms, physiology, or social characteristics of the human user, as well as algorithms, technology, or interface design on the computer side, not to mention the properties of the physical environment where the interaction takes place. These elements have been grouped into a few major areas: Use and Context (U), Human Characteristics (H), Computer and Interface (C), Development Process (D). This thesis addresses the following areas of HCI (as presented on Figure 3): U2, U3, H1, H2, H3, C1, C2, C4, D3.

Computer

The computer's hardware and software side responsible for detecting users input and generating an appropriate feedback augmenting human abilities should be useful to its users and support their goals (Engelbart, 1962). The most popular technological solutions are subjects of constant development and can be profoundly different from each other. Therefore, the properties of hardware and software and their interdependencies shape the quality of experience and constitute the area where the majority of the user problems originate.

Drawing tasks are usually performed with a mechanical intermediary (e.g., a pencil) and that can be matched by a form factor and technical parameters of the physical sensor. In such a case the successful use of a modality requires an additional physical object at a cost of acquisition time required by its user to locate and grasp that object (e.g., a stylus) vs. the case in which such an object is not required (e.g., direct touch input). The type of property sensed is a parameter of the physical sensor (capturing transducer) such as linear position, motion, or force (W. Buxton, 1986; Card, Mackinlay, & Robertson, 1991) and can be measured in a number of dimensions (e.g., x and y axis of a surface) at a certain sampling speed.

The computer *mouse* was presented in 1968 by Douglas Engelbart together with the "oN-Line System" (NLS) in which he used the mouse as a device controlling movements of the cursor (in the form of a small arrow) on a screen that could be used at some distance from the user (Engelbart & English, 1968; English, Engelbart, & Berman, 1967). In general, a mouse detects its two-dimensional motion (not position) in relation to the supporting surface and is equipped with buttons that are used to execute contextual commands at the current position of the mouse cursor. Mouse movements are performed with a *control-display gain*, i.e. a factor by which the cursor movements are amplified and translated to longer or faster ones (Casiez, Vogel, Balakrishnan, & Cockburn, 2008).

Ivan Sutherland's Sketchpad (Sutherland, 1963) is the most historically important example of the use of computing technology for creative drawing. The Sketchpad was a major breakthrough because it demonstrated a computer Graphical User Interface (GUI) operated with a light pen. It allowed its user to control the freehand creation of computer drawings in real-time directly on the computer's monitor (Buxton, Baecker, Clark, Richardson, Sutherland, I., Sutherland, W.R., & Henderson, 2005). Since that time, *pens* used for computer drawing were detached from the screen and used on a dedicated digitizer pad, which recently became re-integrated with the computer screens. However, the inherent problems of the pen as input device remain (Vogel & Balakrishnan, 2010). These problems include *parallax*, which is the displacement between the sensing and display surfaces causing the parallax error that is a mismatch between the sensed input position and its input position as apparent to the user because of the viewing angle (Ramos, Cockburn, Balakrishnan, & Beaudouin-Lafon, 2007). Further, the *occlusion* that takes place when the user's hand or forearm covers portions of the display during interaction (Figure 4) leads to user errors, fatigue, and inefficient movements (Vogel, Cudmore, Casiez, Balakrishnan, & Keliher, 2009; Vogel, 2010).

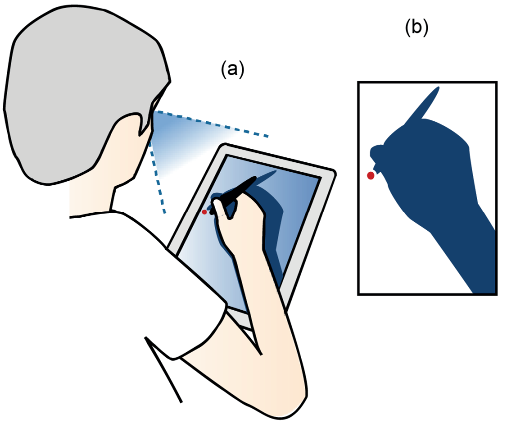

Figure 4. Occlusion caused by the hand with direct pen input (*a*), and an occlusion silhouette image taken from the point-of-view of a user and rectified (*b*). Adapted from (Vogel et al., 2009). © ACM.

Fingers also became input devices. Modern touch sensing methods can detect the position of one or multiple points of contact (*multi-touch*) and control their states (e.g., finger-down and finger-up) (Hinckley & Sinclair, 1999): Resistive *touch* sensors, which require significant pressure to detect touch position, and capacitive sensors, which also react to gentle touches. The *occlusion*-related effects of the user's hand are even more pronounced with fingers than the tip of the stylus. Additionally, the touch sensor uses the *contact area model* of touch sensing that increases the inaccuracy of the user input.

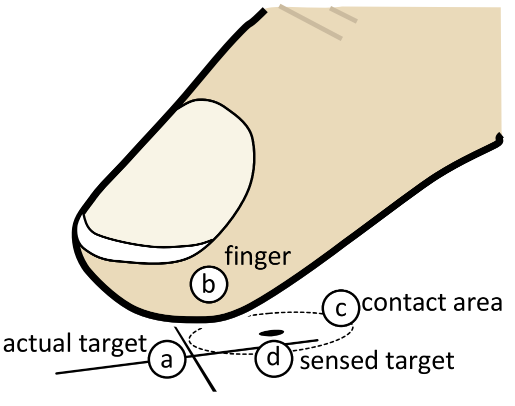

Figure 5. Contact area model. On traditional touch devices, the finger leaves a contact area (*c*), which is detected by the touch sensor and reduced to its 2D centroid (*d*) while the actual target is here marked with 2 crosshair lines (*a*) is missed by the users. Adopted from (Holz & Baudisch, 2011). © ACM.

Studies show that users do not aim by pointing with the center of the contact area (Figure 5), which causes unintentional offsets from the real measurement and differs from a user's assumption of where the intended input position is (Holz & Baudisch, 2011).
This thesis uses three popular non-keyboard input devices: mouse, stylus, and touch-screen.

For drawing, the surface of the drawing medium is the default area where the outcome of the user's actions is expected to appear. In modern computer setups this is still the surface of a Liquid-Crystal Display (LCD) computer screen and has a prominent role in the form factor of a typical PC. It is usually characterized by its *size* (the length of diagonal of the rectangular display's viewable image area), *aspect ratio* (the ratio of the width of a screen to its height), *screen resolution* (the number of the distinct pixels available on the vertical and horizontal side of the display), and *pixel density* (a value of pixels per inch, PPI) of the screen that allows the representation of the length of physical objects (e.g., fingers) in screen pixels.

The fusion of input and output including their hardware and software elements constitutes an interaction technique based on the input device's sensing capabilities and employs a particular user's physical abilities.

A mapping between the two can be natural, i.e. more or less similar to observations of the physical world (Norman, 1990). The direct stylus offers more natural mapping (e.g., its movement in contact with the drawing surface leaves a trace of the tool's path) than the mouse (e.g., amplified on-screen cursors movements and drawing mode available after pressing the mouse's button). This not only leads to an immediate understanding of how the stylus operates but also allows to directly transfer and apply the drawing skills acquired with a physical pen or pencil. An input device with inexistent control-to-display gain is an *absolute* input device (e.g., stylus or touch-sensitive screens), whereas *relative* devices sense only changes in position (mouse) and need an on-screen cursor that resumes movement from its current position in response to the motion of the device with predefined control-to-display gain. In absolute mode the cursor (if present) simply jumps to the new position.

Generally, absolute mode is preferable for drawing, handwriting, or tracing (C Forlines, Vogel, Kong, & Balakrishnan, 2006; Clifton Forlines, Wigdor, Shen, & Balakrishnan, 2007).

The system's feedback can be provided in a different physical space (the screen) than the input space (e.g., in case of the mouse controlled cursor movements). This separation eliminates the occlusion effects but requires a representation of the *indirect* input device in the output space (e.g., a display cursor). Stylus or touch-sensitive screens are examples of *direct* input devices. To distinguish between pen and touch input on the same screen independent digitizing layers are required (Engelhardt, 2008).

Even small differences in the physical properties of a particular input device (such as size, weight, and friction) can be expected to influence a user's results even with the same kind of input method used (Mizuhara, Hatano, & Washio, 2013). These can be easily introduced by a combination of different hardware and software solutions in which sampling resolution, sampling frequency, and sampling delay affect the way the computer system detects and quantifies the users' action. Delays are introduced at every stage of hardware and software operation and are accumulated over the interaction loop. *Latency* is the end-to-end measure of the time between a physical user's action and the system's feedback that can be perceived by the user. High latency can result in the discrepancy between the actual position of the stylus or a finger and its position currently sensed by the system. It can also trigger undesirable effects on a user's performance (MacKenzie & Ware, 1993).

When hardware capabilities and software functionality are effectively matched, they create a space where interaction between humans and machines can occur, namely the User Interface (UI) (Marcus, 2002). Since the times of Sketchpad, UIs allow for interactive, artistic drawing (Sutherland, 1963). This takes place within GUIs that permit the operation of computers with the use of graphical elements metaphorically representing and indicating the system's functionality on the monitor display with immediate, real-time feedback (Dix et al., 2004).

Human

It is not possible to talk about the UI without talking about its actual user(s) and their capabilities (Norman & Draper, 1986). The human mind operates on perceived information originating from a number of sources such as the sense of vision or tactile sensing. The understanding of the surrounding world is limited by the mind's capabilities (limitations such as memory capacity, attention, and information processing or decision-making speed). Additionally, while drawing, the integration of sensory information about the current state of the body and the surrounding world allows humans to use their motor control abilities to organize and execute drawing movements or actions. This process employs particular sets of muscles at appropriate forces and involves cooperative interaction between the central nervous system and the musculoskeletal system engaging the user's perception, cognition, information processing, and motor coordination (Rosenbaum, 2010).

Human Motor Control Theory

The theoretical approach to how humans control their motor behavior has been historically divided into two camps: the centralists and the peripheralists (Schmidt, 1988). The centralists view motor control behavior as driven by *motor programs*, i.e. inside-out processes originating from internal representations in the mind. The emphasis on the outside-in feedback from the environment regulating motor control behavior is characteristic of peripheralists who would claim that the shape produced during drawing would be impacted by the different types of interaction of the finger or the stylus and the surface of a screen. In contrast, the effector independence theory (Wright, 1990) proposes that the use of a finger or a stylus in writing brings little difference to the shape produced in that both are driven by internal representations. This duality shows that it is important to assess how shape perception affects drawing movement, and how drawing movement affects shape perception when combined.

The Perceptual-Motor Integration

In the perspective of ecological psychology sensory signals could be directly coupled to motor commands, suggesting that interactions within the ecology of motor and sensory processes are bi-directional (Gibson, 1978). However, voluntary actions have been traditionally viewed as mediated by the brain processing sensory information and computing motor commands (Latash, 2012; Rosenbaum, 2010).

The progressive movement of the drawing tool over the surface is both felt and seen. In some situations the perceived information about the past or the present influences the drawing process in the present or future and forms a looped chain of cause-and-effect events that "feeds back" into themselves and may cause correction attempts in drawing movements if the error is noticed by the user in a negative *feedback* loop. In a *feed-forward* system the controlled variable adjustment is not error-based. Instead, the system responds in a predicted or pre-defined way without responding, e.g., to how big the drawing error is (Rosenbaum, 2010).

Visibility of visual feedback in the form of a permanent trace left by the tool is what is assumed during drawing. When using a non-tracing pencil for drawing, children stopped scribbling and did “refuse to 'draw a picture in the air' on request, and asked for paper on which they could draw a 'real picture'” (Gibson, 1978). The visual feedback that is visible can be considered an external aid, as in the distributed cognition view of cognitive support (Hutchins, 1995; Norman & Draper, 1986), or as a trigger of difference-sensing and difference-reducing mechanisms of the human mind, as in the computational theory of mind (Pinker, 2005). These theoretical views, together with previous experimental results on interaction feedback (Sun, Ren, & Cao, 2010), lead us to expect that the presence of visual feedback has a positive influence on the results of the drawing task.

On the other hand, the studies on handwriting showed that visual feedback is too slow to be used for correction during fast handwriting (Teulings & Schomaker, 1993). It took 100ms to write a substroke (Smyth & Silvers, 1987) with human reaction time for light stimuli oscillating approximately 125ms (Luschei, Saslow, & Glickstein, 1967), which suggests that time to make corrections based on visual feedback is not sufficient. The general observation that handwriting is not noticeably impaired by the withdrawal of vision was explained by increased processing time as a compensation for the inaccuracy preventing strategy, indicated also by the increase in reaction time (van Doorn & Keuss, 1992). These specific strategies employed to preserve shape in the absence of visual feedback show flexibility of writing as a motor skill.

Perception of the drawn *shape* has been studied extensively and multiple qualities of shapes have been identified as perceptually demanding (Attneave & Arnoult, 1956; Attneave, 1957). The size and shape of a tool's trajectory while drawing are important factors in scribbling and cursive handwriting movements. It has been found that they obey the two-third power law (Viviani & Terzuolo, 1982) for curved movements and originate from effects of muscle mechanics and limb dynamics (Gribble & Ostry, 1996). The shape of the tunnel affecting the results of tunnel-steering have been found significant and modeled by the Steering Law (SL) (Accot & Zhai, 1997).

Yet, another source of inaccuracy originates in the general rule, i.e. humans are subjects of the *speed-accuracy trade-off* **(SATO)** (Fitts, 1954; Latash, 2012). This trade-off effect means that they trade speed for accuracy (or vice versa) when they perform aiming movements after being told to do it "as fast and as accurately as possible". However, it has been also observed that the users demonstrate operational biases toward speed or accuracy in steering movements (*subjective operational bias*) when the task was not explicitly spatiotemporally constrained (Zhou & Ren, 2010).

Finally, the lack of precision of the computerized tool may yield negative reactions that lead to a user's frustration when facing *ambiguity* (Huh, Ackerman, & Douglas, 2007). The drawing inaccuracies originating from the input method may have similar effects (W. Buxton, 2007). However, the fact that the user can see the line drawn or not (or to what extent it can be seen) is a parameter of the visual feedback and it can be controlled and manipulated.

Cognition and Creative Drawing

Skilled performance is perceptually driven and occurs without the need for conscious attention. The constrained action hypothesis states that performance often suffers when one thinks about performance (Wulf, 2007). The same happens in decision making (Mowbray & Rhoades, 1959; Smith, 1968) and memory retrieval tasks (Collins & Quillian, 1969). However, these kinds of tasks can benefit from *learning effects* regularly observed as a reduction in the relation between the participant's progressing experience and measured task efficiency (e.g., shortening task duration or reducing the user's error) (Schmidt, 1988).

Sketching has been identified as a means of extending the working memory of the designer (Ullman, Wood, & Craig, 1990), but line drawing is also intriguing because it offers stimuli that are very different from sensory perceived real scenes. The central issue, also addressed in this thesis, is the strategy used by our visual system and how it deals with elements of a shape that carry more visual information than its other parts. Sketching of an image constructed from a mental image in the mind has been identified as a subject of mental transformations (Gibson, 1978; Attneave, 1954). In cases when that mental image has to be created first not only perceptual and motor mechanisms and processes are employed but also more high-level cognitive ones that involve creativity (Finke, Ward, & Smith, 1992). However, from the many definitions of *creativity* available, none is commonly accepted (Treffinger, Young, Selby, & Shepardson, 2002). Even though creativity is considered a desirable phenomenon in education, arts, and science, the lack of a structured empirical approach from psychology (Finke et al., 1992) makes it difficult to define what exactly a creative drawing behavior is. The ability to produce many appropriate and refined ideas has been identified by Guilford as a main feature of the creative process and termed a divergent production (Guilford, 1956). Such an ideation process is characterized by multiple production factors, including expressional and ideational fluency (quantity of ideas), together with originality, flexibility of closure, and elaboration, which are the measures of quality of ideas. Examining final products of figural creative production through the lens of these ideation factors has become the basis of creativity assessment methods evaluating participants' creative performance in a fixed time-span. Guilford's divergent production factors have been conveyed as creative thinking characteristics tested by two widely used creativity assessments: The Torrance Tests of Creative Thinking (TTCT) (Torrance, 1990b) and the Wallach–Kogan Creativity Tests (WKCT) (Lau & Cheung, 2010). Participants solving the WKCT do not have to create drawings in that the test requires only their verbal responses, even though both verbal and figural stimuli are given. Therefore, the TTCT became the most widely used set of creativity tests involving paper and pencil drawing (Kim, 2006). The TTCT was developed in the 1960s and its validity has been debated over the years (Almeida, Prieto, Ferrando, Oliveira, & Ferrándiz, 2008; Lubart, 2001), but confirmed by longitudinal studies carried out internationally (Cramond, Matthews-Morgan, Bandalos, & Zuo, 2005).

Research Approach

This chapter describes the research approach taken.

Computerized Drawing as an HCI Task

To describe computerized drawing as an interaction between computers and humans we need to define the task, its context, and all the elements involved on both the human and computer side of the interface.

A drawing task can be formulated differently for different experimental conditions and can be interpreted differently by the test participants. Accordingly, a task might convey different meanings for different people under different circumstances (Draper, 1993). Therefore, the way even similar drawing tasks are formulated strongly affects a user's understanding of the expected outcomes.

Technically speaking, drawing is a manual task mediated by a drawing tool. It takes place in three dimensions and has an important aspect of duration. The outcome of the process of drawing is reduced to a static form preserved on a surface of the drawing medium and constitutes a shape visually resembling the intended one. Drawing is a truncated form for a diverse set of tasks, influenced by the tool, the purpose, the artist's skills, and the amount of time and detail needed. Drawing can be performed using multiple drawing techniques and tools combined to achieve intended outcomes (Encyclopædia Britannica Inc., 2012):

- to draw: to represent an object or outline a figure, plan, or sketch by means of lines.
- to draft or to sketch: to make a rough drawing (outline) to note down preliminary ideas that will eventually be realized with greater precision and detail.
- to trace or to delineate: to copy (carefully or painstakingly) or make apparent the outline of the lines or letters by following them as seen through a superimposed transparent sheet.
- to write: to manually reproduce elements of alphabetic or pictorial language with calligraphy as the art of beautiful handwriting.

The drawing style chosen by the artist may be highly dependent on the context of a particular drawing task, but a small change to a particular drawing task may make it harder to categorize it clearly (e.g., drawing a single letter vs. writing the same letter as part of a word). In my view creative and non-creative drawing tasks represent two types of task that are different in nature. Creative idea sketching is a high-level cognitive task that is much more demanding to the user than a low-level non-creative shape tracing task, which mostly engages perceptual-motor mechanisms.

Interaction Analysis of Computerized Drawing

Understanding the situational context of the interaction is not only limited to the device in use, the user, or the environment of use but also to the tasks that the device is used for (ISO, 1999a).

To analyze the interaction that takes place during the drawing task a framework is needed that would help to identify the influential aspects of the process with high descriptive power. The detailed analysis of relations between users, artifacts, and the task's situational contexts should result in improved categorization of tasks and might even help to interpret experimental results.

A set of principles, rules, and properties that guides the design or can help in the analysis of an interface is called an interaction model (Beaudouin-Lafon, 2000). Multiple frameworks for analyzing computer-based tasks have been proposed that could be used for analyzing computerized drawing tasks. Such frameworks include, for example, generic interaction models: Direct Manipulation (Shneiderman, 1983, 1997), Surface Interaction (Took, 1990), Direct Combination (Holland & Oppenheim, 1999), or Instrumental Interaction (Beaudouin-Lafon, 2000).

A dedicated model focused particularly on drawing with pens has been presented (Heinrichs, Schreiber, Huber, & Mühlhäuser, 2011). The W^5 meta-model has been designed to describe the use of a digital pen and normal paper and seems to be well-matched for the purpose of analyzing computerized drawing tasks. W^5 describes actions executed by the user in the physical and digital world and offers a standard of notation for describing paper-based drawings. The W^5 meta-model originally uses:

W_1 – "Where": Spatial dimension that relates to the location where the drawing tool and the medium meet and where the user's drawing takes place.

W_2 – "When": Temporal dimension that relates to the aspect of time of the user's drawing.

W_3 – "What": Content dimension that relates to the drawing outcome created by the user (including gestures or written commands).

W_4 – "Who": Originator dimension that relates, e.g., to the user as a person and human being.

W_5 – "Why": Contextual task dimension that relates to the drawing task that is being performed.

While W^5 already addresses many important issues, it assumes the context of pen-and-paper interaction. However, the majority of computer-assisted drawings take place in a paperless context with the use of intermediary (direct or indirect) input devices. The interaction with a graphical input (Figure 6) has been characterized by a three-state model (W. A. S. Buxton, 1990).

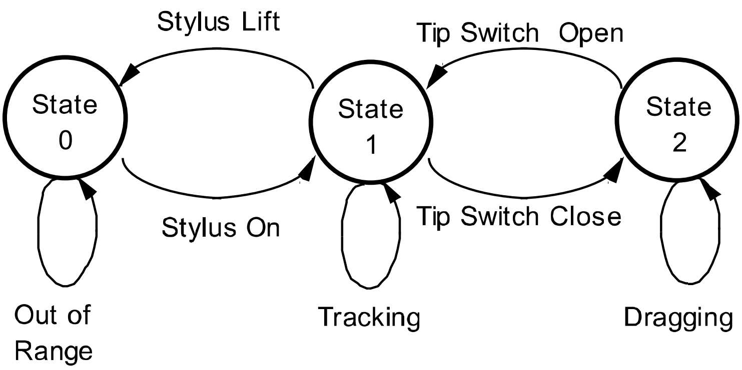

Figure 6. Three state transaction represents interacting with a tablet digitizer and a pressure sensitive stylus. *State 0* represents the situation when the stylus is out of the tablet's sensing range (the stylus' tip switch in its open state). In *State 1* (position tracking) the stylus is in tablet's sensing range and the on-screen cursor follows the stylus' motion. In *State 2* the system detects the extra pressure applied on the stylus that closes the tip switch and appropriate feedback is delivered (e.g. icon's movement if dragging or a trace if drawing). Adopted from (W. A. S. Buxton, 1990).

This model directly shows the differences between the direct and indirect input methods used in this research:

- on-screen stylus and touch input operate using two states only: State 0 (out of range) and State 2 (drawing).
- mouse also operates between two stages: *State 1* (tracking), which is never out of range (i.e. in *State 0*) and *State 2* (drawing) when a mouse button is pressed.

The key aspect of *the tool* that mediates the drawing has been already introduced in the *Instrumental Interaction* model (Beaudouin-Lafon, 2000) as a conceptual separation between tools (called *instruments*) and domain objects (dimension W_3). The concept of *instrument* contains a hardware component (e.g., input devices) and a software component (e.g., components of a UI) that have their impact on the outcome of the whole process (dimension W_3). The Instrumental Interaction model identifies three properties that help to evaluate the instruments used (Beaudouin-Lafon, 2000):

- *Degree of indirection* – a measure of the spatial and temporal distance between the input and output space introduced by the instrument.
- *Degree of integration* – the ratio between the degrees of freedom of the instrument and the hardware input device.

- *Degree of compatibility* – a measure of similarity between the actions performed on the instrument and the feedback received.

Because the majority of computer-assisted drawing takes place in a “paper-less” context with the use of intermediary input devices, it is necessary to include the properties of the *tool* used in the analysis of such interaction and assess their expected influence on the drawing outcomes (MacKenzie, 1992; Zabramski, 2011a).

Evaluation of Computerized Drawing

Measureable human performance together with the facts from physiology, perception, and cognitive psychology traditionally constitute the core of HCI. Such measurements are generally made with clearly described test conditions in which the users’ responses can be measured with error rates and within a given time frame. This thesis will use the same approach and measure the users’ performance in clearly specified drawing tasks. The comparison of users’ performance in different test conditions can serve as illustration of how more or less useful given UI is for drawing.

Definition of Usability

Multiple approaches toward defining usability can be found in the literature. The general concept of usefulness (Nielsen, 1993) defined as how a system is suitable to achieve certain goals encompassed *utility* and *usability* (Grudin, 1992). Utility is defined if appropriate functionality is available but usability is defined by a set of terms consisting of learnability, efficiency, memorability, errors, and satisfaction (Nielsen, 1993), or task completion, resources needed, and the user’s comfort level (Kulyk, Kosara, Urquiza, & Wassink, 2007). The definition established by the International Organization for Standardization (ISO) is closer to the latter and defines usability as:

> The “extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.” (ISO, 1998)

Usability is a combination of many concepts that include:

- ***Effectiveness***: "accuracy and completeness with which users achieve specified goals".
- ***Efficiency***: "resources expended in relation to the accuracy and completeness with which users achieve goals".
- ***User satisfaction***: "freedom from discomfort, and positive attitudes towards the use of the product".
- ***Context of use***: "users, tasks, equipment (hardware, software and materials), and the physical and social environments in which a product is used".

These definitions are very useful because they provide a standardized meaning to the concepts. They highlight that the overall usability of a given technological solution not only depends on how it is designed but also on multiple factors that are independent from the technology used, i.e. on who will be using the system, in what environment, and for what kinds of tasks. Usability is not an attribute of the tool's design and a usable tool in one situation might not be usable in other contexts of use.

Evaluation of Usability

Evaluations of usability can have different goals and can be performed at different stages of the development process. They can be divided into two categories: Formative evaluations and Summative evaluations. Formative evaluations are performed during the design process to identify usability problems that could be immediately addressed in the same or next design cycle. Summative evaluations are performed after the design is finished and its resulting properties can be assessed (Hartson, Andre, & Williges, 2001).

Moreover, methods for measuring usability can be divided based on how the evaluation is done. Analytic evaluation is based on analysis of a design through examination by an evaluator(s) with, e.g., a list of evaluation heuristics (Nielsen, 1992). Alternatively, empirical evaluations are based on observations of performance or opinions of actual users using the design (Hartson et al., 2001).

The ISO standard is given in the form of a guidance, general principles, and techniques, rather than in the form of requirements to use specific methods. It also shows that, under certain conditions (e.g., the same task context, tools, and user group), the usability can be objectively assessed and can deliver measurements for meaningful comparisons. These conditions can be kept unchanged in the studies in a laboratory setting, which is the most commonly used empirical evaluation method for usuability. In this thesis a summative approach to evaluation in the form of laboratory studies will be used. This will deliver mainly quantitative but also some qualitative results.

The laboratory tests are designed and preparations take place according to a plan that includes recruitment of the participants with intended characteristics and selection of tasks performed in a certain order with the use of appropriate tools. After the test, participants can complete post-test questionnaires and are debriefed. More on laboratory usability testing can be found in (Dumas & Redish, 1999; Rubin & Chisnell, 2008).

The ISO standard is quite specific about what elements constitute the *context of use*, i.e. elements of the evaluation environment that should be tested:

- ***User***: "person who interacts with the product".
- ***Goal***: "intended outcome".
- ***Task***: "activities required to achieve a goal. These activities can be physical or cognitive".
- ***Equipment/product***: "part of the equipment (hardware, software and materials) for which usability is to be specified or evaluated".

As noted above, the ISO standard suggests how to evaluate effectiveness and efficiency, and to a certain degree, satisfaction. These suggestions can be translated into potential measures, i.e. values resulting from measurements will highly affect selection of the process of obtaining them.

Evaluation methods are strongly related to typical tasks and activities in a tested system. Freehand drawing (called *inking*) and tracing have been proposed as a means to evaluate the match of input devices to drawing applications (W. A. S. Buxton, 1987; ISO, 1999b). However, the elements that constitute the *context of use* of the computerized drawing tools, according to the ISO definition of usability, are very similar to certain dimensions of the W^5 framework: e.g., "user" (in ISO) is equivalent to dimension W_4 ("who") (in W^5), "goal" is equivalent to dimension W_3 ("what"), and "task" is equivalent to dimension W_5 ("why"). Additionally, the measures of the usability's outcomes (i.e. effectiveness, efficiency, and user satisfaction) give more details to the dimension W_3 ("what"). On the other hand, W^5's spatiotemporal dimensions W_1 ("where") and W_2 ("when") give more detail to the ISO's rather general *context of use*. In addition, the ISO definition of usability highlights the aspect of "equipment/product" that points to the role of computerized tools used in drawing. Therefore, the W^5 model and ISO approach to usability will be used jointly to formulate more detailed research questions and later precisely identify what elements of the interaction during drawing tasks should be controlled and measured and with what methods for both creative and non-creative drawing.

Research Questions

Computerized tools (i.e. GUIs and input methods) used in the idea-sketching process affect to varying degrees the outcome of the drawing process. However, depending on the degree of freedom originating from constraints imposed by the task formulation, the drawing task can be perceived differently and has to be considered as:

- non-creative shape tracing in which no new idea is created but varying user's speed and accuracy is affected,
- creative idea sketching with the ideas that are being created and visualized are affected (in terms of their quantity and quality).

The main goal of the present thesis is to determine and evaluate:

How does the user interface affect the outcome of computerized non-creative (shape tracing) and creative drawing (idea sketching)?

To assess these effects several sub-questions have been formulated:

RQ1: How does task formulation affect the results of idea sketching and shape tracing?

RQ2: How do different computer software and hardware tools affect the results of idea sketching and shape tracing?

RQ3: What are the user-related effects and in which way do they affect the results of idea sketching and shape tracing?

Initially, the approach towards drawing tasks in HCI has been presented and discussed in Paper I. Shape tracing has been defined and used as a baseline task in comparative studies on the usability of the three input methods (Paper II–IV). The results from that part showed the influence that the input methods have on the outcome of shape tracing. Other observed effects related to task formulation and shape used are noted and addressed experimentally (Paper II & IV). The issues related to users' preferences and satisfaction in tracing are described in Paper VI. Paper V presents a summary of three experiments focused on ideation in a sketching task and the results are compared with the findings from a tracing task.

Apparatus and Methods

This chapter presents an overview of the studies performed, lists the hardware and software elements of the experimental setup used, and describes the data collection and analysis methods.

Methodological considerations

To get valid and generalizable results an experimental approach was chosen for the investigation. The research questions were investigated with a series of empirical studies performed in a usability laboratory setting where multiple measurements have been collected.

The comparative studies on shape tracing involving variable visibility of the trace drawn (e.g. Study t3 in Paper II) had a mixed design. The participants were randomly assigned to two visual feedback conditions in the balanced between subjects design. All studies on shape tracing (Paper III and IV) had input methods (mouse, stylus, and touch input) administered within subject and randomly distributed to the conditions for counterbalancing potential order effects.

Table 1. *Overview of the studies on shape tracing with mouse, stylus, and touch.*

Paper	Study	Shape	Sample Size
*	t1	1, 2	8
*	t2	2	34
II	t3	1	16
*	t4	3	9
III	t1, t2, t3, t4	1, 2, 3	–
IV	t5	4, 5	12

"" – study not reported separately*

In the case of the comparative studies on ideation (Paper V) it would not be possible to get unbiased results from a series of full consecutive creativity tests taken by each user with multiple test conditions. Therefore, a between subject study was performed where randomly assigned participants used one version of the test and the remaining participants used the latter one, and performed all three activities of the TTCT in original order.

Table 2. *Overview of the studies on ideation.*

Paper #	Study #	Condition	Sample Size
V	i1	pen & paper vs stylus & PC	16
V	i2	mouse vs stylus vs touch	24
V	i3	simple GUI vs advanced GUI	16

As a complement to the quantitative performance measures, user satisfaction was measured by post-test questionnaires. Pre-test questionnaires were used to capture the demographics of the test groups in both the studies on tracing, and ideation.

Apparatus

The combination of particular hardware and software tools must be expected to bring multiple consequences like e.g. using a stylus to operate a conventional GUI (Vogel & Balakrishnan, 2010). Therefore, the technical details of the hardware and software setup must be presented to support potential attempts of studies' replication.

Hardware

HP TouchSmart tm2-1090eo Notebook PC (Figure 7) was used in the majority of the studies presented in this thesis (Paper II, III, IV, and Study i1 and i2 from Paper V). This model was equipped with 1.3 GHz Intel Core2 Duo processor
and 4GB of system memory (HP, 2012).

Additionally, the stationary HP desktop computer was used. It was equipped with 3 GHz Intel Xeon CPU and 3GB RAM.

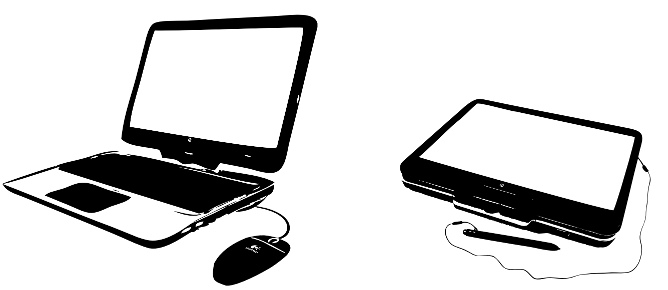

Figure 7. HP TouchSmart tm2 in "laptop mode" with mouse (*left*) and in "tablet mode" with stylus (*right*).

PCs' Form Factor

The display panel of HP TouchSmart rotates 180° and folds flat with the screen facing upward what – made it functionally similar to a tablet and it was used as such. Study i3 from Paper V used the traditional stationary desktop computer with the 17" LCD display, standard keyboard, and optical mouse.

Displays

HP TouchSmart had integrated 12.1" Diagonal WXGA LED BrightView Widescreen Display (16:10 wide aspect ratio) with resolution of 1280x800 pixels with the pixel pitch of 0.204 mm.

The desktop HP used Samsung SyncMaster 172x display that is a 17" LCD screen with 1280x1024 pixels resolution with 0.294 mm pixel pitch.

Input methods

The display of HP TouchSmart was integrated with two sensing mechanisms produced by Wacom Co., Ltd. (Wacom, 2012): capacitive digitizer that supports touch sensing using RRFC™ (Reversing Ramped *electro-static* Field Capacitive) technology, and inductive digitizer detecting the position of the stylus using EMR® (Electro-Magnetic Resonance) technology.

Stylus

Inductive transducer sensing the position of the stylus used in HP TouchSmart suffers from the parallax offset that is a result of the physical distance between the tip of the stylus and the coil that is located deeper in the body of the electromagnetic stylus. Additional parallax error may result from the distance of the display's glossy surface and the actual sensing surface located under the LED display but becuase the tilt angle of the stylus is known, this offset is compensated.

Touch input

Touch transducer allowed to sense two points of touch simultaneously. It could also be switched on or off therefore it was possible to implement so called palm-rejection mechanism which allowed the user to rest the palm on the display while drawing using the stylus, without affecting the results.

Mouse

Additionally, HP TouchSmart computer was operated with an external mouse. Logitech Basic optical mouse was used (Paper II and IV, and Study i2 in Paper V) or and DELL Optical USB 5 Button Scroll Mouse was used with the desktop PC in Study i3 from Paper V.

Input-Output Mapping

The entire Tablet PC's screen was mapped directly as the touch and stylus sensing area. However, mouse movements were amplified by a factor of 2 and translated to longer cursor movements therefore a constant control-display gain was achieved resulting in one centimeter of the mouse movement corresponded to 2 centimeters (i.e. 98 pixels) on the screen.

Latency

In experimental studies on pointing, latency of about 100ms and higher typically exhibited strong negative effects on user performance (MacKenzie & Ware, 1993). Therefore, it was important to measure the end-to-end latency of the system – i.e. cumulative latencies introduced by the hardware and software components. These would include the position accuracy, sensor's sampling rate and computing demands of the Operating System and the test software application. Therefore, a test session was video recorded where a rapid drawing task was executed with the use of the three sensors used. The detected latency rates were 0.058 sec. for mouse, 0.102 sec. for stylus, and 0.122 sec. for touch input. All latencies were satisfactorily low for the purpose of drawing tasks and should not be expected to affect the measures used. The measured latency was not observable during typical drawing and any potential effects of the latency introduced by the computer used were balanced by the fact that the same software and hardware setup was used for all input methods – equally affecting the results.

Software

The details of the software setup were as follows.

Operating System

The test computers were running 64bit version of Microsoft Windows 7 with default settings for all input methods with standard system cursors visible while interacting: "✧"for stylus and touch, and "↖" for mouse cursor visible always.

Test Application

Test applications offering the tracing functionality and showing test stimuli with different GUIs described above, used for Paper II, III, and V were developed in Action Script 3.0, and for Paper IV in Java. Additionally, TechSmith Morae v.3.2 was used to record all the user's actions, system events, computer's screen view and a picture from an external video camera.

Methods

This work falls into the branch of HCI that borrows concepts, terminology and methods from experimental psychology. Thus the methodological description will be in the general form of the treatment and effect paradigm.

Independent Variables

Task Type

As identified by the W^5 meta-model the task formulation and its multiple properties can become the factor potentially influencing the users' performance. The two basic groups of tasks addressed in this thesis are creative drawing (idea sketching) and non-creative drawing (shape tracing).

Idea Sketching

The figural part of the TTCT provides the participants with the drawing situation and additionally offers a standardized measure of the participant's creativity and therefore must be performed according to the manual (Torrance, 1990b). It includes three activities:

- Compose a drawing (*Picture Construction Activity)* – requires the participant to draw a picture in which a closed shape presented becomes an integral part.
- Finish a drawing (*Incomplete Figures Activity)*– where the participant is provided with 10 different open shapes and is required to draw as many pictures as possible with each shape as an integral part.
- Compose different drawings (*Repeated Figures Activity)* – provides 30 sets of paired parallel lines (form A) or 36 circles (form B) distributed over multiple pages for a participant to make and draw multiple associations to a single stimulus.

In each activity participants have to write the titles of their drawings which are also used for grading purposes.

Shape Tracing

Multiple geometrical properties of shapes have been identified by considering the curvature of a given shape (Costa and Cesar-Jr. 2001). Multiple general characteristics of shapes like transient events or asymmetries have been found to have extensive impact on human visual perception. Therefore, the shape used in the tracing task can be expected to pose a challenge to the user trying to trace over it. And that challenge can vary when different shapes are being traced. To address this issue asymmetrical, semi-random, non-sense, contour shapes have been generated using a modified version of Method 4 from (Attneave and Arnoult 1956). The modification of that method was limited to making the shapes consisting of at least two instances of each property: convex corner, concave corner, straight line segment, and curve line segment. The linear segments of the shape did not cross at any point. Their parameters like length or corners' angle were randomized but created closed contour shapes. The shapes were closed (ended at their beginning) to counterbalance potential effects related to occlusion and handedness.

The shapes that have been selected for the tests did not resemble any character of the alphabet, well-known shape or popular object (Figure 9 and Figure 10). They were meant to be hard to guess or predict by the participants skilled in hand-writing in case of hand occlusion-related uncertainty (e.g. Figure 8).

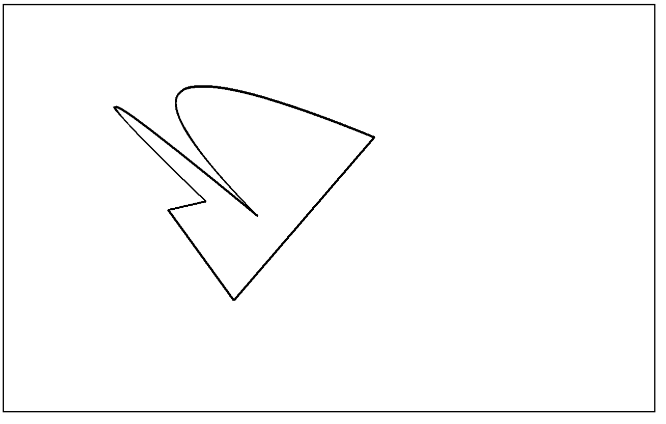

Figure 8. The semi-randomly generated contour shape (Shape 1) with its placement and proportional size to the test PC's panoramic screen. Its line is 1601 pixels long. Adopted from Paper II. ©ACM.

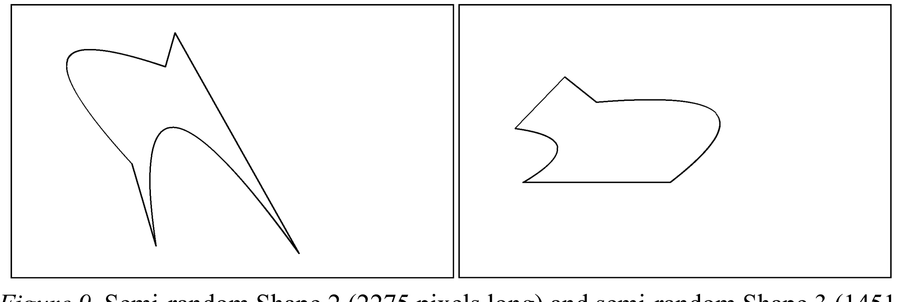

Figure 9. Semi-random Shape 2 (2275 pixels long) and semi-random Shape 3 (1451 pixels long) which together with Shape 1 (Figure 8) were used in Paper III. Adopted from Paper III. ©ACM.

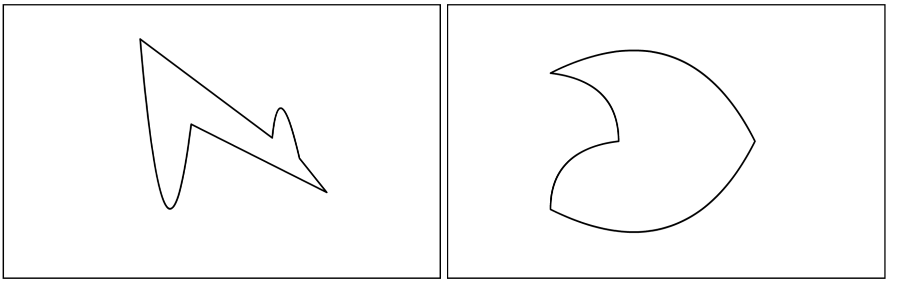

Figure 10. Shape 4 (*easy*) and Shape 5 (*hard*) were used in Paper IV. Both shapes were 1879 pixels long. Adopted from Paper IV. ©ACM.

A greyed-out (70% opacity) version of the shape was displayed and the participants traced clockwise over the shape in one uninterrupted stroke, starting from the top right corner.

Tools

For each experiment, all properties of the hardware and software were kept identical in the different conditions tested, except for those that constituted independent variables.

Hardware

Input Methods in Idea Sketching

Three input methods: mouse, stylus, and touch input were randomly assigned to the test participants during the Study i2 on ideation as described in Paper V (Study i1 used the stylus, and Study i3 used the mouse only).

Input Methods in Shape Tracing

Three input methods: mouse, stylus, and touch input were randomly assigned to the test participants during studies on shape tracing i.e. Paper II, III, IV.

Software

GUI in Idea Sketching

On one hand the previous research on computerized TTCT shows that UI design has a profound impact on user's experience and performance. On the other hand, any implementation of paper-based technique into computer software is a result of many compromises therefore it is not a perfect solution. E.g., it would be hard to implement a uniform navigation functionality for the mouse and stylus or touch input without defining an on-screen hand-gesture or creating some kind of GUI metaphor in form of a button to "press", or some other kind of visual artifact. Also the basic decision if to implement an eraser's functionality or not, may have consequences in the UI design and potentially influence the user-generated outcome. This function can be offered by the input device or by the GUI only – e.g. in form of a button. E.g. in case of mouse the right-click could offer the eraser mode while the left-click could be used for drawing. Capacitive stylus might offer an eraser function if used with its opposite end than the one used for drawing. But it would be hard to implement an eraser e.g. for touch input, without creating some visual metaphor. On the other hand, the GUI eraser button could be used with mouse, stylus, and touch input – but no buttons are available in a paper version of the test. Additionally, after overcoming the functional fixedness (Birch & Rabinowitz, 1951; Dusink & Latour, 1996) the eraser can also be used as a kind of a brush tool - that kind of conceptual appropriation (encouraging alternative uses of system's functions) might influence the outcome of the test. The TTCT method is not explicitly clear about offering the eraser function suggesting using ordinary pencils or crayons, but some negative effects of its use have been previously noted (Kwon, 1996). As a result of those trade-offs, two versions of the GUI have been developed and tested.

"Simple GUI"

This base-line version of the TTCT's GUI has been developed in an attempt of creating a digital equivalent of the paper-based TTCT. No GUI artifacts like buttons, menus or sliders have been implemented and only the test stimuli of the current TTCT's activity were presented on the screen. E.g. the Activity 3 as presented on the Figure 11 shows only the three rows of circles displayed on the screen. The program allowed the user to leave a 5 pixel thick solid-black trace of drawing over the stimuli shapes generated using 5 pixel thick solid-black lines, and displayed on a white background that occupied the full area of the screen. Due to the restrictive design assumption of GUI's simplicity - the navigation between the activities of the TTCT was done with use of the arrow buttons on an external keyboard for all three input methods. Also, no eraser's functionality was made available.

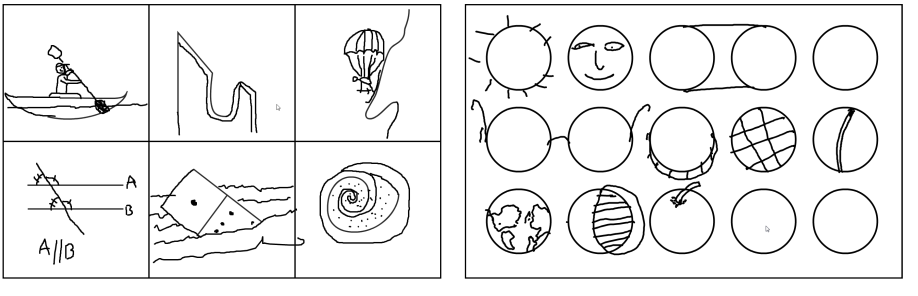

Figure 11. Screenshot of a simple GUI used in the Studies i1 and i3, showing Activity 2 *(left)* and Activity 3 *(right)* of the TTCT.

“Advanced GUI”

This version of the TTCT’s GUI (Figure 12) has been heavily based on the Kwon’s version (Kwon, 1996) of the computerized TTCT (Figure 13). The program allowed the user to leave a 5 pixel thick solid-black trace of drawing over the stimuli shapes generated using 5 pixel thick solid-black lines, and displayed on a white background. The activities of the TTCT were switched with navigation buttons constantly visible on the screen during the test. The eraser’s functionality was also available in form of a GUI button.

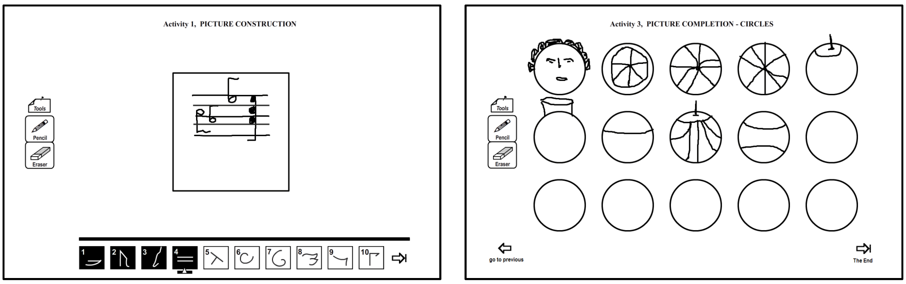

Figure 12. Screenshot of advanced GUI used in Study i3, showing Activity 2 *(left)* and Activity 3 *(right)* of the TTCT.

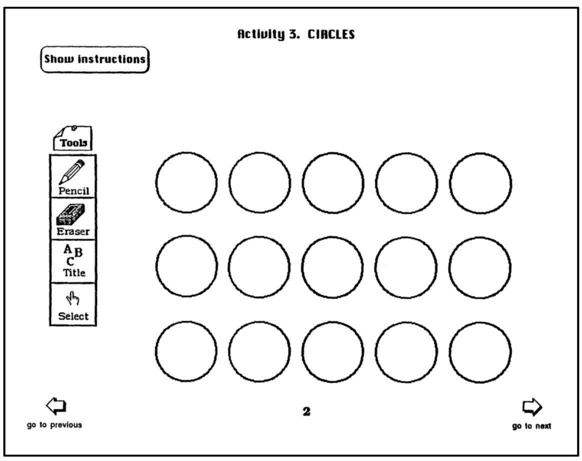

Figure 13. Screenshot of the GUI used in the study of (Kwon, 1996) showing Activity 3 of the TTCT. Adopted from (Kwon, 1996) . © Myoungsook Choi Kwon.

Due to inaccuracy of mouse and touch input when used for writing, and to avoid a potential bias of the keyboard-based text entry solution - in both cases of the GUI the titles of the participants’ drawings were written on an external sheet of paper and later assigned to the appropriate drawings.

GUI in in Shape Tracing

Some shape tracing tasks (Paper III) had a controlled visual feedback of drawing (visible or invisible) in a form of a solid black line of the same thickness as the other graphical stimuli displayed on the screen (greyed-out shapes presented on Figure 8, Figure *9*, or Figure *10*). No visual feedback condition imitated drawing with an invisible ink.

Users' Experience

To analyze users' skills their reported experience with all input methods will be collected pre-test in all studies. It is expected to reveal additional explanatory factors of users' performance in shape tracing and ideation tasks.

Dependent Variables

The aspects of usability of input methods in drawing tasks addressed in the studies were effectiveness, efficiency and satisfaction. Effectiveness and efficiency were assessed by measuring differently defined users' performance in shape tracing and idea sketching tasks.

User Performance in Idea Sketching

A key measure of ideation is the objective characterization of ideation effectiveness (Shah et al., 2003). While more ad-hoc measures of ideation effectiveness are applicable in a "free form" idea generation, this thesis represents a comparative approach that requires a more structured methodology.

Quantity and Quality of Ideas

The analysis of the idea-quantity and idea-quality during ideation and their relationship has been identified as an important factor (Reinig & Briggs, 2008). Therefore, the scoring of the TTCT performed. The TTCT scoring is complex therefore must be performed according to the manual (Torrance, Ball, & Safter, 1992). It produced useful quantitative assessment of users' performance in form of scores of five principal qualitative characteristics of creative ideation:

- *Fluency* – number of images produced as relevant responses
- *Originality* – uniqueness and novelty of unusual but relevant responses
- *Elaboration* – the number of details added to stimuli to extend a response
- *Resistance to Premature Closure* – a person's ability to stay open and tolerate gestalt ambiguity e.g. by not closing an open-shape stimuli with a straight line
- *Abstractness of Title* – an assessment of the verbal description of the drawing

The scoring procedure suggests factoring of a normative composite score called Creativity Index (CI) that consists of National Percentile Rank assessed with the use of the norm tables (Torrance, 1990a) based on Standard Scores (that are based on the raw scores) and thirteen Creative Strengths (e.g. using emotional expressiveness, unusual or internal visualizations, reach of imaginary, humor, fantasy or synthesis of test's stimuli) evaluated and added as a bonus.

While CI is an interesting measure that represents the participants' overall creative performance in relation to the rest of population, their actual ideation performance in creative drawing task is best reflected by the raw scores obtained.

The assessments of five qualitative characteristics of creative ideation constitutes the raw scores – a final summative score obtained as a result of the test.

These scores are assessed across the TTCT tasks in the following way:

- *Activity 1*: originality, elaboration, and abstractness of title.
- *Activity 2*: fluency, originality, elaboration, abstractness of titles, and resistance to premature closure.
- *Activity 3*: fluency, originality, and elaboration.

This shows that the scores cannot be used to compare the user's performance between test activities but might work as a means for comparisons within each activity e.g. between experimental conditions. Therefore, using the intermediary raw scores and grouping these scores within each activity is a practice used in other studies, although it is not directly supported by the TTCT method (Jackson, Witt, Games, Fitzgerald, von Eye, Zhao, 2012).

The extensive grading manual helps to assess the raw scores as an intermediary measure on the way to CI and directly relate to the ideas contained in the drawings that participants created and do not include the demographic factors of the participants. Moreover, CI scores are summarized over all three activities of the TTCT test what makes detailed comparisons at task level impossible.

The test situation also offers a generic ideation situation with varying conditions (e.g. different stimuli offered). The users' performance understood as actual idea production over limited time of the test is best represented by the raw scores which reflect the creative properties of a drawn idea.

The ultimate purpose of ideation is to produce good and relevant ideas, not only a large number of ideas (Briggs & Reinig, 2007; Reinig & Briggs, 2008). Therefore, for the purpose of this study, the raw scores describing the outcome's quantity (Fluency) and quality (Originality, Elaboration, Resistance to Premature Closure, and Abstractness of Titles) will be grouped and analyzed separately.

Time of Active Sketching

In Study i3 (Paper V) the time the participants spent actively on continuous sketching was measured in each activity of the TTCT. The sketching was considered continuous if it was not interrupted for more than 5 seconds.

User Satisfaction in Idea Sketching

After the ideation study (Study i2 in Paper V) comparing mouse, stylus, and touch input (Zabramski, Gkouskos, & Lind, 2011), post-test questionnaires based on The Creativity Support Index survey (Carroll & Latulipe, 2009) were used to collect information about participants' positive or negative responses to evaluation statements.

Participants were asked to evaluate four statements on a symmetric Likert-like psychometric scale and their responses were coded in the 10-point Likert scale, where 1 = "agree" and 10 = "disagree", reflecting the level of expressed agreement or disagreement on an ordinal scale.

Q2: "I was very absorbed/engaged in this activity – I enjoyed it and would do it again"

Q3: "What I was able to produce was worth the effort required to produce it"

Q4: "While I was doing the activity, the input tool "disappeared" and I was able to concentrate on the activity"

Q3 and Q4 was evaluated for each input method separately.

User Performance in Shape Tracing

The measure of users' performance in producing high quantity and high quality outcomes in tracing is traditionally approached by measuring task time and users' error.

Time of Tracing (Quantity)

In all of the experiments timing data were collected in form of the task time measured – i.e. one uninterrupted stroke, starting and ending in the top right corner of the displayed shape. Time data were non-normally distributed and positively skewed which is typical (Hockley, 1984; McCormack & Wright, 1964). Therefore a logarithmic transformation of these data was used before statistical testing.

Error of Tracing (Quality)

There are many factors that can describe a given shape e.g.: general shape, translation, rotation, and scale (Costa & Cesar-Jr., 2001). Different methods can be used to describe independent shapes and assess their dissimilarity as a measure of differences between them (Grauman & Darrell, 2004; Mori, Belongie, & Malik, 2005; Zabramski, 2011b). In case of experiments on tracing only general shape was expected to change with remaining factors left unchanged. To estimate that change as a measure of input device induced user error – the deviation between the original shape and the version created by the participant has been assessed (ISO, 1999b). The average value of pixel-wise distances between corresponding points located on the original shape and on user-generated version has been computed as the difference between the two shapes. To select these points, all shape properties like corners and peaks of the curves have been marked. This can be done based on the shapes' heuristics identifying a set of curvature maxima and local extrema of other geometric properties (Mori et al., 2005) or machine learning techniques to infer the segmentation of strokes into lines and arcs (Herold & Stahovich, 2013 – pre-print).

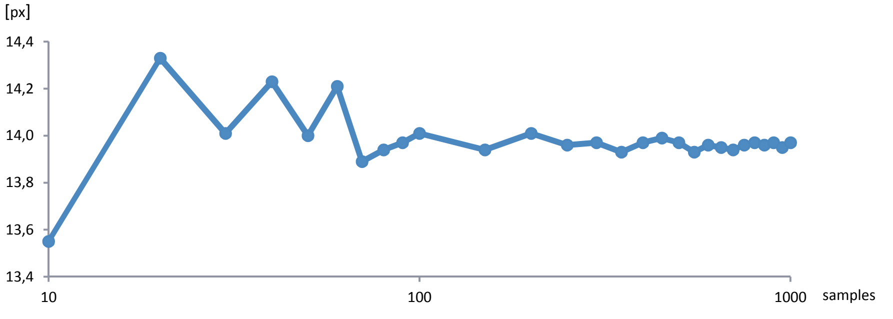

Figure 14. Average tracing error to number of points sampled from Shape 5 traced with mouse by the participant 1 in the study reported in Paper IV *(horizontal axis uses logarithmic scale)*. Eventually, that shape was sampled in 125 points and average error of 13.97 px has been achieved and used in the analysis.

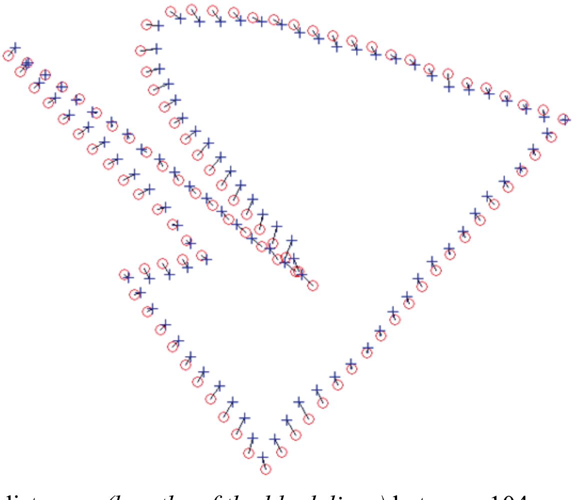

Figure 15. The distances *(lengths of the black lines)* between 104 corresponding points on the original Shape 1 *(centres of the red circles)* and the user generated version *(centres of the blue crosses)*. Adapted from Paper II. ©ACM.

Next, the constant quantities of proportionally distributed points have been selected between the shape's properties marked previously. Every given version of the shape has been sampled and represented by a set of points. It has been found that sets of more than 100 sampled points (Mori et al., 2005) do not increase the accuracy of the error estimation (Figure 14).
The exact number of sampled points varied between the shapes and was governed by the uniformity of distribution of the sampled points that depended on the features of the particular shape used (e.g. see Figure 15).

While performing such a tracing task it is theoretically possible to achieve maximum accuracy (error of zero value). This would mean that a user has traced over a shape perfectly and created the shape in the exact same position as the original shape that was presented.

User Satisfaction in Shape Tracing

After the tracing studies, post-test questionnaires were used to collect information about participants' experience and opinions regarding following aspects:

- preferred input device (statement S1)
- perceived ease of use (statements S2 and S4)
- perceived learnability (statements S3 and S5)

To avoid potential distortions originating from acquiescence bias the scale was balanced by offering equal number of positive and negative statements regarding the most important aspects (Schriesheim & Hill, 1981). The users' ratings of negative statements were later inverted and the final ratings then computed as the median of the responses to the paired questions (S2&4, S3&5). The questionnaire included:

- S1 - I think that I would like to use this input device frequently for sketching.
- S2 - I thought that the input device was easy to use.
- S3 - I would imagine that most people would learn to sketch with this input device very quickly.
- S4 - I found the input device very cumbersome to use.
- S5 - I imagine I would need to practice a lot before I could sketch efficiently with this input device.

Participants were asked to evaluate five statements on a symmetric Likert-like psychometric scale. The choices offered were: strongly disagree, somewhat disagree, indifferent, somewhat agree, strongly agree. Every statement was evaluated for each input method separately. All the questionnaire responses were coded between 1 and 5 reflecting the level of expressed agreement or disagreement on an ordinal scale. Some of the scales were inverted to deal with acquiescence bias – it is illustrated by adding a "-" sign in front of the statement number (e.g. -S4). The paired statements, S2&-S4 and S3&-S5, were compared to check for acquiescence bias.

Polychoric correlation coefficients (pcc) were calculated and used in the analyses of correlation between users' responses to statements. To investigate the significance of potential differences between groups of responses a Wilcoxon matched-pairs test was used.

Participants

Test participants that volunteered to participate in the empirical studies have been selected through convenience sampling from students or employees of Uppsala University. The detailed user demographics and experience are described in the respective papers.

Procedures

The standard usability evaluation procedures were used in the studies to evaluate users' performance in the creative and non-creative drawing tasks (Rubin & Chisnell, 2008). The tests took place in a usability laboratory in Ekonomikum campus at Uppsala University. The participants received information about the purpose of the experiment, signed consent forms, filled in pre-test questionnaires and took part in a short introductory warm-up drawing sessions in MS Paint. Then, the experimental part took place (details described in the respective papers). After that participants were asked to fill in post-test questionnaires regarding their preferences and opinions about the devices they were using. This procedure was the same for all the studies.

Summary of Papers

Sketching is not navigating (Paper I)

Despite the progress in the field of HCI, there is no agreement on how to categorize or analyze drawing tasks. Drawing tasks are rarely addressed experimentally by the HCI community, and even then pointing, steering, or gesturing is promoted as an approach towards drawing. These evaluation frameworks are restricted to pointing or steering tasks performed "as fast and as accurately as possible", which do not represent well the conditions of, e.g., creative drawing tasks. Drawing tasks are rarely addressed by the HCI community and when drawing is addressed, it is usually framed as pointing steering, or gesturing.

Purpose

This paper considers computer drawing as a manual task mediated by a drawing tool and highlights the dichotomy between the process and the outcome of drawing. The goal was to find similarities and differences between drawing and navigation tasks popular in HCI, i.e. pointing (MacKenzie, Sellen, & Buxton, 1991; MacKenzie, 1992), steering (Accot & Zhai, 1997; Zhou, Cao, & Ren, 2009), and gesturing (Cao & Zhai, 2007; Castellucci & MacKenzie, 2008; Vatavu, Vogel, Casiez, & Grisoni, 2011).

Results from the Study

The W^5, a dedicated meta-model focused particularly on drawing with digital pens and normal paper, seems to be well-matched for the analysis of computerized drawing tasks (Heinrichs et al., 2011). However, because the majority of computer-assisted drawing tasks take place in a paper-less context with the use of intermediary input devices, it is necessary to include the properties of the *tool* used in the analysis of such an interaction. Therefore, W^5 model's five *dimensions* that describe the interaction's context (i.e. place, time, product, user, and goal; see *page 29* for more details) have been supplemented with the key aspect of *the tool* that mediates the drawing. This aspect has been based on the concept of *instrument* already introduced in the *Instrumental Interaction* model (Beaudouin-Lafon, 2000) and includes its hardware part (e.g., input devices) and its software part (e.g., components of a UI) that have their impact on the outcome of the whole process.

The W^5 meta-model has been supplemented with one additional *dimension* describing the tool that mediates the drawing:

W_6 – "With what": Instrumental dimension that relates to use of tools (hardware and software) in the drawing process and their degree of indirection, integration, and compatibility.

This extended analysis tool has been named the ***W^6 framework***. It describes the tools used and actions executed by the user in both the physical and digital world (Figure 16).

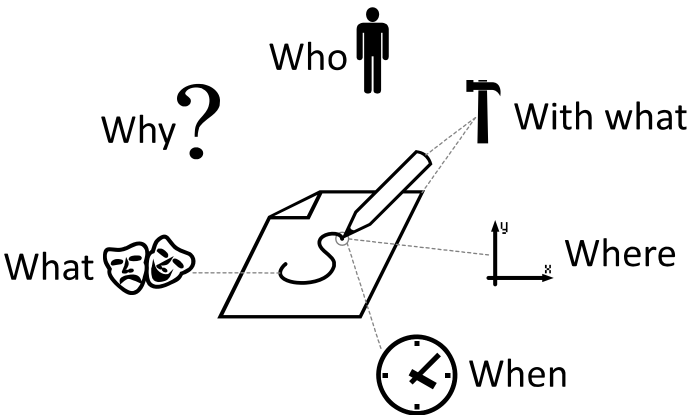

Figure 16. Dimensions of W^6 framework. Adopted from Paper I. ©ACM.

The W^6 framework has been used to analyze and describe potential differences and similarities between diverse surface-based types of interaction similar to drawing tasks. This helped to distinguish drawing from navigation tasks (such as pointing or steering through tunnels), which represent the user's goal of getting from point A to point B as quickly and as accurately as possible. In case of drawing (especially creative drawing) these spatiotemporal constraints do not exist (Figure 17) and the activity is as important as its outcome (product).

Drawing is a product-oriented task, which is not true of navigation tasks. This distinction points to the process vs. product dichotomy as a space where the balance is shifted towards performance in navigation tasks and towards the visual quality of outcome in the case of drawing, which could explain the importance of time in pointing and steering tasks and the accuracy in drawing tasks. Therefore, the postulate is that the analysis of drawing should be focused on the product, and not so much on the process.

Unconstrained tracing, i.e. shape replication by drawing over the original pattern, is proposed as a suitable baseline task for comparisons of input methods. This is because it not only delimits the influence of potential perceptual and cognitive mechanisms that may be involved in creative drawing or drawing from memory, but also because the influence of any spatial and/or temporal constraints related to the task's formulation and description added on top of an unconstrained tracing task can be clearly shown.

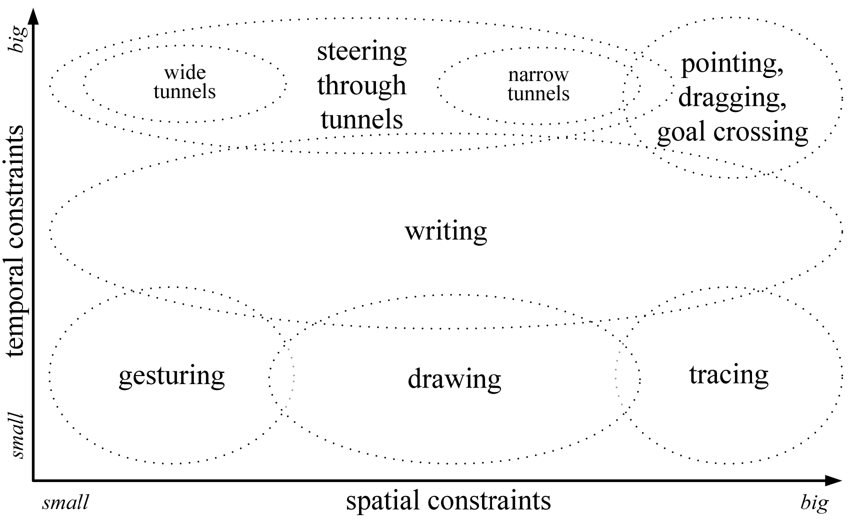

Figure 17. Temporal and spatial constraints imposed by a typical task formulation of popular HCI tasks. Adapted from (Zabramski & Stuerzlinger, 2013a). ©ACM.

All the aspects of drawing tasks mentioned in the W^6 framework are expected to serve well as a basis for a comparative analysis of other types of surface-based interaction and be a step toward creation of an extended taxonomy of surface-based tasks.

The W^6 framework also identified the areas of interaction (the W^6 dimensions) that should be controlled and the measurable impact of which should be assessed empirically in computerized drawing.

Effects of UI and Task Formulation on Users' Tracing Performance (Paper II, III and IV)

Research on input methods and their influence on humans have primarily focused on the performance aspects in navigation tasks, which eventually became the subjects of mathematical modelling. However, for drawing, it is not possible to directly apply existing HCI models, such as Fitts' Law for two dimensional tasks (MacKenzie and Buxton 1992) or the SL (Accot and Zhai 1997).

For unconstrained freehand line-tracing, which is typically used in creative drawing or gesturing, the outcome depends on the tool used as well as on task difficulty, i.e. what shape and how quickly or accurately it is being drawn (Zhou et al. 2009).

Purpose

Many input devices have been tested for their effectiveness in pointing, dragging, goal crossing, and path steering navigational tasks (Forlines et al. 2007; MacKenzie et al. 1991). However, creative, artistic drawing can be an example of a task that might be negatively influenced by the low accuracy of the input method used for drawing. Moreover, any kind of spatio-temporal constraints imposed on the user can affect the results. Therefore, the navigational models are not suitable to describe spatially and temporally unconstrained freehand drawing with initially unpredictable user error and no known mathematical model describing the original path or shape. Consequently, to assess the effects of an input device and the shape drawn, a series of tracing tasks have been addressed experimentally.

Empirical Studies

Paper II presents the experimental investigation of a user's performance in using a mouse, a stylus, and a touch input in the unconstrained freehand replication task (tracing) of a semi-randomly generated shape with and without visual feedback of drawing.

Paper III summarizes observations from four similar empirical studies focusing on shape tracing (incl. Paper II) with the same three input methods used but different semi-randomly generated shapes traced. The aim was to identify and assess how the shapes' components influence the accuracy of tracing by untrained users.

Paper IV reports on an experimental comparison and evaluation of users' performance in using mouse, stylus, and touch input in tracing, lasso selecting, and two steering tasks. The properties of the two shapes used in this study reflected the observations from Paper III and are examples of two classes of shapes: easy and hard to replicate.

Results from the Studies

The findings from Paper II describe the stylus as the least and touch as the most error-prone input method in terms of deviation from the traced shape. However, touch input significantly outperformed stylus and mouse for task time. Nevertheless, this or very similar "input effects" in terms of the pattern of differences between devices in time or error produced were later found in the following shape tracing studies. No effect of controlled visual feedback of the line drawn was detected.

The results of multiple shape tracing studies, including distributions of tracing errors in relation to the shapes used, were analyzed and summarized in Paper III. This analysis allowed detection of shape properties that make shape replication more difficult. These results have been used to design two shapes: a hard and an easy one to trace.

As expected, the two shapes (easy and hard) of the same length that were designed based on the findings from Paper III had a different impact on the user's performance in each task tested (tracing, lasso selection, and steering through a narrow and wide tunnel). The results from Paper IV show that the participants replicating these shapes using a touch input device were the least accurate but were the fastest in comparison with the remaining input methods. The stylus was the least error-prone method and the mouse was the slowest device (tracing and selection). The differences in errors between the input methods were less pronounced in steering tasks but timing data showed that the mouse was still the slowest device. Although the time of replication did not differ between the two shapes tested, differences between errors were significant for all the tasks and input devices. These differences were also consistent between the shapes. These results confirm the "shape effect" predicted in Paper III and show what properties of the shape can make its replication more difficult.

Effects of UI on Users' Ideation Performance, Preferences, and Satisfaction (Paper V)

Idea generation (or ideation) includes creating, developing, and communicating new ideas (Briggs & Reinig, 2007; Jonson, 2005). Nowadays, computerized tools mediate this process but their properties can have an impact on it in multiple ways. It is hard to predict whether a particular UI's constraint (e.g., the inaccuracy of the input device or cognitively demanding GUI functionality) will hinder or promote a user's creativity during ideation (Stokes, 2005).

Purpose

Paper V analyzes the potential of the UIs to facilitate ideation and divergent production in drawing tasks, i.e. how particular properties of the ele-ments of UIs (such as the accuracy of the input method and design of a GUI) can affect users' ideation performance in terms of the quality and quantity of drawn ideas.

Empirical Studies

Paper V is a summary of three empirical studies using the methodological framework of the figural part of the TTCT (Torrance, 1990b), which is the most widely used set of creativity tests involving paper and pencil drawing (Kim, 2006).

In **Study i1** the original pen and paper-based version of the TTCT was compared with the digitized version of the test running on a Tablet PC and operated with a stylus (Zabramski & Neelakannan, 2011). The experiment had a balanced between-subjects design and was performed by 16 participants randomly assigned to one of the two test conditions. The aim of the test was to investigate the influence of transition of the test from pen and paper to stylus and screen.

Study i2 aimed to test the influence of the computer input method (mouse, stylus, and touch input) on the scores obtained by the users on the computerized version of the TTCT (Zabramski et al., 2011) used in Study i1. The performed test had a factorial design. Every participant (n=24) used one of the three input methods (assigned in randomized order for counterbalancing) to perform one of three activities of the TTCT administered in original order.

Study i3 (Zabramski, Ivanova, Yang, Gadima, & Leepraphantkul, 2013) used two implementations of the GUI of the computerized TTCT: simple one (used in Studies i1 & i2) and a more advanced one (similar to the one used in previous research on the computerized TTCT (Kwon, 1996)). They were used to investigate their impact on the users' scores and the time they spent actively on drawing. The programs were running on a desktop PC operated with a mouse. The experiment used a balanced between-subjects design and was performed by 16 participants randomly assigned to one of the two test conditions (simple and advanced GUI).

Results from the Studies

In all studies the outcomes of participants' drawings were analyzed by two untrained raters who performed the scoring using the TTCT scoring manual (Torrance et al., 1992) as a reference. The average scores from both raters were used in the analyses.

In **Study i1** A Pearson's correlation coefficient of 0.78 was achieved, indicating a strong positive correlation between raters (high inter-rater reliability). An analysis of variance (ANOVA) of the participants' scores representing the quantity and quality of ideas produced revealed no significant difference between the results obtained from the paper-based version and the digitalized version of the test. Post-experimental power analysis revealed that for effects of this size to be detected with a 90% chance as significant at the 5% level, a sample of 1326 and 294 participants in each test condition would be required for quantity (Cohen's d = 0.13) and quality (Cohen's d = 0.38) of ideas, respectively.

These results suggest that the stylus did not significantly influence the users' ideation abilities when compared with users using the pen on paper to solve the same test.

The *Pen-and-paper* condition was perceived as slightly better than the *stylus or screen* condition, even though the participants' overall results were very similar.

In **Study i2** A Pearson's correlation coefficient of 0.79 was found, indicating a strong positive correlation between raters. For this study, the participants' scores representing quantity and quality of ideas produced were also grouped within each activity, which is not directly supported by the TTCT method, but allowed an analysis of potential differences between activities from the perspective of each input method.

The participants were randomly assigned to eight *triads*. Each *triad* used a Latin-square design to produce a 3x3 array of the input methods, each occurring exactly once in each row and exactly once in each column, with the rows representing the unique permutations (reordering) of the input devices to be used. The raw scores of the three participants constituting each *triad* were combined to create eight "virtual" users performing every activity of the TTCT with every input method. Such an operation reduced the variance in the data by 41%. The raw scores within each *triad* were first grouped by input device and subsequently analyzed. An ANOVA revealed no statistically significant differences between the quantity and quality scores for all input methods tested. Power analysis revealed that for effects of this size to be detected with a 90% chance as significant at the 5% level, a sample of 33 triads would be required for the quantity of ideas produced (Cohen's d = 0.59) and 15 triads for the quality of ideas produced (Cohen's d = 0.90). However, the pattern of these differences for quantity and the inversed pattern of differences for quality of ideas are similar to the pattern of differences between the results of tracing accuracy (error) achieved with these input devices (Figure 27 in Results section or Paper II). This finding suggests that the larger the error introduced by the input-method (i.e. deviation from the intended shape), the more negatively the quality scores are affected but a greater number of ideas are produced. These effects are not as strong as in the shape tracing tasks, but indicate that the impact on drawing during ideation originates from the domain of drawing accuracy rather than the time domain, which is influenced by these input devices in a different way (Figure 28 in Results section or Paper II). In general, touch input helped to produce more ideas (higher quantity scores) but stylus facilitated higher quality scores. These results also suggest the presence of a form of quantity-quality trade-off moderated by the accuracy of the input device.

The stylus was reported by the participants as the most favored and the mouse as the least favored tool.

In **Study i3** A Pearson's correlation coefficient of 0.82 was found indicating a strong positive correlation between raters. An ANOVA of the participants' scores revealed a significant difference ($F_{1,14}=4.9$; $p=0.044$) between the quantity of ideas produced with the two versions of the GUI. This finding shows that the participants in the simple GUI condition produced significantly more ideas. However, for the quality of ideas that difference was not significant. Power analysis revealed that for effects of this size to be detected with a 90% chance as significant at the 5% level, a sample of 25 participants in each test condition would be required for the quality (Cohen's d = 0.92) dimension. However, an ANOVA of the time the participants actively spent on drawing showed a significant difference between the two versions of the GUI ($F_{1,14}=9.9988$; $p=0.0069$). More specifically, the participants in the advanced GUI condition spent significantly more time on drawing, achieving an insignificantly lower quantity and quality scores.

Multiple ANOVAs of the time the participants actively spent on drawing in each activity revealed significant differences between the two versions of the GUI in case of Activity and 2 of the TTCT.

These activities offered a small number of stimuli but promoted the original and in-depth representation of an object, scene, or situation. The users in the simple GUI spent more time on ideation, which resulted in slightly higher scores. The users in the advanced GUI were forced into an exhaustive drawing mode and obtained slightly lower scores, even though they spent significantly more time on continuous drawing than the users in the simple GUI, suggesting the presence of a new form of operational bias induced by the GUI.

The present results demonstrated that both the quantity and quality of the users' ideas are negatively affected in the advanced GUI condition compared with the simple GUI condition (Figure 31 in Results section). This observation is associated with the use of the eraser function available in the advanced GUI. The use of the eraser function reduces the likelihood of idea reinterpretation that would occur in the event there was erroneous drawing in the simple GUI task, which did not offer the eraser functionality.

Paper V concludes with a discussion summarizing the findings from all three studies. The paper suggests that the differences between the inferior results obtained with the mouse-operated computerized version of the TTCT (similar to the advanced GUI used in Study i3) and the pen and paper-based test observed in previous research (Kwon, 1996) might be explained by the cumulative negative effects introduced by the different input devices used (mouse instead of pen), and the way the TTCT was digitized, i.e. introducing an advanced GUI. These differences in UI design might be responsible for 10% of the difference between the mean raw scores obtained with mouse and pen (as in Study i2), and for 18% of the difference between the mean raw scores obtained with an easy and complicated visual interface: in analog to the differences between simple and advanced GUI (as in Study i3).

The results from Study 3 provide evidence that the advanced GUI was perceived as easier to use than the simple GUI. Moreover, the outcomes of drawing with the mouse were perceived as easier to achieve with the advanced GUI (which may be connected to the availability of the eraser function), but the participants were equally satisfied with their final drawings, regardless of the GUI version.

User's Preferences and Satisfaction in Tracing (Paper VI)

Usability of any technical solution can be perceived from the pragmatic point of view that focuses on only "getting things done". However, together with objective measurements, subjectively perceived user satisfaction and preferences should be assessed during usability evaluations and integrated into one consistent, dynamic picture (ISO, 2010). Even though subjective perceptions of usability are generally not correlated with objective measurements (Frøkjær, Hertzum, & Hornbæk, 2000), their comparison is rarely done in practice (Barkhuus & Rode, 2007).

Purpose

Paper VI presents the use of Correspondence Analysis (CA), a multivariate exploratory technique, in an attempt to analyze objective measurements of users' performance, i.e. task time and error, together with subjective evaluations of users' satisfaction in a shape-tracing task. CA is applied here to get a quick and simplified view of the experimental data set and use it to evaluate whether drawing performance can be a predictive factor of users' preferences (Nielsen & Levy, 1994) towards input methods tested with controlled visual feedback.

Empirical Study

The data set analyzed in this study originated from a comparative usability study of tracing with the use of mouse, stylus, and touch input, and contains both categorical and continuous data (Paper II) (Zabramski, 2011a). Sixteen participants filled in pre-test questionnaires and provided basic screening information about demographics, as well as their daily familiarity with the investigated computer input methods in the past 3 years. After the shape tracing experiment, post-test questionnaires were administered to collect information about the participants' experience and opinions regarding their input device of preference, perceived ease of use, and perceived learnability of the device. The participants were asked to evaluate the questionnaire's statements on a symmetric five-point Likert-like psychometric scale (1=strongly disagree, 2=somewhat disagree, 3= indifferent, 4=somewhat agree, 5=strongly agree). Every statement was evaluated for each input method separately. Timing data were collected for each task and user error was calculated using a method that computes the average deviation of the user-generated shape from the original version (ISO, 1999b; Zabramski, 2011a).

Results from the Study

There was no main effect or significant difference between the visibility of feedback conditions for time or error. However, there was a main effect of input device on task time, and a post-hoc analysis identified significant differences between touch input and mouse. In this study, stylus had the best measured performance and was preferred by the users. Touch input was the least accurate of all input methods, but was preferred by the users over the mouse, especially in the conditions lacking of visual feedback of drawing. The presence of visual feedback had no significant effect on users' performance but that effect was significant for *learnability* in case of mouse. The stylus remains an obvious choice for drawing tasks from both a performance and preference point of view.

The CA technique allowed one to visually identify and numerically assess the main variables in the data set, and the way in which these variables interact with each other. It was also sensitive to the secondary effect of touch *preference*, although this phenomenon is not reflected in the performance results alone. The importance of the impact of a user's previous experience is also noted because it influenced both the measurements and the subjective factors. It also strongly varied between participants. However, because of inhomogeneity in the participant's group user's previous experience varied in a way that could not be easily interpreted in a meaningful way (e.g., experience did not correlate with error or task time). Therefore, it was excluded from the analyses.

The CA method suggested that time should be contrasted with error, which is evidence that the well-known SATO (Zabramski, 2011a) took place in this study. CA is recommended as a well-suited method to quickly evaluate the results of a usability study with mixed types of data.

The results presented in Paper II demonstrate patterns of differences between the input devices that are consistent for all three shapes studied (Figure 27 and Figure 28).

Results

The results are presented in sections related to particular topic and grouped by task type.

Task Formulation Effects

Task formulation is strongly connected to the expected outcome (content dimension W_3). The analysis with the W^6 framework also suggested the importance of the task dimension (W_5 – “Why”) that relates to the purpose and objectives of the drawing process that is being performed. W_5 is the place for conceptualization of the user’s goals and the final outcome. It may also restrict the spatio-temporal dimensions W_1 – “Where”, and W_2 – “When” – affecting user performance in drawing.

Idea Sketching

The set of TTCT tasks is static and the task formulation is standardized and advised to be followed rigorously. Therefore, for the sake of compatibility with the TTCT, method the aspect of task formulation in idea sketching was not actively manipulated in ideation studies. However, the three TTCT activities expose the participants to a dynamic task context that changes from creating a single idea/story, through creation of a few ideas, to mass production of ideas in a fixed time frame. That allowed analyzing the results from different perspectives.

Spatio-Temporal Constraints

Ideation during drawing was assessed using the TTCT methodology, which requires an enjoyable, thinking, or problem-solving atmosphere to be created during the tests. Stressful or threatening situations commonly associated with testing must be avoided so the participants should expect to “have fun” with the enjoyable activities (Torrance, 1990b). Therefore, no temporal or spatial constraint was applied directly.

The users’ performance understood as actual idea production over limited time of the test is best represented by the raw scores which reflect the creative properties of drawn ideas.

Because the time factor could not be actively controlled in Study i2 (Zabramski et al., 2011) screen snapshots were collected with the participants' drawings after 10 minutes - that is on the end of every activity, but additionally, snapshots of participants' drawings were collected at the beginning of the 5th minute in tasks performed using touch and 8th minute in case of tasks performed using stylus. These time-points approximately corresponded to the time-wise performance differences between input methods in shape replication tasks (Figure 28).

A Friedman non-parametric ANOVA for dependent samples showed no difference exists between the raw scores obtained with more, stylus-, and touch when the same 10 minutes time frame is used.

The same procedure revealed significant differences (Chi Sqr. $(N=8, df=2) = 8.58$; $p=0.0137$) between the input methods when a modified time-frame was used (8 minutes for stylus-input and 5 minutes for touch input).

A post-hoc test was then performed by pair wise testing these conditions using the Wilcoxon matched pair test. It revealed that in 10 minutes mouse input produced significantly higher creativity scores both compared to 8 minutes of stylus usage ($N=7$, $T=1$, $Z=2.1974$; $p= 0.028$) as well as compared to 5 minutes of touch input usage ($N=8$, $T=1.5$, $Z=2.3105$; $p=0.021$). However, no significant difference was found between 8 minutes of stylus usage and 5 minutes of touch input ($N=8$, $T=5.0$, $Z=1.8204$; $p= 0.069$).

The finding that there was no difference between 8 minutes of stylus usage and 5 minutes of touch input usage confirms the observation that the participants were using strategies that resulted in valuable elements of their work (e.g. titles or elaborated details) being added on the end of each activity (Zabramski et al., 2011).

Additionally, in Study i3 (Paper V) the users of simple GUI were observed spending significantly more time on ideation in the first two activities, which offer a small number of stimuli but promote the original and in-depth representation of an object, scene, or situation (Figure 18). In those cases the users of the more complex GUI ended in a laborious drawing mode, suggesting the presence of a new form of operational bias.

Multiple ANOVAs of the time the participants actively spent on drawing in each activity (Figure 18) revealed significant differences between the two versions of the GUI for Activity 1 ($F_{1,14}=21.367$; $p<0.001$) and Activity 2 ($F_{1,14}=4.605$; $p<0.05$).

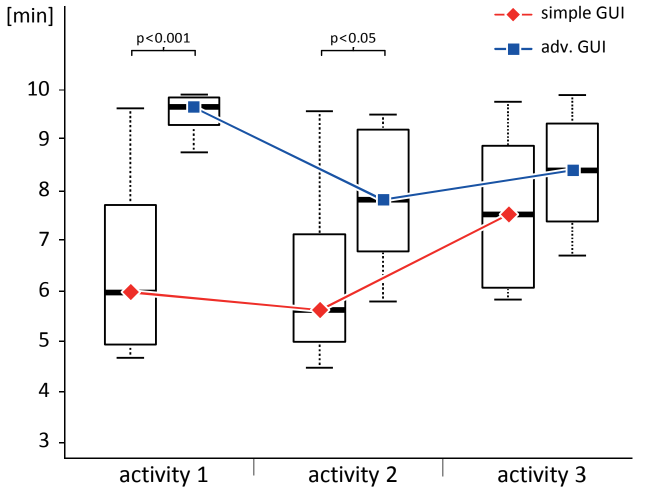

Figure 18. Median drawing time of uninterrupted idea sketching for each TTCT's activity measured for simple and advanced GUI in Study i3 from Paper V. Horizontal lines denote the p-values from ANOVA.
Adopted from Zabramski, Ivanova, et al. (2013). ©ACM.

Visual Stimuli Effects

The W[6] framework highlights the importance of the content dimension (W_3 – "What") that relates to the drawing outcome created by the user. Therefore, the scoring of the drawing's outcomes was performed in case of individual activities of the ideation tasks.

The exact number and difficulty of drawing strokes created during ideation tasks would be hard to quantify and analyze. However, we can assume that due to random variability the effects of their big number and the diversity of the shapes drawn during each test session make the potential problems originating from their properties less pronounced.

The stimuli of the TTCT were also not manipulated during the experiments. Even though, the process of grading the quantity and quality of ideas produced during the test results in scores proportional to the amount of stimuli used by the participant – the relation is not explicit since the same scores can be earned for a small number of detailed ideas and a big number of superficial ideas.

The TTCT offers generic ideation situations and varies the tasks difficulty by offering different sets of stimuli in each test activity – increasing the number of task stimuli (from 1 in Activity 1, to 10 in Activity 2 and 36 in Activity 3). This introduces the dynamic task context that changes from creating a single idea/story, through creation of a few ideas, to mass production of ideas. Figure 19, Figure *20*, and Figure *21* show how that change affected the cumulated scores in each Activity of the TTCT in Studies i1, i2, and i3.

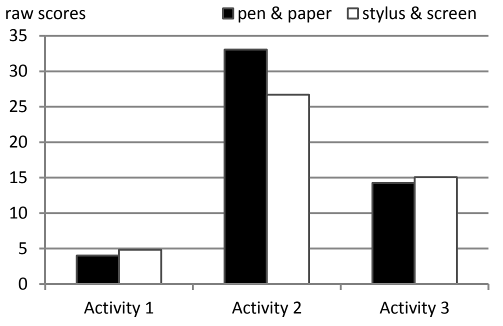

Figure 19. Raw scores obtained in the TTCT summarized per Activity in Study i1.

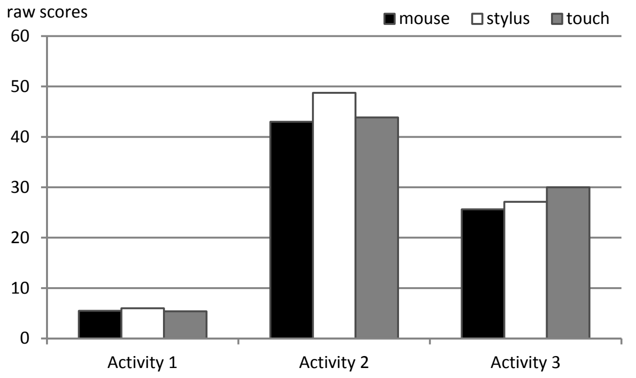

Figure 20. Raw scores obtained in the TTCT summarized per Activity in Study i2.

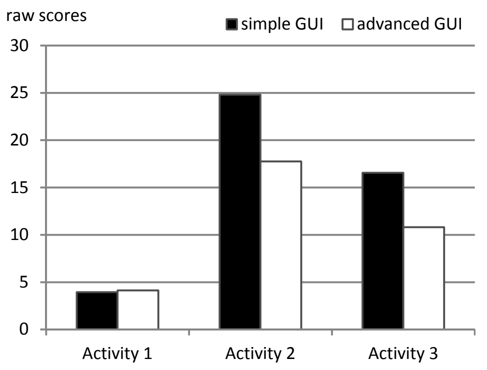

Figure 21. Raw scores obtained in the TTCT summarized per Activity in Study i3.

It must be highlighted that the TTCT stimuli had differnet influence but also were differently graded what is explained in Methods section.

Shape Tracing

To make any comparisons possible, a similar context for the creative and non-creative drawing tasks had to be created. Therefore, to make the potential comparisons between creative and non-creative drawing more meaningful, the studies on shape tracing did not pose any spatio-temporal constraint that could lead to stress.

Spatio-Temporal Constraints

Unconstrained Tracing

Following the assumptions of creative drawing tasks, the task formulation in shape tracing tasks has been tailored to introduce as little stress as possible by not imposing any spatio-temporal constraints on participants. The results show unique individual ratios of speed to accuracy set by each participant (Figure 22).

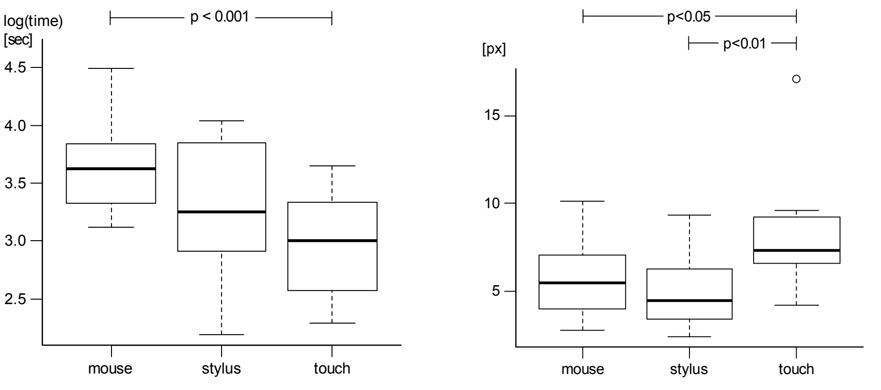

Figure 22. Box plots showing comparison of time *(left)*, and errors measured *(right)* during the tracing task over Shape 1 (Paper II). Horizontal lines with numbers denote statistical significance after Bonferroni test.

Spatio-Temporally Constrained Tracing

Spatio-temporal constraints are the default conditions in performance studies on navigation tasks where the users are explicitly asked to be "as fast and as accurate as possible" (the analysis in Paper I). Speed and accuracy constraints also were investigated in shape tracing (Paper IV). The consequences of adding these constraints on the shape of the distribution of results and on SATO is presented on Figure 23.

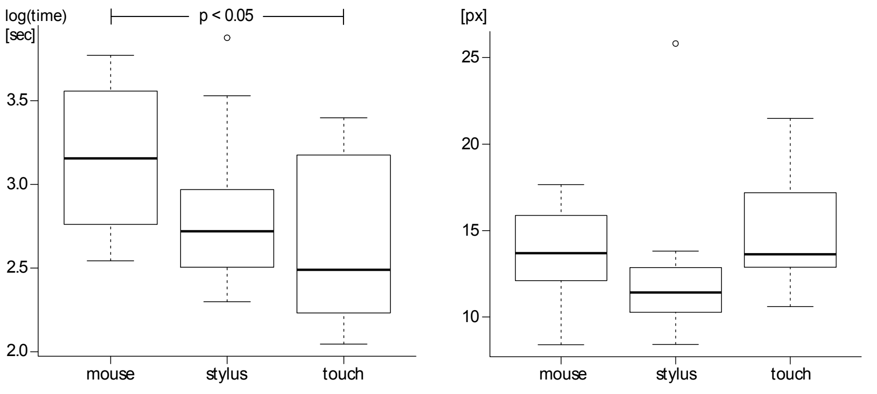

Figure 23. Box plots showing comparison of time *(left)*, and errors measured *(right)* during the tracing task over Shape 5 (Paper IV). Horizontal line with number denotes statistical significance after Tukey HSD test.

Visual Stimuli Effects

The assessment of the quantity and quality of the drawing's outcomes was performed in case of shape tracing tasks.

The shape used as a basis for the non-creative tracing task expected to bias all participants in the same way.

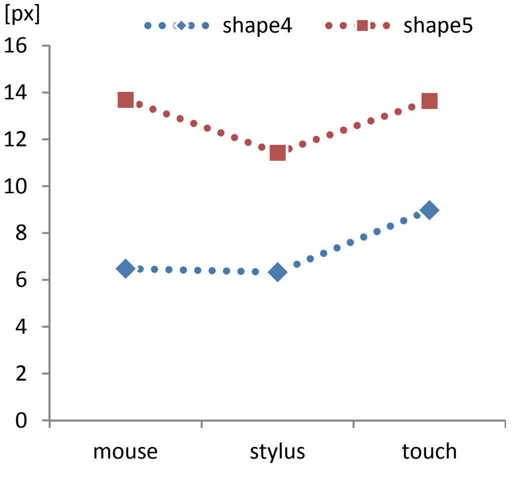

Figure 24. Median values of deviation/error measured for spatio-temporally constrained tracing over Shapes 4 and 5, performed using mouse, stylus-, and touch input as presented in Paper IV.

However, as shown on Figure 29, shape tracing performed without explicit spatial or temporal constraints was clearly a subject of SATO. And the particular ratio of speed to accuracy was subjectively set by the participants depending on the shape traced. While it resulted in similar patterns of differences between the median results obtained with the input methods tested –

all the three shapes posed different levels of difficulty to the participants something that is reflected in different distribution of the time and error data for each shape (Figure 27 and Figure 28). Therefore, the three shapes tested were analyzed and two more shapes have been created that included the least and the most error-prone properties.

These two shapes (Shape 4 (left) and Shape 5 (right) on Figure 10 in Methods section) also have been compared experimentally (Paper IV).

An ANOVA of error data yielded a significant main effect of shape (for all types of task in that study and all input methods used) ($F_{1,11}=73.52$; $p<0.0001$) such that the average error of tracing was significantly lower for *Shape 4* (M=11.4px, SD=4.9px) than for *Shape 5* (M=16.9px, SD=5.01px). The interaction of these factors was also significant ($F_{14,154}=2.71$; $p<0.002$) but dissordinal. Figure 24 presents the medians of these results.

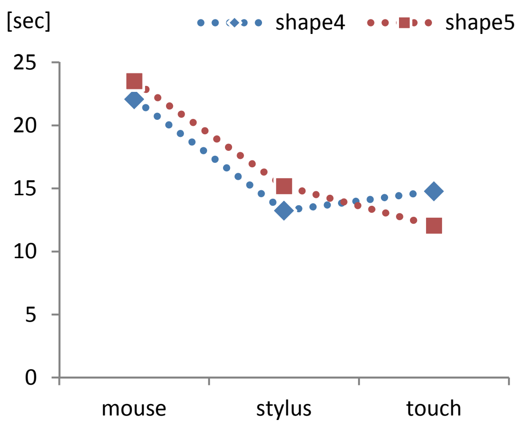

Figure 25. Median values of time measured for spatio-temporally constrained tracing over Shapes 4 and 5, performed using mouse, stylus, and touch input as presented in Paper IV.

An ANOVA of the time data showed that the main effect of shape was non-significant – for all types of task and all input methods in that experiment. However, the interaction of these factors was significant ($F_{14,154}=2.69$; $p=0.002$) but dissordinal. Figure 25 presents the medians of these results.

Computerized Tool Effects

W^6 framework points to the role of computerized tools used in drawing (dimension W_6 – *"with what"*) what goes in line with the aspect of "equipment/product" from ISO definition of usability. However, the UIs of computerized tools consist of hardware and software components that might in a different way influence user's performance in generating the drawing outcomes of high quantity and quality. The influence of the software and hardware components on the user's performance in creative and non-creative drawing was assessed empirically.

Input Method Effects

The assessment of that influence had to be investigated using different methods depending on the kind of drawing task in question and the type of UI component. Creative drawing tasks (i.e. idea sketching) were evaluated with the TTCT method assessing quantity and quality of ideas generated by the users performing three activities of fixed duration. Non-creative drawing task (i.e. shape tracing) was evaluated using the measure of accuracy as a measure of quality, and time as a measure of quantity of drawing (ISO, 1999b).

Idea Sketching

After confirming the equivalency of the digitized and paper-based TTCT (Study i1 in Paper V) (Zabramski & Neelakannan, 2011) the influence of using the mouse, stylus, and touch input on the outcomes of idea sketching was compared in Study i2 in Paper V (Zabramski et al., 2011).

The raw scores obtained by the users in that study have been split into quantitative and qualitative characteristics of ideation scored by the TTCT, and summarized for mouse, stylus, and touch input and analyzed (Figure 26). An ANOVA showed no significant difference between the input methods (Paper V).

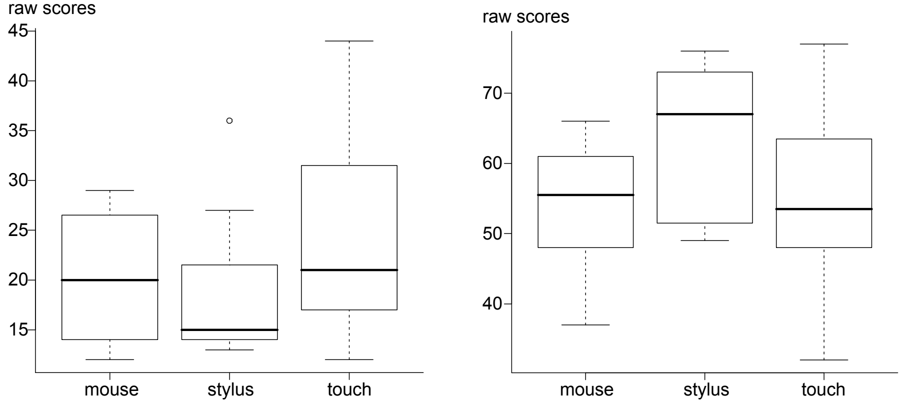

Figure 26. Users' raw scores obtained with the use of mouse, stylus-, and touch input and summarized for quantity (*left*) and quality (*right*) as in Study i2.

Shape Tracing

Accuracy of trace and shape tracing time were the measurements reflecting the user’s performance in generating outcomes of high quantity and quality in non-creative drawing.

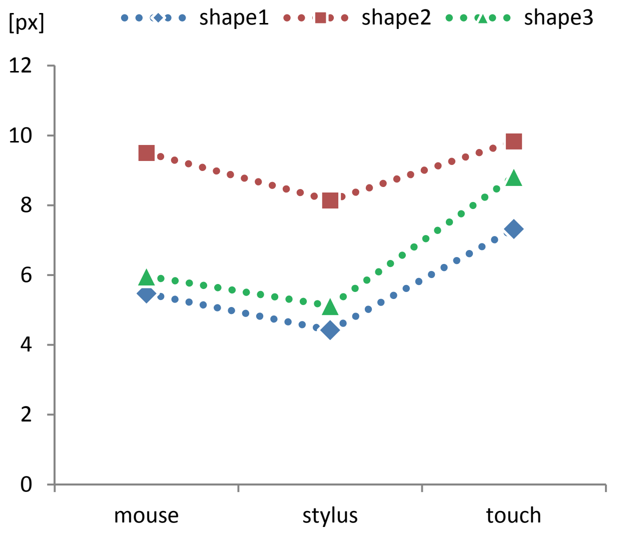

Figure 27. Median values of deviation/error measured for unconstrained tracing over semi-random Shape 1, 2, and 3, performed using mouse, stylus, and touch input as partial results of Study t3, t2, and t4 respectively.

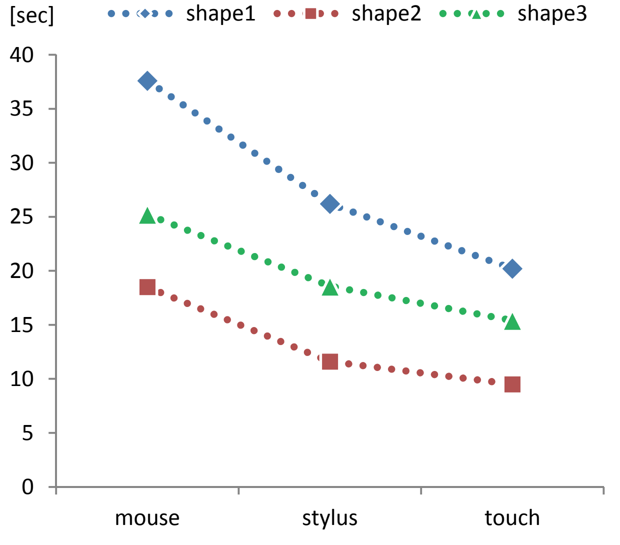

Figure 28. Median values of time measured for unconstrained tracing over semi-random Shape 1, 2, and 3, performed using mouse, stylus, and touch input as partial results of Study t3, t2, and t4 respectively.

The results presented in Paper II show patterns of differences between input devices used that are consistent for all three shapes studied (Figure 27 and Figure 28).

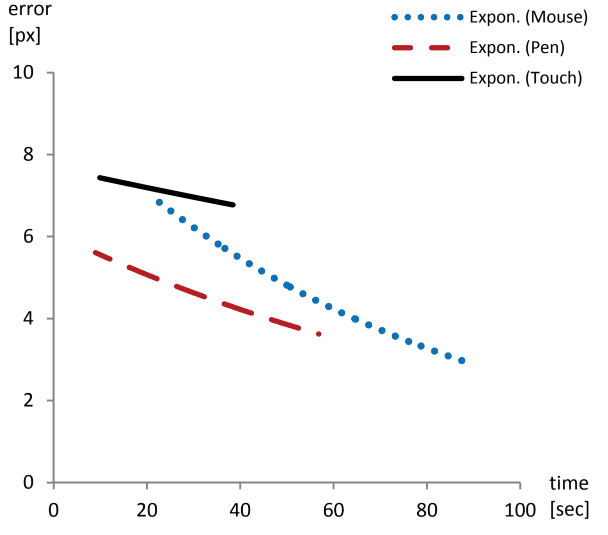

Figure 29. Regression lines of time measurements and error values for Shape 1, as reported in Paper II.

Figure 29 presents the time to error plot where the regression lines show typical SATOs that took place when Shape 1 was traced (Paper II). Their meaning is that the more accurate the tracing was the longer it took and vice-versa.

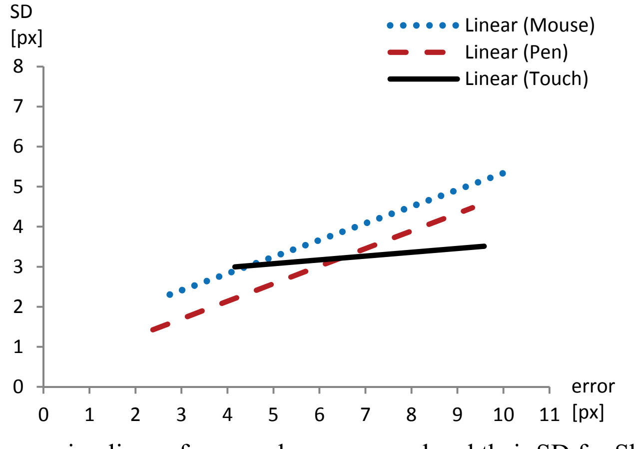

Figure 30. Regression lines of error values measured and their SD for Shape 1, as reported in Paper II.

Figure 30 shows the relationships between tracing errors and their SD. They were analyzed for Shape 1 with the use of a linear regression model (Paper II).

GUI Effects

The potential influence of the software components on the user's performance in computerized drawing was also empirically investigated for both kinds of drawing tasks.

Idea Sketching

The Study i3 in Paper V compared two drawing applications offering:

- simple GUI (Figure 11 in Methods section) – with the GUI limited only to presenting the TTCT's simuli, and
- advanced GUI (Figure 12 in Methods section) – additionally equipped with the navigation buttons and eraser function.

The users' raw scores have been split into creative characteristics scored by the TTCT, and summarized for quantity and quality of ideas. Figure 31 shows these scores grouped for both versions of the GUIs. An ANOVA of the participants' raw scores revealed a significant difference ($F_{1,14}=4.9$; $p=0.044$) between the quantity of ideas produced with the two versions of the GUI. This finding shows that the participants in the simple GUI condition produced significantly more ideas.

For the quality of ideas that difference was not significant. Power analysis revealed that for effects of this size to be detected with a 90% chance as significant at the 5% level, a sample of 25 participants in each test condition would be required for the quality (Cohen's d = 0.92) dimension.

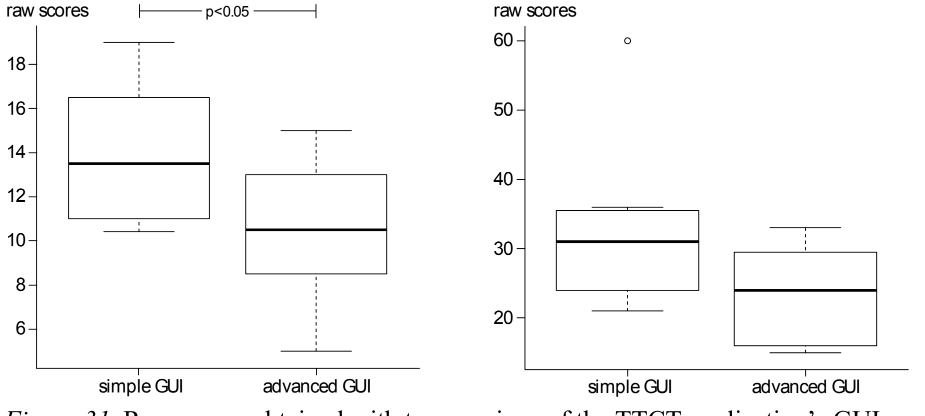

Figure 31. Raw scores obtained with two versions of the TTCT application's GUI (Study i3 in Paper V) and summarized for quantity (*left*) and quality (*right*). Horizontal line with number denotes statistical significance from the ANOVA.

The TTCT method delimits the time of each activity to 10 minutes. Also the requirement of maintaining a relaxed atmosphere imposed by the TTCT's task formulation delimited any time-based manipulations or assessments. However, in Study i3 (Paper V) the time the participants actively spent on drawing was measured and summarized for each participant (Figure 32). An ANOVA of these results showed a significant difference between the scores obtained with the two versions of the GUI ($F_{1,14}=9.9988$; $p<0.01$) showing that the participants of the advanced GUI spent more time on active drawing.

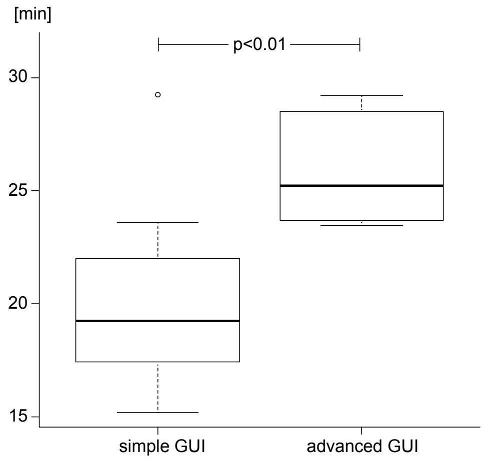

Figure 32. Total drawing time measured during idea sketching for simple and advanced GUI in Study i3 from Paper V. Horizontal line with number denotes statistical significance from the ANOVA.

Multiple ANOVAs of the time the participants actively spent on drawing in each activity (Figure 18) showed significant differences between the two versions of the GUI in case of Activity 1 ($F_{1,14}=21.367$; $p<0.001$) and Activity 2 ($F_{1,14}=4.6049$; $p<0.05$).

In this study, the eraser function available in advanced GUI was used 25 times in total, at least once by 5 of 8 participants. 3 of 8 participants using simple GUI asked for the eraser functionality.

Shape Tracing

The GUI used in the shape tracing tasks was rudimentary. It only displayed a greyed-out version (70% opacity) of the shape stimulus, and for each input method used for tracing it provided the visual feedback of drawing in the form of a solid black line of the same thickness as the shape stimulus.

Only the visual feedback of drawing was manipulated during the experiments by introducing the condition of no visual feedback that imitated drawing with an invisible ink (Paper II).

Input methods (mouse, stylus-, touch input) were tested with or without visual feedback of drawing but an ANOVA detected no main effect of visibility of visual feedback of drawing on task time or user's error, nor any interaction between visibility of visual feedback of drawing and input device used.

User Effects

The user as a person and human being is included ISO definition of usability and in the W^6 framework in the originator dimension (W_4 – "Who").

User Experience

The analysis of users' skills was based on their reported experience with all the input methods. It was expected to reveal additional explanatory factors of users' performance in drawing tasks.

Idea Sketching

In pre-test questionnaires to idea sketching tasks (Study i2 in Paper V) 24 participants (aged between 20 to 38 years, M=28 years) reported their average daily experience of: 6.9h (SD = 2.2) with computers in general, 5.5h (SD = 2.9) with a computer mouse, 0.4h (SD = 0.6) with stylus devices (incl. mobile phones), and 1.6h (SD = 2.3) with touch devices (incl. mobile phones). Figure 33 shows regression lines of raw scores to participants' declared experience.

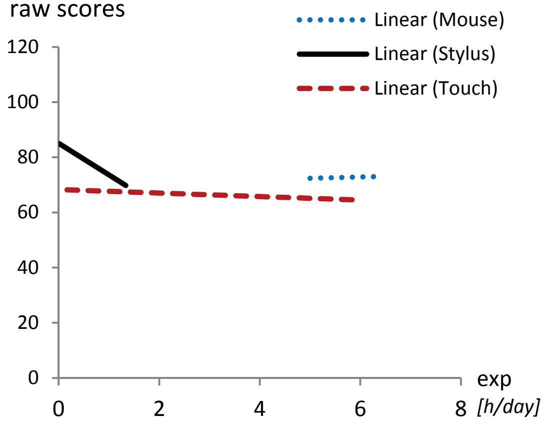

Figure 33. Regression lines of participant's declared daily experience in using each input method and the raw scores obtained during idea sketching in Study i2.

Shape Tracing

In pre-test questionnaires to shape tracing tasks (Paper VI) sixteen participants (four females and twelve males; aged between 21 to 29 years, M=24 years) reported their average daily experience of: 8.2h (SD = 5) with computers in general, 3.7h (SD = 4.7) with a computer mouse, 0.8h (SD = 1) with stylus devices (incl. mobile phones), and 3.3h (SD = 5.3) with touch devices (incl. mobile phones). The results showed no relation to task time (Figure 34). Figure 35 presents regression lines of error data from the same study.

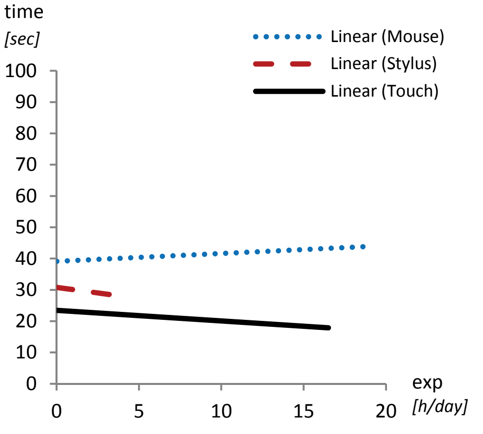

Figure 34. Regression lines of participant's declared daily experience in using each input method and the time of tracing over Shape 1 (Paper VI).

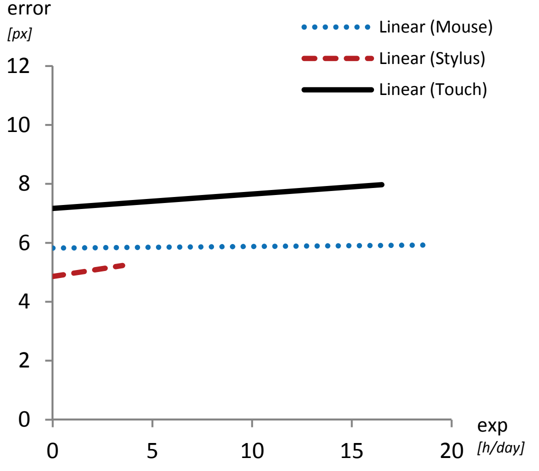

Figure 35. Regression lines of participant's declared daily experience in using each input method and the error of tracing over Shape 1 (Paper VI).

User Satisfaction

As the important element of the overall perception of the usability, satisfaction levels were assessed with post-test questionnaires in the studies on both types of drawing tasks.

Idea Sketching

A post-test questionnaire was created on the basis of The Creativity Support Index survey (Carroll & Latulipe, 2009). It was administered after Study i1 and showed participants' positive or negative responses to evaluation statements on a 10-point Likert scale, where 1 = "agree" and 10 = "disagree".

Q2 "I was very absorbed/engaged in this activity. I enjoyed it and would do it again." gave median response of **1.5** for pen and paper and **2** for stylus and screen.

Q3 "I believe the outcome of my drawings was worth the effort." gave median response of **3.5** for pen and paper and **4.5** for stylus and screen.

Q4 "It felt as though the pen vanished in thin air and I was able to concentrate on drawing." gave median response of **1.5** for pen and paper and **3** for stylus and screen.

Q5 "I was able to be very expressive and creative while doing the activity." gave median response of **1.5** for pen and paper and **2** for stylus and screen.

The post-test questionnaire used in Study i2 was also based on The Creativity Support Index survey (Carroll & Latulipe, 2009) and showed participants' positive or negative responses to evaluation statements on a 10-point Likert scale, where 1 = "agree" and 10 = "disagree".

Q2 "I was very absorbed/engaged in this activity. I enjoyed it and would do it again." gave median response = **2**.

Q3 "What I was able to produce was worth the effort." gave median responses for the mouse = **7**, stylus = **4**, and touch = **5**.

Q4 "While I was doing the activity, it felt as though the pen vanished and I was able to concentrate on the activity." gave median responses for the mouse = **7**, stylus = **2**, and touch = **5**.

The post-test questionnaire used in Study i3 showed participants' positive or neg-ative responses to evaluation statements in the adaptable five-point Likert scales.

Q1 "How clear did you find the tasks?" gave median response of **4** for simple GUI and **3** for advanced GUI on the scale: poor (1), fair (2), good (3), very good (4), excellent (5).

Q2 "How satisfied are you with your final drawings?" gave median response of **3** for both simple and advanced GUI on the scale: not at all (1), slightly (2), moderately (3), very (4), extremely (5).

Q3 "Was it easy for you to use the interface and make drawings?" gave median response of **2** for simple GUI and **4** for advanced GUI on the scale:

strongly disagree (1), disagree (2), don't know (3), agree (4), strongly agree (5).

Q4 "Was it easy for you to use the mouse and make drawings?" gave median response of **2** for simple GUI and **4** for advanced GUI on the scale: strongly disagree (1), disagree (2), don't know (3), agree (4), strongly agree (5).

Shape Tracing

After the tracing study on Shape 1 (Paper II) post-test questionnaires were used to collect information about participants' experiences and opinions regarding preferred input device, perceived ease of use, and perceived learnability (Paper VI).

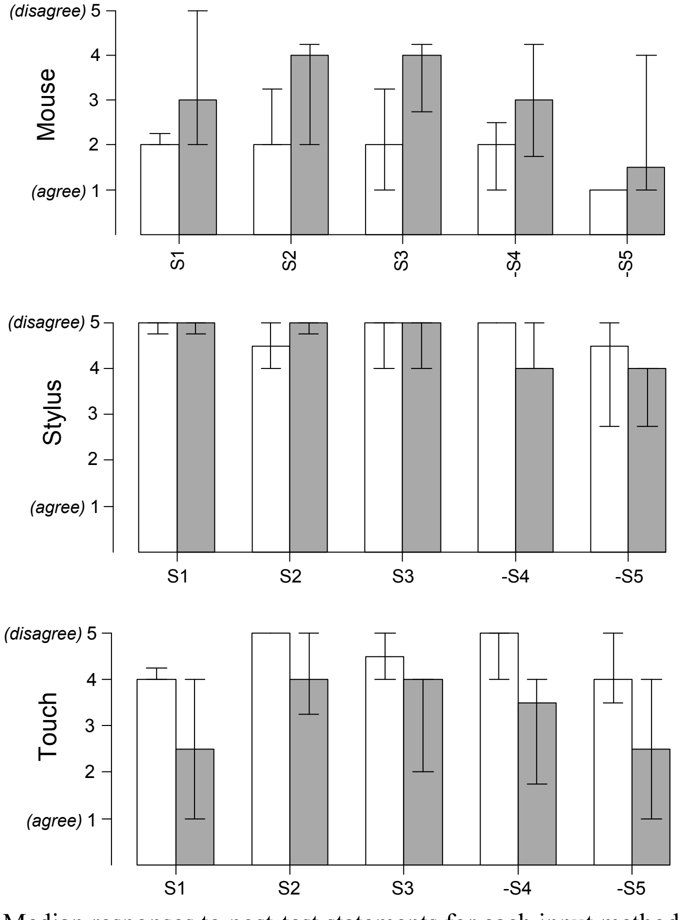

Figure 36. Median responses to post-test statements for each input method and visibility of feedback mode *(white bars for visual feedback "off", and grey bars for visual feedback "on")*. The scale is ranging from "agree" (1) to "disagree" (5). Whiskers represent the interquartile range. Adapted from (Zabramski & Stuerzlinger, 2013b)

Participants' responses to the statements were collected for each input device separately and coded between (1) and (5) reflecting the level of expressed agreement or disagreement on an ordinal scale:

S1 "I think that I would like to use this input device frequently for sketching."

S2 "I thought that the input device was easy to use."

S3 "I would imagine that most people would learn to sketch with this input device very quickly."

S4 "I found the input device very cumbersome to use."

S5 "I imagine I would need to practice a lot before I could sketch efficiently with this input device."

Discussion

Answers to Research Questions

The W^6 framework worked out as a comprehensive method of surface-based interaction analysis. It points to all the elements of not only what kind of tools is used but also how it is used, for what purpose, why and even includes the expected results as a part of the full picture of the computerized drawing task. The results related to the particular dimensions of the W^6 are elaborated below in respective sections.

Task Formulation Related Effects (RQ1)

Idea sketching and shape tracing are drawing tasks representing two extremes of the spectrum of the task dimension (W_5) when it comes to creative freedom. The basic differentiation into creative drawing (new ideas produced) and non-creative drawing (no new idea produced) is the result of different user goals represented by these tasks. That also had to be reflected in different task formulations that implied different expected outcomes of these processes. Therefore, the major consequence of different task formulations were the different evaluation methods that had to be used in this thesis to assess the outcomes of idea sketching – the TTCT (Torrance et al., 1992), and shape tracing (ISO, 1999b). These methods use different tasks, scales and measurement units – therefore, no direct comparisons between these tasks are possible and any similitudes must be based on the analysis of the patterns in results and logical inference on the meta-level.

Spatio-Temporal Constraints

Idea Sketching

In ideation, the main properties of the interaction outcomes are the quality and quantity dimensions of ideas represented by the shapes sketched. To be properly evaluated according to the manual, the formulation of each of the three activities of the TTCT could not be manipulated. The task time was limited to 10 minutes and the freedom was left to the user of how to utilize that time. The TTCT methodology also defines the constraint-free and relaxed atmosphere for the act of ideation to be most successful.

In Study i2 on input methods in ideation there was no difference between the scores obtained by the participants at the intermediary point during the task (8 minutes of stylus usage and 5 minutes of touch input usage). That did not support time-related approach to performance in creative drawing – that would reflect time measurements of the input methods tested in shape tracing. These results suggest that the participants planned the time of the task in advance and used time management strategies that resulted in valuable elements of their work (e.g. titles or elaborated details) being added on the end of each activity (Zabramski et al., 2011). These time related strategies can be observed also in Study i3 (Figure 18) where a form of operational bias has been observed that forced the participants into laborious drawing mode in the first two activities, but what negatively contributed to their final scores.

Shape Tracing

In tracing, the shape stimulus is given and no new idea is created therefore the accuracy and speed (time) were used as the measures of the quality and quantity of the interaction's outcomes.

Because of freedom of the ideation tasks the formulation of the tracing tasks has also been freed from the typical spatio-temporal constraints of the performance tests in HCI (e.g. like in Fitts' Law tasks or SL tasks). That change however was expected to affect the results of shape tracing tasks and has been additionally experimentally investigated in Paper IV testing shape tracing with the participants instructed to be "*as fast and as accurate as possible*".

The meta-analysis of the experimental results (Figure 22 and Figure 23 in Results section) shows that the deliberate decision of not imposing any spatio-temporal constraints (dimension W_1 and W_2 of the W^6 framework) on participants created a space for subjective operational biases towards speed or accuracy also noticed previously in target acquisition or trajectory-based tasks (Zhou & Ren, 2010). That user's unconscious decision of setting a particular focus on speed or accuracy is the consequence of the lack of constraints. It produced narrowly distributed results representing unique individual ratios of speed to accuracy set by each participant.

The difference between the formulations of unconstrained and spatio-temporally constrained shape tracing tasks is reflected in more spread measurements of tracing time and their lower median value, but also in increased error of tracing (Figure 22 and Figure 23) – something that could be attributed to the particular shape traced. However, the significant differences between input devices in the error domain became insignificant in the case of tracing with constraints imposed. This suggests the shift of users' focus toward the time of tracing that changes the ratio of task time to error according to the SATO. This also suggests that SATO in shape tracing – when interpreted as the trade-off between quantity and quality of the interaction outcomes – represents the inversed relationship between these two aspects of the tracing task.

Visual Stimuli Effects

Task formulation directly relates to the content dimension W_3 identified by the W^6 framework that focuses on "what" is being drawn.

In both creative and non-creative drawing, the empirical studies that were performed for this thesis had between subjects or even between groups design. Therefore, some of the results might be affected by the performance of the members of the particular user group tested (e.g. setting a unique ratio of SATO). However, the repeating pattern in the results allows for generalization and meta-analyses.

Idea Sketching

In idea sketching W_3 is represented by the idea and the shapes drawn to represent it. That is however highly affected by test stimuli that are gradually introduced by the activities of the TTCT – starting with 1 closed shape in Activity 1, through 10 open shapes in Activity 2, up to 36 circle shapes in Activity 3. These differences in gradually changing number of stimuli forced the participants to create more ideas in the course of the test. That naturally, delimits the quality and detail of ideas produced and found to be a factor in the test comparing two versions of the GUI *(elaborated more in following sections)*.

Figure 19, Figure *20*, and Figure *21* in Results section show the effects the particular type of stimuli presented with the way of grading each activity had on the average raw scores obtained by participants in the given test condition.

Activity 1 contributed the least to the final scores and was the least sensitive to the differences between test conditions. The most contributing one was Activity 2 contrasting the test conditions the best. The similarity of these stimuli to the scale and level of complicacy of the shapes used in tracing studies suggests that they were optimal for detecting the differences between test conditions. Activity 2 is also the kind of task that triggered different users' strategy reg. the continuous drawing in Study i3 (Figure 18). It was also the case with Activity 1 but the resulting raw scores cannot be successfully compared for differences.

Shapes drawn have an impact on the shape based tasks and each ideation activity of the TTCT included drawing many shapes with similar or different properties. In idea sketching it should be expected that re-using or repeating an idea created and drawn before is faster than creating a new one. The uniqueness of an idea sketched is highly valued by the TTCT scoring manual (Torrance et al., 1992). Any repeated idea or ideas that belong to the same family of ideas were not granted with any scores.

Obviously, any sketched idea can consist of multiple repeatedly drawn shapes of the same kind. It can be assumed that in these cases the impact of the properties of each single shape drawn during ideation gets averaged/diluted in the mass of different shapes produced. This seems to be supported by the fact that the Activity 1 (and its grading method) contrasted the test conditions the least.

Shape Tracing

In case of non-creative shape tracing W_3 dimension is represented by the replica of the shape pattern displayed. The results of shape tracing tasks (summarized on Figure 27 and Figure 28 in Results section) show that the three semi-randomly generated shapes (Shape 1, 2, and 3) used in these studies forced the participant to produce different ratios of speed to accuracy while tracing over them. This has been expected to be caused by the properties of these three shapes and led to creating and empirically testing two additional shapes (Shape 4, and 5) that included selected properties expected to make them easier or harder to replicate. Such a Shape Effect has been indeed confirmed by the results of the follow-up study (Figure 24 and Figure 25 in Results section) that show significantly different tracing error between the easy and hard to replicate shape while the tracing time did not differ.

Because of the different task formulation the results of unconstrained and constrained tracing cannot be directly compared, but their results clearly show that tracing time should not be considered as an explanatory factor in tracing tasks. Especially, when the task formulation includes spatio-temporal constraints – it may be expected that the participants will be biased towards speed (the average times of tracing Shape 4, and 5 were the same) what due to SATO will be compensated on expense of tracing accuracy. That is exactly why the SL and Curves, Lines and Corners (CLC) models have been reported to lack predictive power for complicated trajectories (Pastel, 2006; Vatavu et al., 2011). On the other hand, individual subjective bias in unconstrained tracing seems to be connected to the properties of the shape-patterns offered to replicate and driven by maximization of the tracing accuracy (that is minimization of the tracing error).

Apparently, test participants judge the shape's complicacy what helps them to set the particular speed to accuracy ratio. This creates a shape-dependent bias towards speed or accuracy resulting in more accurate tracing in case of unconstrained tasks, and faster tracing in case of constrained tasks.

The shape's lengths have not been found related to the tracing error produced in unconstrained tracing tasks (Paper III). However, in spatio-temporally constrained tracing the shapes used where equally long and were on average equally quickly reproduced but with significantly different error of tracing (Figure 25 in Results section or Paper IV).

In tracing tasks, where not so many shapes are drawn (just one or two), the effects induced by the properties of each shape are more likely to be clearly pronounced, more strongly affecting the results, and therefore easier to isolate and measure.

Due to expected effects of practice – i.e. faster and more accurate performance caused by repeated drawing of the same shape – only the first initial attempts of shape tracing (with each input method) were considered in this thesis. It allowed to expose all potential perceptual effects of the shapes traced and delimit the interference of expected learning effects originating e.g. from frequent task repetitions. However, the improvement over time related to learning effects was investigated in the tracing task too. Shape 3 was tested twice - before and after a short free-form drawing session (7 minutes long on average). The results show a decrease of an average tracing time and error that took place during the second attempt of tracing over the same shape (Figure 37 below).

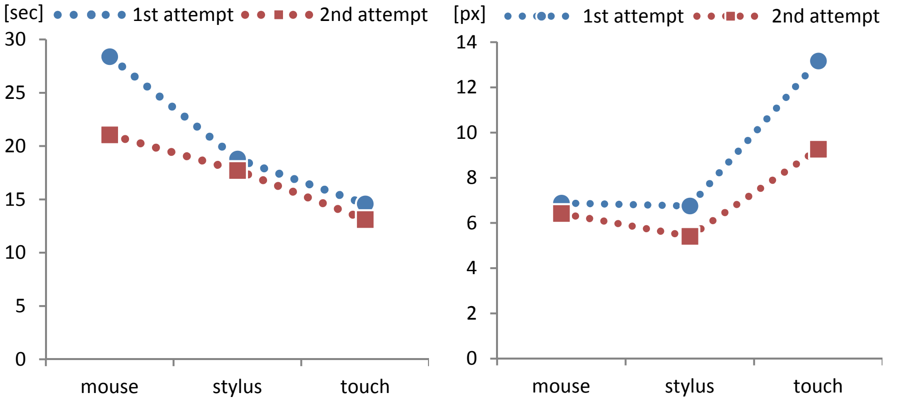

Figure 37. Learning effects observed in average tracing time (*left*) and average error (*right*) for the Shape 3 (in a follow-up task of Study t4 from Paper III).

UI Related Effects (RQ2)

The central aspect of usability assessment is how the UI of the computerized tools affects users' performance (the sixth dimension of the W_6 framework). This was investigated from the perspective of the quantity and quality of the outcomes of creative and non-creative drawing, and how these are affected by the input method and the GUI used.

Input Method Effects

Idea Sketching

Even though the results of Study i2 (Figure 26) were not statistically significant with the sample size chosen there, they indicate that user's ideation performance in creative drawing tasks is influenced in different ways by the computer input device used with simple GUI. This influence is expected to originate from the drawing inaccuracy induced by the device – similar to the observations from shape tracing (Figure 27) and is twofold: positive in case of quantity of ideas produced and negative in case of quality of ideas produced. This finding also suggests the existence of an accuracy dependent quantity-quality trade-off in ideation. Apparently, the highest drawing accuracy of stylus (Figure 27) made the users unconsciously investing more resources in developing the quality at the expense of quantity of ideas produced.

This confirms the previous observation that the count of ideas generated is not a reasonable alternative of the measure of idea quality (Reinig & Briggs, 2008), but also suggests a positive impact of the ambiguity originating from the UI's inaccuracy being limited solely to the number of ideas created.

Limitations of input devices are costly from a motor and cognitive point of view and are reflected by the aesthetic properties of the drawings created. Touch users produced the least aesthetically appealing drawings. Yet, the aesthetic appeal of drawings is not rated by the TTCT and hence did not contribute to the raw scores of the user.

The results of Study i1 indicated no significant difference in the raw scores between the analog and digital versions of the TTCT for both the quantity and quality analyses. These results suggest that using the pen to draw on paper or on a computer screen does not significantly influence the users' ideation abilities, if the GUI is similar to the paper-based version of the test (e.g. as in simple GUI).

Shape Tracing

In shape tracing, the measurements of the accuracy and time can be considered as the measures of the quantity and quality of interaction.

The regression lines on time to error plot (Figure 29 in Results section) show a typical SATO that took place in the shape tracing tasks. It means that the more accurate the tracing was the longer it took and vice-versa.

The influence of the different input methods used on users' performance was consistent. The same patterns of differences between mouse, stylus, and touch input could be observed in the tracing studies even if different shapes were used as the test stimuli (Figure 27 and Figure 28 in Results section).

The touch input outperforms stylus and mouse in case of task time and this observation may be potentially surprising in light of previous works on human motor behavior (Balakrishnan & MacKenzie, 1997) but has been previously noticed in a drawing task (Cohen, Meyer, & Nilsen, 1993). An explanation might be the spatio-temporal bias of navigational tasks and the fact that the shape stimuli used for tracing are rarely simple enough to be sufficiently predicted by Fitts' model.

In the consequence of SATO this must have affected the accuracy of tracing – what is reflected in the finding that touch input caused the biggest user error of all input methods tested can be explained by phenomena that take place during this kind of interaction.

For instance, the experimental PC system used the *contact area model* of touch sensing, what might have been different from user's imagination of how the touch input works. This might have caused unintentional offsets between the measured and the input position assumed or intended by the user – increasing the tracing error detected (Holz & Baudisch, 2011). Additionally, the users' hands caused a big occlusion of the drawing area with drawing fingers occluding the most crucial space when using touch input – particularly the area where the shape's creation took place. This can be observed in the plot of regression lines where the touch-induced tracing error does not change with its size as it is in case of the mouse and stylus that showed high correlations between error and its size (Figure 30 in Results section).

The differences in time or error between the stylus and mouse were not significant for any shape tested in unconstraint tracing. However, it may be observed that the stylus was always more accurate and faster than mouse.

Study i2 from Paper V directly compared mouse, stylus, and touch in idea sketching and the results show non-significant differences between the scores obtained using these input methods (Figure 26 in Results section). However, the stylus helped to obtain on average the most scores (with highest quality of responses) and touch the least scores (with highest quantity of ideas). That pattern of differences between the three input devices tested is more similar to the inversed pattern in results of tracing accuracy (error) achieved with these input devices (Figure 27 in Results section) than to the pattern in results of tracing time (Figure 28 in Results section). This means that the bigger the error introduced by the input-method (i.e. deviation from the intended shape) – the more negatively the quality of ideation is affected. This may indicate that the global effects of the input device that impact drawing during ideation originate from the domain of drawing accuracy rather than the time domain. Moreover, the relation between the number of ideas and their quality confirms the predictions from (Reinig & Briggs, 2008).

GUI Effects

Idea Sketching

Study i3 on idea sketching compared a simple GUI and its more complex version. The results of this study show that participants had lower raw scores for both quantity and quality of ideas produced when using the more elaborated version of the GUI (Figure 31). The users created significantly less ideas and obtained lower quality scores with the advanced GUI, despite spending significantly more time on continuous drawing (Figure 18). The users of simple GUI spent more time on ideation in the first two activities, which resulted in a small number of stimuli but promoted the original and in-depth representation of an object, scene, or situation. In those cases the users of the more complex GUI ended in a laborious drawing mode, suggesting the presence of a new form of operational bias. It also suggests that a form of relationship exists between active drawing time and the quality of ideas produced with quantity of ideas affected in the same way – i.e. more and better creative ideas are drawn when the GUI offered is simplistic or even non-existing. However, Figure 18 shows that this effect can be expected only when the users work on a single or couple of ideas like in Activity 1 and 2 of the TTCT. That observed difference tends to disappear when a lot of small ideas are expected to be created quickly like in Activity 3.

Since the results obtained with the simple GUI are comparable to drawing with pen and paper – simplistic GUI design can be considered as a base-line for other digital GUIs.

Shape Tracing

The GUI of the shape tracing application was extremely rudimentary. Besides the shape stimulus displayed, its only controlled parameter was the visual feedback of the trace. The expectation that the visibility of the line drawn will aid the user in the tracing task has not been supported by the results because there was no difference between the time or error results obtained with and without the visible trace. The user's focus does not appear to be split between performing the action and controlling its state what could cause a decline in performance (Kluger & DeNisi, 1996). Instead, it may seem like human perception system mainly uses feed-forward mechanisms to deal with the drawing process and feed-back mechanisms secondary only.

The latency introduced by the hardware and software components of the computer system was hard to observe during normal drawing but any potential effects it might have did not significantly affect the condition with visible feedback of drawing. It may also mean that the strategies used by the test participants to compensate for the delay of visual feedback were not different than in no feedback condition.

The only noticeable influence of the visibility of the traced line was the positive bias of user's satisfaction metrics toward touch input *(elaborated more in the following section)*.

User Related Effects (RQ3)

Dimension W_4 refers to the user that is a central element of the interaction thus user related effects have also been investigated.

Previous Experience

The users' daily experience with using the mouse, stylus, and touch input was expected to help to estimate the amount of training and participants' dexterity in using of these computer input devices and its influence on the performance.

Idea Sketching

In idea sketching different levels of users' experience with the input methods had no effect on the scores they obtained while using them during ideation (*Figure 33* in Results section).

Shape Tracing

While being observed as a very influential variable in shape tracing neither the correlation nor regression analysis of the previous experience and error or time data gave any significant or consistent results (Paper VI contains the extensive analysis). These results showed no relation of participants experience to shape tracing time and error. The regression lines show that the participants were skilled the most in using mouse but were tracing more slowly than with stylus despite being less experienced with it. However, to explain the positive attitude toward stylus, and the participants' scores in creative and non-creative drawing, it has to be assumed that the training transfer from the regular pen and paper takes place in the case of computerized drawing with styli. That improves the results even though the experience reported was the lowest out of all input methods tested.

Satisfaction

ISO standard puts the high user satisfaction as a concept defining a good usability of the tool.

Idea Sketching

In creative tasks regular pen and paper is the golden standard and serves a baseline for comparisons. The pen and paper condition gave slightly better median responses to all post-test questionnaire statements when compared with the stylus and screen condition in Study i1 (Paper V). Drawing with the regular pen was reported as more engaging and enjoyable, with the pen being perceived as a "transparent" extension of the body that allowed the participants to be creative, focus on the task and create the drawings worth the effort.

In Study i2, solving the TTCT was perceived as an engaging and enjoyable experience with the stylus as the most, and the mouse, as the least favored tool regarding perceived value of the drawings produced and the tool's appropriation. Mouse was mostly perceived as the tool that did not allow producing the outcomes worth the effort. Participants also reported being mostly aware of the tool's presence what interfered with the concentration on the activity. Because the touch input was perceived indifferently this suggests a straightforward relation between user satisfaction and level of directness of the input device used.

The participants of Study i3 (Paper V) perceived the clarity of the test's tasks as good or very good and were moderately satisfied with their final drawings in both the simple and advanced GUI groups. However, the advanced GUI condition was perceived as easier to use and draw with the mouse than the simple GUI condition. This looks like a counterintuitive preference since the results achieved with the more preferred advanced GUI were lower than results obtained with the alternative. However, advanced GUI gave the participant the means of control over the drawing process by offering the eraser functionality that was not available in the simple GUI and might contribute to the satisfaction levels declared.

Generally, the participants using the TTCT method in idea sketching reported that it was an absorbing and enjoyable activity.

Shape Tracing

In shape tracing the overall satisfaction of the input devices was also strongly in favor of the stylus (independently of the visual feedback conditions) while the touch was less favored and the mouse was the least graded device (Figure 36). However, the attitude toward touch improved in relation to mouse when the visual feedback of the line traced was not visible (Paper VI shows the detailed analysis).

The responses to the questionnaire statements were grouped by their association to three major aspects of users' satisfaction: *ease of use* (median value of replies to S2 and reversed S4), *learnability* (S3 and reversed S5), and *preference* (replies to S1). Interestingly, these aspects were strongly correlated with each other for each input device. This means that fewer questions could be asked to obtain similar results – and that approach has been suggested and validated in case of other questionnaire-based usability assessment tools (Lewis, Utesch, & Maher, 2013).

UI's usability (Main RQ)

The main question posed in this thesis was:

How does the usability of the User Interface affect the outcomes of computerized non-creative (shape tracing) and creative drawing (idea sketching)?

The overview on the results from the perspective of usability of tools used gives a complex picture. Many factors like user performance and satisfaction have to be contrasted with the effects of tool's and task formulations used. Additionally, a few of non-obvious results esp. regarding user preferences were not related to performance what makes creation of the overall picture even more complicated.

The specific context for all the tests performed within this thesis was limited to the educational environment where the test participants were sampled from, and where the popular desktop, and tablet computers were used in a controlled environment of a usability laboratory. Multiple parameters have been controlled when possible, and their influence on the interaction's outcomes has been evaluated to assess the extent to which different versions of the UIs tested are suitable for effective, efficient, and satisfactory use in creative and non-creative computerized drawing.

However, these summarized results allow us to create a generalized overview of how the outcomes of the computerized drawing tasks of two categories, can be affected by the properties of the computerized tool used. While the users were able to effectively complete all the drawing tasks but how effective and satisfied they were varied among different tasks and test conditions.

Idea Sketching

The results of Study i2 demonstrate that the participants' raw scores when using simple GUI with mouse, stylus-, and touch input were not significantly different (for the sample size chosen there). However, these results indicate that user's ideation performance is influenced in a different way by the computer input device used. This influence is expected to originate from the drawing inaccuracy induced by the device and is twofold: positive in case of quantity of ideas produced and negative in case of quality of ideas produced. Apparently, the highest drawing accuracy of stylus made the users unconsciously invested more resources in developing the quality at the expense of quantity of ideas produced. That suggests the existence of an accuracy dependent quantity-quality trade-off in ideation similar to the one observed in tracing studies (i.e. SATO).

Limitations of input devices are costly from a motor and cognitive point of view and are reflected by the aesthetic properties of the drawings created. Touch users produced the least aesthetically appealing drawings. Yet, the aesthetic appeal of drawings is not rated in ideation studies and hence did not contribute to the raw scores of the users. Therefore, to assess the usefulness of the tool in ideation the key factor is not drawing accuracy of the device but how good or how many ideas users are able to generate using it. And the value of both factors is defined by the goals and context of particular ideation task performed. That is, if the goal is to create many ideas of lower quality or vice versa.

This points to the importance of task formulation in ideation. Even though the grading method was different for each Activity of the TTCT, they posed a varying challenge to the users and reflected the differences between conditions. Each activity of the TTCT increased number of stimuli and forced the participants to create more ideas as the test progressed. That naturally, comes at a cost of the delimited quality and detail of ideas produced.

While users previous experience with the input methods had no consistent impact on their ideation performance, different versions of GUI tested in ideation tasks (Study i3) showed that better performance of the participants using the less advanced GUI can be explained by the negative effects of the operational bias that forced those users into a more laborious but less rewarding drawing mode.

The availability of undo/delete function available in ideation or creativity supporting tools might be a major cause of worse user performance. Eraser available in advanced GUI introduced means for editing, reshaping, or even destroying ideas produced. The use of eraser might be an explanation factor of smaller quantity and quality of ideas produced with the system offering such functionality to its users.

In general, if the objective of the ideation task is high number of ideas produced the inaccurate input device like touch, mouse should be chosen, even if it is a less preferred option. Smaller amount but better ideas will be generated with stylus that was favored the most. Simplistic drawing software will afford the production of more and better ideas than the more preferred complicated one – esp. when it offers eraser functionality.

Shape Tracing

The properties of the input method used significantly affect the accuracy and speed of shape tracing tasks that completely lack any creative component. The users of stylus were the most accurate but the use of touch input made them the fastest and the least accurate (due to SATO). The modified GUI in shape tracing in form of invisible trace had no effect on the speed or accuracy of tracing.

However, user performance can be highly affected by the nuances of tracing task's formulation. E.g. even different shapes traced posed varying level of difficulty to the users. Moreover, the way users are instructed to perform a tracing task (explicitly or not) can bias their performance by leaving them more or less freedom. When it is large, that freedom allows the users to devote their resources to the quality of the trace (increasing the time of tracing). However, when that freedom is constrained e.g. by ordering the users to be as fast and as accurate as possible, they will devote more attention to speed of tracing.

The results of tracing tasks are independent from the declared amount of users' previous training with the input devices tested. This observation goes in line with the observations from previous research that the users' satisfaction is high when their performance is high (Nielsen & Levy, 1994). However, the touch input may be perceived as offering more satisfactory performance than the mouse, even though it offers the worst accuracy – especially in case of its more experienced users.

In general, stylus is the best and most preferred tool for shape tracing. However, the final user performance will depend on the specifics of the drawing task that have to be described in detail.

General discussion

There are no universal solutions. A UI may be good for one application but worse for other one. The degree of directness of the input device seems to have a mixed impact on the results obtained with devices of different kinds. E.g. the touch input and stylus are both direct input devices but they affect the users' tracing performance in extremely different ways, with skilled users of the indirect mouse fitting in between.

The computer's form factor as an element of the computer system's usability does not appear to be an important characteristic when it comes to the influence on the results of drawing. The results obtained in ideation with the use of Tablet PC when compared to the desktop PC (Study i1 vs Study i3 in Paper V) do not allow inferring any reasonable conclusions.

However, the Tablet PC used while having appropriate screen size for convenient operations with the stylus might be too small for operations with fingers due to occlusion effects. And the regression analysis of the tracing error data (Figure 30 in Results section) suggests that occlusion (or even the size of tool-tip) contributes in inaccuracy awareness and production.

The low usability of the UI's hardware side (input methods) affects more the performance in tracing (noncreative drawing) and that influence on the software side should be considered more impacting the performance in ideation (creative drawing). However, the quantity and quality of the outcomes of both types of drawing tasks seem to be shaped by the effects related to the input's accuracy, related trade-offs, and the availability of the software methods of improving it (i.e. eraser). The results of this thesis may suggest that the tool's accuracy in spatiotemporally unconstrained tracing might be used as a form of predictor of the tool's performance in ideation – particularly, because the quantity-quality trade-off can be observed as an outcome of both types of task.

Generally, the assessment of the overall level of usability of the UI in drawing tasks appears to be a helpful tool in evaluating how a given UI will affect human capabilities. The augmentation of these capabilities should always be the goal of the hardware and software designers (Bush, 1945). The results of this research allow to suspect that such enhancement might not always take place and reverse effect – that is a reduction of the user' capabilities induced by the UI used – might take place here, and that effect should be limited when possible. Therefore, supported by the measures of the users' satisfaction, the results clearly show that the stylus together with a simplistic GUI are the most usable combination of hardware and software suitable for tracing but also for creative drawing.

There are multiple implications of the results of this research that go beyond this thesis and are worth of being mentioned.

The ambiguity introduced to the interaction by the UI was expected to have a supportive role positively influencing users' scores in creative drawing. Indeed, the rudimentary GUI introduced higher ambiguity than the more complex one, and helped to achieve slightly better results. On the other hand, the inaccuracy introduced by the input method used (esp. in case of touch input) should be expected to increase the UI's ambiguity but it resulted in lower scores therefore its influence on ideation has to be considered as negative.

Similarly to what have been previously observed in navigation tasks, the spatiotemporal constraint in tracing task's formulation might be related a bias toward speed observed in users' performance results. That is suggested by the findings from the comparative study on constrained shape tracing (Paper IV) and is dissimilar to the findings from unconstrained shape tracing tasks (Paper II). That bias is compensated (due to SATO) with increased inaccuracy of the trace but this effect gets gradually more visible for lasso-selecting polygon or traversing the tunnel of a given shape – keeping similar speeds as a basis of these varying inaccuracies. That also confirms the analysis from Paper I that suggests that due to different user goals drawing tasks cannot be considered (and modelled) as navigation tasks. In navigation tasks, the speed is in focus and the accuracy of the path of getting from point A to point B is a secondary problem. The higher focus on tracing accuracy (i.e. quality of outcomes) in drawing (i.e. reduction of error produced) has been reflected in the error results in Paper IV where due to minor differences in time – the error (quality of action) is the predictor of performance. Paper IV shows the problem with the definition of shape tracing task that needs to be specified to include the cases of different spatial constraints: e.g.: a task of lasso-selection of a polygon shape (1 sided spatial constraint), or a task of shape tunnel steering (2 sided spatial constraint), and comparison to the regular shape tracing (lack of any spatial constraint).

The original paper on SL (Accot & Zhai, 1997) refers to drawing as an example of a steering task. However, the preliminary comparisons to a dataset modelled with the SL model *(unpublished results from Study t5)* produced a mismatch up to 300% between these predictions and experimental results from the Paper IV. That shows that the role of the shape traced (Viviani & Terzuolo, 1982) is even more important and worth researching in case of computerized tools taking in to consideration the problems suggested by (Pastel, 2006). That also shows that contrary to navigation tasks, tracing time should not be considered as an explanatory factor in tracing tasks.

Conclusions

Drawing has an important role in supporting the ideation process, which includes creating, developing, and communicating new ideas. The ultimate goal of that process is the production of good and relevant ideas, and not only a large number of ideas. Furthermore, the computer UI as a tool to facilitate drawing should not hinder the outcomes of the drawings or the outcomes of the ideation process, or at least it should affect these outcomes minimally.

This thesis experimentally investigated the consequences of using different computer UIs in two types of drawing task that represent two ends of the ideation spectrum: a creative drawing task (i.e. an idea sketching task in which new ideas are created) and a non-creative drawing task (i.e. a shape tracing task in which no new idea is created). In that context, the goal was to identify and evaluate the consequences of the various issues originating from properties of a computerized tool's UI, i.e. the inaccuracy of the input device used and the functionality of the GUIs, as well as the drawing task formulation and user experience.

W^6, an extended analysis tool, is a new framework for interaction analysis introduced in this thesis. The framework improves the theoretical and practical understanding of a computerized drawing task and the phenomena that result from the varying accuracy of UI. Theoretical investigations together with meta-level analyses of observations made in the studies helped to identify that drawing tasks are largely oriented on quality of outcomes. Therefore, the more accurate the input method helped participants to achieve not only a higher quality of traced shapes but also helped produce a higher quality of ideas. This finding was characterized by a trade-off between the quantity and quality of the interaction products. In ideation, less accurate input devices significantly facilitated the production of a larger number of ideas but the quality of the ideas was not good. In shape tracing, higher drawing speeds also caused lower quality of outcomes, which is consistent with the well-known SATO associated with these input devices.

Furthermore, users tend to prefer UIs that are more accurate (and more direct) but also inaccurate ones that offer correcting GUI functions e.g. in the form of an eraser function. However, the use of the eraser led to a change in the participants' ideation strategies. In this condition, the users drawing mode could be characterized by intense activity during the drawing process. This allowed the participants to avoid the reinterpretation of ideas that were inaccurately drawn, which could potentially result in the production of ideas of better quality and quantity, and therefore higher scores.

Furthermore, new phenomena specific to shape tracing are reported, including shape difficulty effects leading to varying tracing accuracy. This kind of effect is currently not covered by the interaction models (e.g., SL) that predict the time of a shape-based path-steering task based on the shape's length. The results of the study comparing tracing over two types of shape (hard and easy) clearly showed that these shapes are replicated in about the same time; however, the errors produced are significantly higher in the hard shape condition. This finding suggests that the particular properties of shapes that the participant draws affect the outcome of that drawing task. That however, may affect also the idea these shapes represent.

Other effects observed in tracing studies are those related to task formulation, which led to different results, even when the tasks were similar but where slightly different constraints were imposed on the spatial or temporal aspect of the task. This finding implies that users under stress tend to draw faster and therefore less accurate. However, the best way to reflect the test conditions of the ideation tasks, no constraint should be imposed on the users so they would be able to be more creative and therefore achieve better scores in ideation. And these conditions when transferred to the tracing tasks reduce the constraint on users what results in triggering free subjective operational biases towards speed or accuracy. However, the typically used HCI models (e.g., Fitts' Law or SL) constrain the performance of users during the navigation task (i.e. by ordering them to be as fast and as accurate as possible). That makes them inapplicable for free drawing tasks during ideation, which is focused on the product, not the process.

This thesis demonstrates that the overall usability of the tool for ideation and tracing is based on its accuracy and the level of satisfaction it brings to the user.

In the tracing studies the stylus input device resulted in the best performance and was most preferred by the users. Touch input was the least accurate of all input methods but the users preferred it to the mouse, especially when they could not see and judge the outcome of their drawing. In ideation studies the stylus was found to create smaller number of ideas but with the best quality and was also the most preferred device, suggesting that the inaccuracy of computerized tools cannot only make drawings less aesthetically pleasing but also negatively affect the ideas created in the process. This suggests that the tool's accuracy in spatiotemporally unconstrained tracing might be used as a form of predictor of the tool's performance in ideation.

These considerations further show that the final selection of the properties of the UI might be guided by a potential anticipated outcome of the process. Higher inaccuracy of the input affects the quality of ideas but leads to the generation of a slightly higher number of ideas. Optionally, accuracy can be improved by using correction functions, which are preferred by the users but lead to fewer and inferior ideas. Accuracy can also be improved by using a more accurate input device, which leads to a higher quality of ideas but might affect the number of ideas produced.

Therefore, supported by measures of the users' satisfaction and performance the stylus together with a simplistic GUI are the most usable combination of hardware and software for the least experienced users in tracing tasks, and for all users in creative drawing tasks.

Additional to the obvious applications in ideation and drawing, the potential applications of the results from the shape tracing experiments range from research on gestures (used, e.g., as computer commands) to security systems (e.g., graphical Captcha codes or hand-drawn passwords for authentication). The influence of the shape properties on the performance of small amplitude movements and the path taken can be applicable in microsurgery and micromechanical applications that have become increasingly more important.

Limitations of the Study

Obviously, this thesis has some limitations that need to be addressed. First, not all aspects of creative and non-creative drawing could be controlled in symmetrical laboratory studies. In particular, the selection of the method of ideation assessment imposed multiple constraints on the design of the ideation studies, as well as on the design of the shape tracing studies. Second, the author is aware that this thesis strongly focused on the outcomes of idea sketching and shape tracing. Future research needs to focus on the analysis of the actual process that results in the particular outcomes produced by the participants. The interaction laboratory setting imposes a special test atmosphere during the experiments. Therefore, settings that are more natural could elicit more relaxed behavior, which might lead to results that differ in an important way.

Due to the fact that the studies presented in this thesis were exploratory the sample size chosen was relatively small, what can be considered as the limitation of this study. Additionally, the participants taking part in the empirical studies were limited to university students or employees at the university. Thus, any generalization of the results to a broader population must be done with extreme caution.

Contributions

The contributions of this thesis can be summarized as follows:

- Extending the previously published method (the W^5 meta-model) to the W^6 framework that takes into account the tools used for drawing

- Presenting that pointing and navigation tasks are not equivalent to drawing task due to conflicting user goals. Therefore the tracing time should not be considered as an explanatory factor in tracing
- Empirically comparing the computer input devices (mouse, stylus, touch input) and different GUIs used in shape tracing and idea sketching and assessing their effects on user's performance in terms of varying quantity and quality of outcomes
- Identifying a new form of quantity-quality trade-off in ideation that is introduced by the input device used, and confirming the SATO in tracing
- Identifying a new form of operational bias in ideation that is introduced by the GUI used. This bias was found to affect both the quality and quantity of ideas created
- Showing the effect of the shape's properties that were found to significantly affect user tracing accuracy. That accuracy was additionally shown to be influenced by the tool used
- Identifying different task formulations as a factor affecting the outcomes, comparing the unconstrained tracing to the spatiotemporally constrained version, and finding a negative impact of constraints
- Successfully applying Correspondence Analysis as a suitable exploratory method in the analysis of usability data
- Finding that the users' previous experience not only biases objective measurements of a user's performance (task time and error) but also a user's subjective satisfaction in a shape-tracing task
- Addressing the notion of user satisfaction in tracing and ideation tasks
- Acknowledging the learning effects in a shape-tracing task

Suggestions for Future Work

The significance of the inaccuracy of UI in drawing tasks raises some interesting issues for future research. Future studies should isolate and experimentally address the inaccuracy of the input methods by, for instance, introducing controlled programmatic noise to the user's input within the same modality and by employing different types of task.

The issues related to the effects of a shape's difficulty and the lack of a relation between the results on unconstrained tracing tasks from the shape's length indicate a need for supplementing the interaction models with the properties of shape. Presently, the SL model (Accot & Zhai, 1997) does not allow one to make reliable predictions for the paths based on complex shapes.

- The effect of the shape's properties should also be investigated to improve our understanding in the following areas:
- The effects of shape size on tracing error

- Feature-based methods for classification of a shape's difficulty level for easier comparisons of shapes
- Algorithmic or artificial intelligence-based shape features categorization and tracing error estimations
- The influence of properties on shape retrieval and the influence of the shape's meaning on success rate (e.g., in the context of shapes used as easy or complicated passwords)

The effects of the tool used in shape tracing would need more attention in, e.g., the following areas:

- The role of increasing level of indirectness, i.e. the distance between the stimulus and the medium or tool (e.g., direct vs. indirect stylus, direct vs. indirect touch input) that results in spatial dislocation of the shape drawn or copied of shapes, including controlled distance between the stimulus and the user-generated version
- The influence of input methods on shape retrieval

Research should examine different aspects of task formulation and its effects on task outcomes:

- Spatial and temporal constraints imposed in generic shape tracing, lasso selection, and steering tasks
- Basic comparative studies between computer-based and paper-based shape tracing

Future research should focus not only on the outcomes of the process but also on the nature of the creative process. Additional studies are needed to evaluate the effects of particular UI elements on creative tasks:

- How controlled ambiguity that is introduced by the UI influences the outcomes of the creative tasks
- The comparison of the eraser and undo functions on ideation during creative drawing and which elements and functions of invisible GUIs are considered intuitive (similar to resize or zoom functions on touch screens)
- The methods of development and evaluation of computerized tools for supporting particular outcomes of the creative process

Summary in Swedish (Sammanfattning)

Nya ideer formas genom en process som består av att skapa, utveckla och kommunicera idéer till andra människor. Att rita eller teckna har i århundraden varit ett sätt att stödja idé-processen.

Idag används ofta datoriserade ritverktyg för detta ändamål. Sådana verktyg har ett användargränssnitt i form av dels hårdvara i form av ett ritdon och bildskärm och dels mjukvara i form av ett program med symboler, ikoner och menyer. Ritdonet kan vara exempelvis mus, pekpenna eller en tryckkänslig skärm.

Användargränssnittet kan komma emellan den som ritar och resultatet på ett sådant sätt att det påverkar den skapande processen. Därför är det av intresse att veta på vilket sätt olika utformning av avändargränsnitt påverkar ritprocessen i allmänhet och den kreativa ritprocessen i synnerhet.

I denna avhandling studeras med hjälp av kontrollerade experiment hur olika utformning av användargränssnitt påverkar olika faktorer i ritprocessen i två olika typer av ritande: dels en kreativ rituppgift (där nya ideer ska skapas) och dels en icke-kreativ rituppgift (att rita av en färdig figur). Syftet med experimenten har varit att identifiera och utvärdera konskekvenserna av precisionen i ritdonet, funktionaliteten i det grafiska användargränssnittet, formuleringen av rituppgiften och användarnas tidigare erfarenhet av olika ritverktyg.

En metanivå-analys av samtliga observationer visade att hög precision i input-metoden ledde till högre kvalitet vid icke-kreativt ritande men också till högre kvalitet på ideer vid kreativt ritande. Det visade sig också finnas en balansering mellan kvantitet och kvalitet i det ritade resultatet. Vid kreativt ritande ledde sämre precision hos ritdonet till många fler ideer, men dessa var av sämre kvalitet.

Användare föredrog ritdon med högre precision. Detta var också fallet när användargränsnittet erbjöd möjlighet att radera delar av det ritade. Emellertid, att kunna använda radering ledde till en speciell typ av strategi för skapande, användarna ritade omsorgsfullt och tidsödande men undvek att omtolka det ritade, något som inverkade negativt på produktionen av ideer både vad gäller kvantitet och kvalitet.

Vid icke-kreativt ritande påverkade svårigheten hos den ritade formen precisionen hos det ritade, något som inte kan förklaras med dagens modeller. Hur uppgiften var formulerad visade sig också påverka resultatet.

I avhandlingen introduceras ett nytt teoretiskt ramverk för interaktionsanalys som förbättrar den teoretiska och praktiska förståelsen av datoriserat ritande och de olika fenomen som blir resultatet av variationer i användargränssnittet hos ritverktyget.

Resultaten deonstrerar att brister i användargränssnittet hos datoriserade ritverktyg inte bara gör det ritade mindre estetiskt tilltalande utan också påverkar den kreativa processen på ett negativt sätt.

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"You have to give yourself credit, not too much because that would be bragging."

Frank McCourt
from *Teacher Man*

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