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# Analysis of the influence of screen size and resolution on work efficiency

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# Kurzfassung

Die Verfügbarkeit von großen hochauflösenden Bildschirmen und digitalen Anzeigeschnittstellen mit hoher Bandbreite ermöglicht uns eine Benutzerstudie durchzuführen, die die Auswirkungen eines großen hochauflösenden Bildschirms und kleinerer Bildschirme auf die Produktivität und Zufriedenheit bei komplexen Bürotätigkeiten vergleicht, wobei wir die Pixeldichte, die Farben, die Helligkeit und den Kontrast der Bildschirme durch den Einsatz einer virtuellen Maschine und eines einzigen großen hochauflösenden Bildschirms verbunden an einen einzigen hochleistungsfähigen Rechner kontrollieren. Wir beschreiben den Fortschritt und aktuellen Stand der Bildschirmtechnologien, die diese Studie ermöglichen und wir beschreiben wie sich unsere Studie von früheren themenbezogenen Arbeiten unterscheidet. Teilnehmer erfüllen drei abstrakte Tätigkeiten, die komplexe Bürotätigkeiten simulieren, an drei verschiedenen Bildschirmgrößen und -auflösungen, jedoch mit der gleichen Pixeldichte. Sowohl quantitative wie auch qualitative Daten wurden gesammelt und ausgewertet. Wir beschreiben welche Auswirkungen große Bildschirme auf die Aufgabendauer, die Fehlerrate und die Zufriedenheit im Vergleich zu kleineren Bildschirmen haben. Die Ergebnisse deuten darauf hin, dass große Bildschirme die Produktivität von komplexen Bürotätigkeiten signifikant verbessern und dass Benutzer große Bildschirme kleineren Bildschirmen bevorzugen.

# Abstract

The availability of large high-resolution displays and high-bandwidth digital display interfaces allows us to conduct a user study that compares the effects of a large high-resolution display and smaller displays on productivity and satisfaction for complex office tasks, where we control for pixel density, color, brightness and contrast of the displays using a virtual machine and one single large high-resolution display connected to a single high-end computer. We discuss the advances and current state of display technologies that enable this study and we discuss how our study differs from earlier related work. Participants perform three abstract tasks that simulate complex office work on displays of three different sizes and resolutions but with the same pixel density. Both quantitative and qualitative data has been collected and analyzed. We describe the effects that larger displays have on task completion time, error rate and satisfaction compared to smaller displays. Results indicate that large displays significantly improve productivity of complex office tasks and that users prefer larger displays over smaller displays.

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# List of Abbreviations

**CSMT** Colour and Shape Matching Task

**DVI** Digital Visual Interface

**ERR** error rate

**FHD** full high definition

**HD** high definition

**HDMI** High-Definition Multimedia Interface

**ICT** Information Combining Task

**LST** List Search Task

**M** mean

**PPI** pixels per inch

**SE** standard error

**SD** standard deviation

**TCT** task completion time

**TLX** NASA Task Load Index

**TV** television

**UHD** ultra high definition

**VGA** Video Graphics Array

# 1 Introduction

The continuing advancement of display technologies and falling prices for larger displays with higher resolutions could make large high-resolution displays a more common sight in the office and at home. This raises the question whether and how large high-resolution displays can be applied to improve productivity and how their use might change interactions and perceptions of modern office workspaces.

The recent rise of ubiquitous use of smartphones and tablets in the personal life and in the workplace has led to fierce competition between hardware manufacturers to release mobile devices with ever higher specifications. One of the most prominent and most improved specifications are the displays of mobile devices that nowadays reach pixel densities on high-end devices where users with normal visual acuity are no longer able to discern individual pixels. Manufacturers of larger displays like monitors and televisions (TVs) have not had to respond to the same market pressures, so that the majority of monitors between the sizes of 21" and 27" still only feature the so called 1080p or full high definition (FHD) resolution of 1920 x 1080 pixels at 60 Hz in the dominant aspect ratio of 16:9 even though high-end smartphones already feature the same resolution at only 5" - 6" in size. The resolution of monitors and TVs may have been held back by the connectivity options of monitors and TVs, which simply did not support higher resolutions until very recently. The High-Definition Multimedia Interface (HDMI) has established itself as the de-facto standard interface for connecting consumer entertainment devices, where it is available on all digital consumer devices [HDM09]. Compatible and technically based on the Digital Visual Interface (DVI), HDMI has replaced the analog Video Graphics Array (VGA) as the standard connection on modern monitors together with DVI. However, the highest resolution with an aspect ratio of 16:9 that HDMI supported up until version 1.2 (2005) is 1080p at 60 Hz [HDM05]. HDMI 1.3 (2006) [HDM06] and HDMI 1.4 (2009) [HDM09] that support resolutions with an aspect ratio of 16:9 up to 2560 x 1600 pixels at 60 Hz have seen slow adoption since most sources for TVs, including Blu-ray Discs, do not even output 1080p at 60 Hz. ultra high definition (UHD) TVs and so called 4k resolution displays are expected to succeed high definition (HD) TVs and other HD displays in the near future. The HDMI 2.0 standard supports so-called 4k resolutions like 3840 x 2160 pixels at 60 Hz with an aspect ratio of 16:9 (2160p) [HDM13], but even then display configurations are limited to a single display. DisplayPort is an alternative high-bandwidth display interface standard that is becoming more popular with current desktop graphics cards and current high-end laptops. DisplayPort supports multiple displays on a single DisplayPort connector as of version 1.2 (2009) for a total resolution of 2160p, for example

[Kob10]. DisplayPort 1.3 (2014) even allows resolutions of up to 7680 x 4320 pixels at 60 Hz with an aspect ratio of 16:9 (4320p), one of the so-called 8k resolutions [Ves14]. This resolutions allows a single computer to drive one or more displays for a total resolution that is equivalent to four 2160p displays or sixteen 1080p displays from a single DisplayPort 1.3 connector. This 4320p resolution allows a display to be as large as a large desk or small wall and still have such a high pixel density that users with normal visual acuity cannot discern individual pixels from the usual sitting distance on a desk, which would make working with a computer as natural as working with printed materials on a desk. Such a display can cover the entire field of view of an office worker as opposed to the very small view angle that office workers are restricted to on single monitor displays still very common in office workspaces. Scalable resolution displays that cover entire rooms are expected to invade offices in the next 10 years and might completely change the office environment where users can partition large displays for temporary personal workspaces or collaborate together on a large display using gestures, voice commands and other natural input [LJR+13].

Today 30" and 40" LCD monitors are already available, but still more expensive than multiple 24" LCD monitors of similar combined size. Displays larger than 30" or 40" are generally restricted to public displays or TVs and generally suffer from much lower pixel densities compared to smaller monitors because they tend to feature the same 1080p resolution. However, the newest generation of TVs larger than 40" feature a 2160p resolution, and monitors of similar size and resolution are expected to follow soon. In this study, we used such a new generation flat-screen TV (Panasonic TX-50AXW804) that is 50" in size with a maximum resolution of 3840 x 2160 pixels connected to a single high-end computer via DisplayPort to compare the effects of a large high-resolution display and smaller displays on productivity for complex office tasks. Earlier related work compared the productivity with smaller displays to larger displays or one monitor to multiple monitors were restricted to use one or multiple monitors that ranged from 17" to 30" in size or compare those to custom build multi-projector displays ranging from 46.5" to 203" in size. Many of the these studies do not specify the resolution of their displays nor the type of the monitor that was used, which makes it difficult to compare or repeat their experiments. Using different displays for different sizes, the related work mentioned does not control for pixel density, color, brightness and contrast of the displays, which could also have an effect on productivity or satisfaction. Pixel density is measured in pixels per inch (PPI), which affects how many logical pixels (i.e. amount of information) are displayed as opposed to physical pixels (i.e. detail of visual appearance). For example, a display with twice the resolution can display twice the amount of information when PPI is kept constant, but it can also display the same amount of information when PPI is doubled. In the latter case, doubling PPI only doubles the detail of the visual appearance of the information. For example, text looks sharper but still the same amount of text is displayed. We do control for PPI, color, brightness and contrast in our study by using the same monitor across all participants and tasks. Only the usable display size is changed by reducing the resolution and keeping the PPI constant, which is made possible by running the operating system (Windows 7) as a virtual machine in a hypervisor (VMware player) and reducing the resolution within the virtual machine.

# 2 Related Work

The referenced related work explores whether and how multiple monitors and large displays affect productivity, error rates, satisfaction, interaction and perception of users when performing office and navigation tasks on multiple monitors and large displays compared to single small monitors. Their results are largely consistent even though their display configurations vary widely - from the number of monitors, the size of displays, the type of displays, the resolutions of displays, the pixel density of displays, the color of displays, brightness of displays and contrast of displays to the size or existence of bezels.

## 2.1 Unique issues with CRT monitors in the past

While there has been ongoing interest in researching the effects of increased display size on productivity, satisfaction and usability in general since multiple monitors have become affordable and more common since the turn of the century, early related work had unique issues that are less of concern today. Some of these issues included the bulkiness of affordable CRT monitors that were common during that time. For example, "65% of users said the 21-inch display was too large or bulky for the average workspace" [Sim01]. Another problem of CRT monitors were that their bezels were already so big that multi-monitor users were not motivated to reduce the gap between multiple monitors and rarely extended a single window across two or more monitors as can be seen in Fig. 2.1 from Grudin's field study [Gru01, Gru99].

Since larger displays were very expensive at that time and since it was cheaper to add another mid-range graphics card to an existing system than replace an existing graphics card with a high-end graphics card that could drive a large monitor, the most economical way to increase display real estate was to install multiple monitors. This was common practice, even though most users considered a second monitor to be inferior to a larger monitor about twice the size. This could be explained by the missing awareness for multiple monitors at that time that was reported among designers, developers, testers, or usability engineers. Not even those who used multiple monitors themselves considered multiple monitor scenarios for the applications they were developing, so that applications available at that time did not make good use of multiple monitors - including the operating system [Gru01].

**Figure 2.1:** A typical 3-monitor configuration around the year 2000 [Gru01]

## 2.2 Partitioning space with multiple monitors

Grudin argues that multiple monitors can be more about partitioning space than about increasing available space. The division into two spaces can facilitate diversity in use and - unlike larger monitors - multiple monitors force a user to segment their virtual space, which may have advantages. Grudin provides the analogy of a house with many small rooms versus a house with less but larger rooms. While people generally prefer larger rooms, they still value many (smaller) rooms with dedicated functions each [Gru01, Gru99]. Similarly, he argues that not all information requires the same attention. Users might want some information brought to their attention, but prefer to keep other information in the periphery. His qualitative research confirms that one monitor is generally used to focus on a primary task while another monitor is used for secondary tasks in the periphery. The reason for this is that when another monitor displays information that supports the primary task, it reduces the cognitive load of the user by allowing rapid glances to check on information. In fact, developers and testers use the second monitor more for reading than for interaction. Moreover, alerts and communication channels like e-mail or instant messaging are placed on the secondary monitor to avoid taking focus. Some users even go so far as to use a PDA as an additional monitor for having instant access to a resource in a known location in peripheral vision. Other common uses of the secondary monitor are for browsing the web; glancing at background resources such as To Do lists, contact lists, calendars; and non-related tasks such as controlling the audio of digital music playing in the background. Participants also report that it is a relief not to have to use buttons to bring windows into focus that would otherwise be obscured by other overlapping windows. In conclusion, every person likes the multiple monitors so much that they would regret going back to a single monitor and some even consider acquiring multiple monitors even personal use at home [Gru01].

**Figure 2.2:** The experimental "Dsharp" display [CSR+03]

## 2.3 Increasing productivity with high-resolution displays

Czerwinski et al. [CSR+03] presented a study that quantitatively assesses the productivity benefits of very large displays for single users working on complex, multiple window tasks. Such tasks typically involve web browsing and editing office documents. By this time, as many as 20% of the Windows users run multiple monitors from one PC or laptop, reveals their survey research. The study compares a 15" LCD monitor with a resolution of 1024 x 768 pixels to an experimental multi-projector system where 3 projectors project 3072 x 768 pixels in total from the back onto a curved Plexiglas panel to realize a 46.5" display (see Fig. 2.2). Its display size and resolution is equivalent to having 3 monitors tiled side-by-side with a resolution of 1024 x 768 pixels each, but without the bezels.

This enables them to quantitatively compare task completion time, user satisfaction and usability issues of the 15" monitor and 46.5" display for 12 isomorphic office tasks that consist of a sequence of sub-tasks that include searching the web for a certain web page, finding certain information on that web page and storing that information in different Office applications. They find that users on the 46.5" display are able to complete the tasks significantly faster than on the 15" monitor. The large display also receives significantly higher ratings on all user satisfaction questions and is preferred by almost all participants. However, the large 46.5" display was not without usability issues. Several users complain about the brightness of the experimental display and some users think that they were forced to sit too close to the display. Regardless of the specific conditions of the experiment, the two most common issues with the large display include the amount of physical navigation required to move the cursor across the entire display and not being able to easily find the cursor if lost. They also have trouble remembering to click on a window that is not in focus to bring it into focus, even though it is open and not occluded. The small 15" monitor suffers from decreased productivity due to accidental mismanagement of windows and additional window management in general. For example, accidentally opening and closing files, or resizing and moving windows for each task slows them down during their tasks [CSR+03].

## 2.4 Decreasing errors with large monitor arrays

A multi-monitor study conducted by Ball and North [BN05] compares a single 17" LCD monitor with a resolution of 1280 x 1024 pixels to a tiled high-resolution display made up of the same monitor model in arrays of 2 x 2 and 3 x 3 for a total resolution of 2048 x 1560 pixels and 3840 x 3072 pixels, respectively. This study tries to determine the effects of a tiled high-resolution display on basic low-level data visualization and navigation tasks. Asking the participants to find targets of different sizes on these configurations, their quantitative results are not statistically significant in terms of performance across all display sizes when looking for medium or large targets. However, participants are significantly faster when they look for small targets on the 9 monitor configuration compared to the single monitor configuration because they have to pan and zoom on the smaller display. Another task requires participants to compare targets. Similarly, participants are significantly faster - up to twice as fast - in this task when they work on the 9 monitor configuration compared to the 4 monitor configuration. So in both cases, the largest display, which encourages physical navigation, significantly outperforms the smaller displays, which require mostly virtual navigation. The qualitative results show that higher resolution and physical navigation decreases repetition and increases confidence. They speculate that lighter cognitive load of users on the larger displays might be the cause for the decreased repetition since users only accidentally report a result more than once on the single monitor configuration and 4 monitor configuration where loss of context, confusion and frustration are very common due to the requirement of having to navigate virtually by panning and zooming. This is consistent with the overall preference of physical navigation and being zoomed out for greater overview that several participants report on the largest display.

Hall et al. [TSH+08] expand on these results with a study of similar configuration but different task where they ask participants to create a web page on a single 17" monitor and 4 monitors tiled to an array of 2 x 2 for a total display size of 34" excluding bezels. The resolutions of both configurations are not mentioned. The primary aim of Hall et al. [TSH+08] is to understand the relationship between multiple monitors and low level multitasking, as well as the effect of multiple monitors on user performance and correctness. Their quantitative analysis find that users of the multi-monitor configuration make significantly less mistakes than users of the single monitor. Multi-monitor users are also multi-tasking significantly more. While multi-monitor users also take less time to complete the task, the difference was not statistically significant to warrant a conclusion. The qualitative analysis validates their own quantitative results and the results of previous related studies [Gru99, Gru01, CSR+03, BN05]. These include that multiple monitors support task diversity, facilitate multitasking and increase productivity and satisfaction, but still lack good support by the operating system (Microsoft Windows) and applications. For example, they find that multiple monitors enable multitasking while single monitors detract from multitasking because multi-monitor users benefit from peripheral awareness, whereas single monitor users struggle with window placement. Furthermore, multiple monitor users do not need to re-adjust windows after opening a secondary window, whereas the single monitor users frequently have to switch windows and reposition them constantly. They also confirm that multi-monitor users enjoy having extra space so that they are able to "see all you need at once" or have "more space to organize windows" while single monitor users are frustrated by the limited space and find it "too constricting". While the majority of participants enjoy the multi-monitor experience and believe that it enhances their performance, some participants find that four monitors are too much. These participants feel that that many monitors distract them because they are trying to do too many things at once, which affects their performance [TSH+08]. Furthermore, the particular configuration of 4 monitors into a 2 x 2 quad-panel display causes unique usability issues. For example, the participants report that the "cross section is right in the center" and "none of the screens were at eye level” which forces them to "look up and down the whole time". This lead to partial utilization of the display where some participants use only the two left monitors while others use the top two monitors primarily. Hall et al. [TSH+08] conclude that a 4 x 4 monitor array may not be an optimal arrangement of multiple monitors.

## 2.5 More satisfaction, less mental workload and higher preference for dual monitors

More recent multi-monitor studies restrict the number of monitors to dual monitors where they examine the productivity and satisfaction of users in relation to common office tasks [KS08, OTN+12]. Their configurations differ slightly though in that Kang and Stasko [KS08] only compare a single 17" LCD monitor with a resolution of 1024 x 768 pixels to a side-by-side dual monitor configuration consisting of the same monitor model, while Chaparro et al. [OTN+12], also include a single 22" monitor and a side-by-side dual monitor configuration consisting of the same monitor model of unspecified type and resolution, in addition to a single 17" monitor and dual monitor configuration made up of two of the latter. Findings by Kang and Stasko [KS08] are consistent with all the previous studies mentioned so far. Users of dual monitors complete tasks faster, experience less workload and prefer the dual monitors compared to a single monitor by quantitatively rating them more useful, easier to use, more timesaving, and leaving a stronger overall impression. They also note that participants use the dual monitors not merely as increased screen space, but as two separate "rooms" where they allocate resources for different purposes as originally observed by Grudin [Gru01, Gru99]. Surprisingly, different window management practices do not significantly affect task completion time and workload [KS08]. Chaparro et al. [OTN+12] cannot confirm the previous findings with regards to efficiency, because their participants are similarly efficient when completing tasks across all four configurations. However, they do confirm previous findings with regards to

**Figure 2.3:** A 203" projected high-resolution display [BB09]

satisfaction, mental workload and preference of larger and more monitors where a single 17" monitor is preferred least and dual 22" monitors is preferred the most by almost everyone.

## 2.6 Changing interactions with wall-sized high-resolution displays

A recent study by Balakrishnan and Bi [BB09] involves a wall-sized high-resolution display that is much larger than that used by Czerwinski et al. [CSR+03] where they combine 18 projectors in 3 x 6 tiling for a total size of 203" and total resolution of 6144 x 2034 pixels (see Fig. 2.3).

This display is compared to a single 17" monitor, a single 21" monitor, dual 18" monitors and dual 21" monitors of unspecified type and resolution to investigate users' behaviors when they switch to the large high-resolution display over a period of 5 days for 5 hours each day. While they also observe a general partitioning of screen estate of the dual-monitor configurations and the large display, they discover that the location of the focal region and of the peripheral region changes dramatically when users interact with the wall-sized high-resolution display. Instead of designating one half of the display for the primary task and the other half for the secondary task as is typical for dual monitor configurations, wall-sized high-resolution display users would use the center of the display as the focal region and the remaining space around that as the peripheral region, which would form an "inverted-U" shape around the focal region (see Fig. 2.4).

Interactions with windows and peripheral applications also completely change when users have abundant virtual space on the wall-sized high-resolution display. Instead of minimizing or maximizing windows when a new window appears, users opt to resize or move it on the large display. They also no longer turn their head and body slightly to work in the peripheral region as they normally would on a dual monitor configuration, but instead move the peripheral window into focal region to work from there. Another unique behavior on the wall-sized

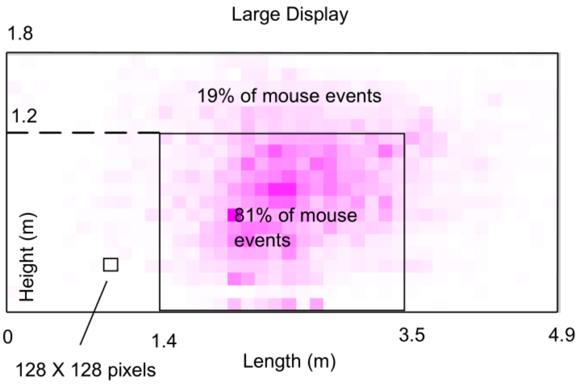



**Figure 2.4:** The focal region on the large high-resolution display is indicated by the large majority of mouse events falling within it [BB09]

display is that users magnify peripheral information which they do not do on dual monitors. In conclusion, Balakrishnan and Bi [BB09] report an unanimous preference for using a the wall-sized display versus smaller single or dual monitors but they also suggest that there might be an upper bound on window sizes that users are comfortable working with since wall-sized display users do not span a window across the entire display. Instead, they use only up to 60 70% for windows with rich information, such as spreadsheets and digital maps.

## 2.7 Designing an optimal workspace with large high-resolution displays

Andrews et al. [EBZ+12] discuss how large high-resolution displays can be placed into regular office environments to be used for everyday office tasks like analyzing data, writing reports or corresponding via email. They find that small design decisions with regards to display height, display curvature, display placement, user stance, and keyboard and mouse placement greatly impact the user's perception of the display and the user's behavior. They provide design guidelines that incorporate a large high-resolution display into a personal workspace suitable for long office work which can also be quickly transformed into a collaborative workspace when needed. For that they recommend a curved display where the user is equidistant from all areas of the display for easy access to all areas of the display. Curved displays are also more personal and engaging while flat displays are often associated with public displays for presentations. The curvature should be easily adjustable to allow flatting the display slightly for ad hoc collaboration with coworkers. They recommend placing the display on a pair of regular office desks and adjust the height so that display is near an average user's eye line while seated. This changes the perception of the display from a powerwall (which is common with displays of that size) to a workspace. Office desks are also a better placement for the display than monitor stands because they avoid interference with the user's feet when rotating

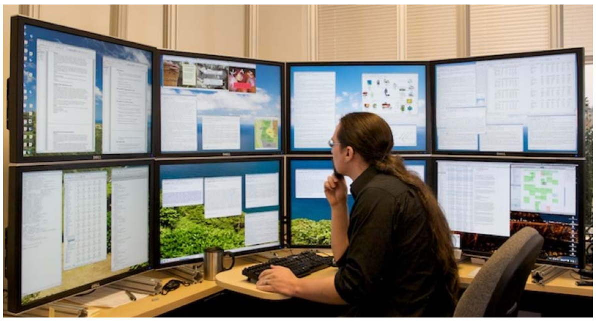


**Figure 2.5:** A curved large high-resolution display [EBZ+12]

in their chair and allow integrating physical artifacts common in office environments, such as coffee mugs and notebooks. Users sitting in a standard desk chair can move freely and perceive the display as personal work area. They find that the best placement for the keyboard and mouse are trays attached to the armrests of an office chair that allows moving the chair to access information on various locations on the display. In line with these guidelines, they tile 8 LCD monitors with a size of 30" and a resolution of 2560 x 1600 pixels each into a 4 x 2 array for a total size of 108.5" x 35" and total resolution of 10240 x 3200 pixels (see Fig. 2.5) that are placed on a pair of desks and connected to a single computer [EBZ+12].

# 3 Experiment

We conducted a comparative user study to evaluate diverse aspects of working performance on different screen sizes. The following chapter will give a detailed insight into the study planning and conduction. All design details, used hardware and software, which is partly self-written will be described in the following in order to provide a comprehensive understanding about how the results, that are presented in the next chapter were measured. The design of the study is described in the first section, followed by a description of the people that participated in it. The section apparatus summarizes the exact circumstances of the experiment, followed by a detailed description of the tasks, the participants were asked to perform during the study. Finally in the last section, the study procedure is explained.

## 3.1 Design

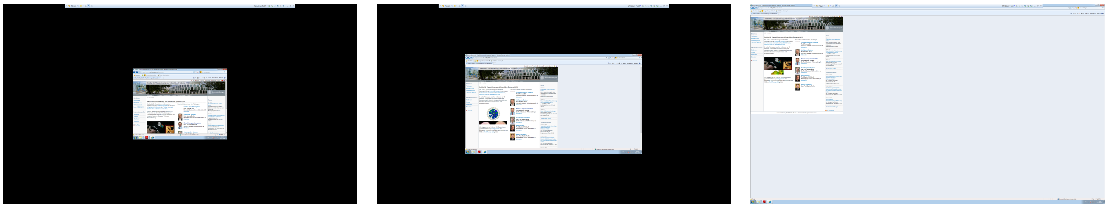
Our comparative study used a counterbalanced repeated measures design [Bai08]. All participants had to perform three tasks. These tasks are described in Section 3.4 for three different screen sizes. The screen size was the independent variable. In order to cancel out possible advantages or disadvantages which could result of the order of the tested screen sizes, a cyclic Balanced Latin Square was used to determine the order of the screen sizes for every participant as it is shown in Table 3.1. We measured task completion time (TCT) and error rate (ERR) for all of the described tasks separately for every screen size in order to acquire objective data about the tested scenarios. Additionally, subjective data was collected with some questionnaires. After performing the tasks on a screen size, a NASA Task Load Index (TLX) questionnaire was handed over to the participants [HS88]. A concluding questionnaire asked the participants to sum up their experience, after they had finished all tasks for all screen sizes.

## 3.2 Participants

We recruited 18 participants from our campus area for our study in order to acquire a meaningful amount of data, in which 4 were female and the remaining 14 were male. The age of our participants spreads from 20 years to 43 years, while the average age was 25.56 and the median age was 24.5 *(mean (M) = 25.56, standard error (SE) = 1.16, standard deviation (SD)*

| Participant | Screen Size Order | | |
|---|---|---|---|
| A | small | medium | large |
| B | medium | large | small |
| C | large | small | medium |

**Table 3.1:** The Study Task Pattern.



**(a)** 768p **(b)** 1080p **(c)** 2160p

**Figure 3.1:** This graphic visualizes the relation of the display sizes and how a standard web page is displayed on them.

*= 4.93)*. Before we started with the actual study tasks a questionnaire was handed out, that asked for the participants age, gender and occupation. The evaluation of this questionnaire revealed, that 17 of 18 participants were working or studying in university related facilities. While 15 of them were students, one research assistant and one secretary took part in our study. One participant is working as a software engineer. All the participants had at least basic knowledge of the German language.

## 3.3 Apparatus

Since the goal of this study is to evaluate the impact of screen size on working productivity three different screen sizes were tested. In order to get reliable results, we used one screen to and restricted the visible working area for each task. This was done by resizing a virtual machine on the entire screen and blacking out the rest of the screen. The display we used was the Panasonic TX-50AXW804[1] a 50 inch screen with a resolution of 2160p, which are 3840x2160 pixels. It also provides the 4K 2.000 Hz BLS IFC technology, which generates a perceived refresh rate of 2000Hz. All settings for the monitor were set to factory state. The second screen size had 1080p with 1920x1080 pixels. It was exactly half of the length and half of the height of the largest used display space and 25 inches diagonally. The smallest screen

[1]https://www.panasonic.com/de/consumer/flachbildfernseher/reference/viera-axw804-serie/tx-50axw804.specs.html

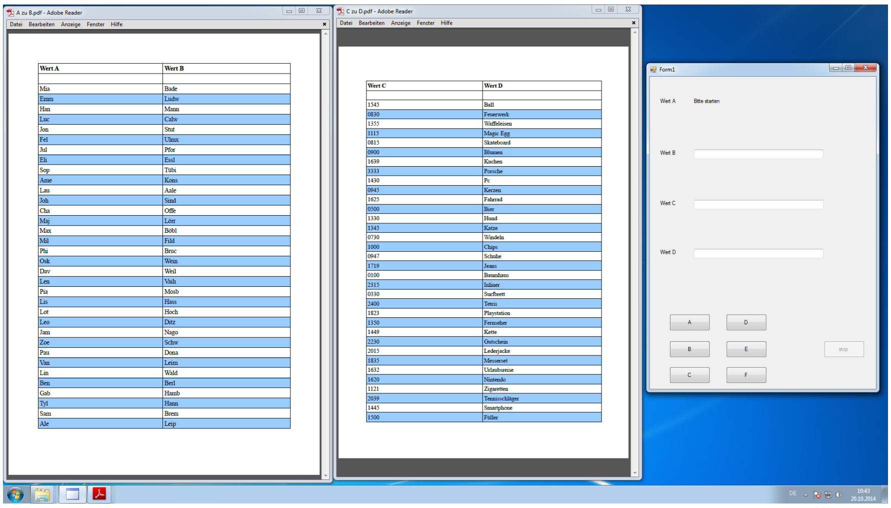


**Figure 3.2:** The Information Combing Task Setup.

size had 768p with 1024x768 pixels and Fig. 3.1 shows how the different screen sizes were simulated on the entire screen. For the study the screen was placed in a lab at the University of Stuttgart. All participants were provided with the same space on the table in front of the screen and the same input devices. They were not instructed how to sit or to keep a fixed distance to the screen. We let them choose their position independently.

For measuring subjective perception of the different screen sizes, two questionnaires were used. The first one is the TLX, which was used in German language. A copy of the used form can be found in Appendix A. Since the TLX is a standard tool to estimate the users task load, it an adequate mean for classifying the subjective perception of the user for the tested conditions [Har06]. Additionally, a concluding questionnaire was designed, that demanded the participants to rate the different conditions on a Lickert Scale from 1(dislike) to 5(like) and choose their favourite condition. A text field gave them the opportunity to leave comments and name some advantages and disadvantages, they see with the system. All questionnaires were prepared in paper form.

In order to be able to retrace and verify the measured results screen captures and related values were recorded.

## 3.4 Tasks

In order to cover as many aspects as possible of working on computer displays, we designed three different tasks, that simulated standard working processes and circumstances. It was important, that none of the participants was familiar to the supplied task, in order to ensure

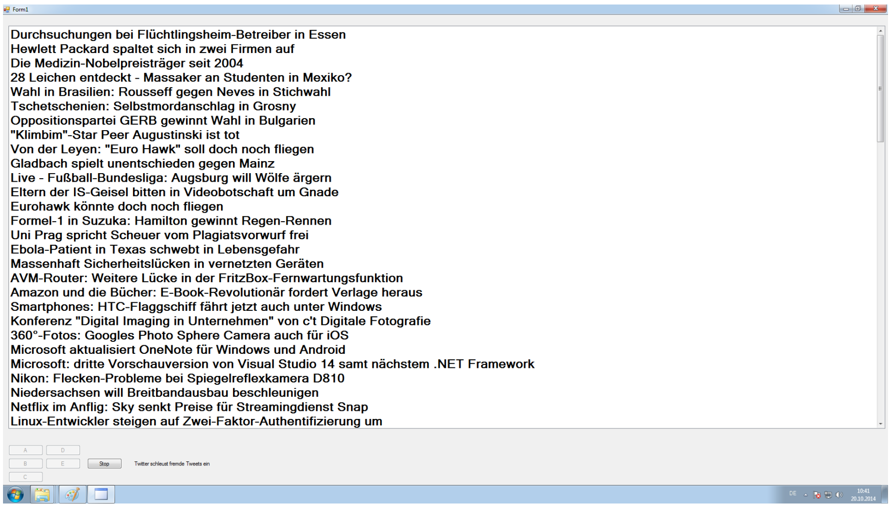



**Figure 3.3:** The List Search Task setup.

the comparability of the results. Therefore, we provided three self-written programs, that were used to measure the participants performance on different screen sizes.

- Information Combining Task (ICT) (Fig. 3.2)

  In this task, the participant was provided with three lists in three different files that were provided in different application windows. Every list consists of key value pairs and every column was labeled with a letter. The files are named according to the lists they are containing. The first list provided a key value matching from value A to value B, the second list from value B to value C and the third list from value C to value E. The lists are shown in the Appendix A. An associated program showed the participant a value A and the participant was asked to find the related value B in the appropriate list, followed by the values C and E in the other lists. The program measured the TCT and the amount of errors, the user made during completion. In order to keep the challenge, our participants were not allowed to use the search function of the PDF viewer. This task is used to measure the users performance in tasks were information from more than one source has to be combined, such as research or programming. There was no restriction in how to arrange the different programs and windows on the screen and how to switch between them, so the participants were free to resize and move the windows. This task was designed to measure the users performance in tasks, were multitasking and the use and combination of information from more than one source is necessary. This is the case in nearly all research tasks, were information from one or more sources are collected to a separate window and programming, were the user often has to look up information in reference documents or do research on the internet.

- List Search Task (LST) (Fig. 3.3)

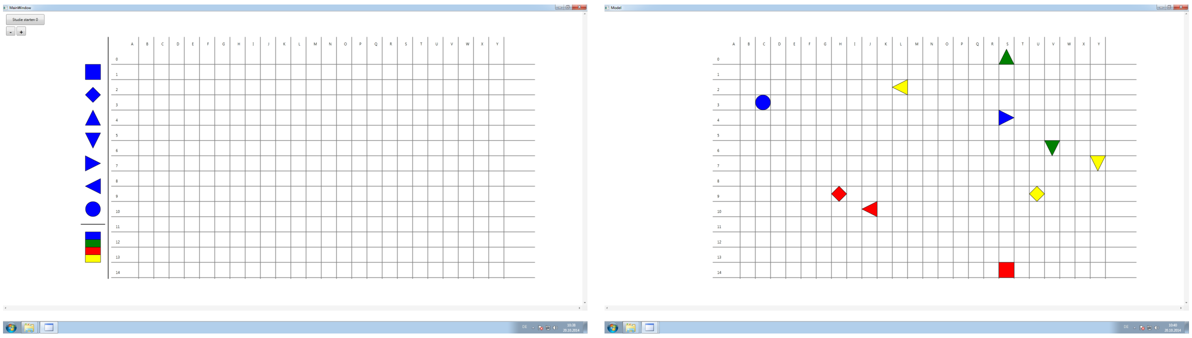


**Figure 3.4:** The Template and the working area of the Shape and Colour Matching Task.

For the second task, the participant was provided with a scrollable list, that contains headlines from news in German language in a random order on task start. Additionally one of the sentences is displayed in a separate line. The user was asked to find the displayed sentence in the list, click on it and confirm the selection with a button click. This task is used to measure the users performance for search tasks in sets of information, that are larger than screen size. Again, we measured TCT and ERR. The Participant was allowed to move and resize the window as he prefers. This task was included because it represents a common search situation that appears for example while scrolling over a text and searching for relevant keywords. This plays also a large role for programming tasks because it offers the possibility to estimate the users orientation in large sets of information.

- Colour and Shape Matching Task (CSMT)(Fig. 3.4)

For the last task, the Participant was provided with another program. The specially developed program, which can be seen in Fig. 3.4 provides a working surface, that consists of a squared white plain and a tool box that contained a set of 7 shapes (rectangle, tilted rectangle, a triangle in 4 different orientations and a circle) and a colour selector that provided 4 colours(blue, green, red and yellow). Every shape is available unlimited times and in every colour. The shapes can be dragged out of the tool box to the squared plane, were they fit into the squares when they are dropped. Shapes on the plane can be moved via drag and drop or deleted by dragging them back to the tool box. Two buttons allow to zoom the whole working surface in and out. When the user clicks on the start button, a second window opens, which contains another squared plane of the same size as the working surface, which zooms in the same way as the working area, when the buttons there are used. This window also contains the template for the study. The participants were asked to reproduce a given random pattern of 10 shapes in different colours by selecting the proper shapes in the right colour and dragging them to the appropriate position. In order to enhance the overview, the rows and columns of the grid are marked with letters and numbers. This task is used to measure the users performance for tasks, were abstract information has to be transferred over window

**Figure 3.5:** Two participants performing the tasks in the study environment.

borders on large working areas. This appears for example while translating requests from a customer into a real product. For software engineering tasks, it is important to transfer requirements into code. The participant was instructed to rearrange and resize the application windows as he prefers. Again ERRs and TCT are recorded.

## 3.5 Procedure

At the beginning every participant had to fill out the introductional questionnaire, that was mentioned before and sign a consent form, where we stated, that no personal data is collected and the participation at the experiment is not related with any risks. In the consent form, we also requested the permission to take photos and record videos. After that, the participant got a short introduction, where a short overview over the following tasks was given. The experimenter explained, that three screen sizes are compared in the study and therefore, three tasks have to be completed on every screen size. It was also mentioned, that we measured the properties of the screen sizes and not the participants effort and that a normal working speed was requested. After the general lead-in, the first screen size was presented to the participant and the three tasks were explained and subsequently performed by the participant as it can be seen in Fig. 3.5. All three tasks were performed on every of the three screen sizes and after every screen size, the participant was asked to fill out a TLX as it was explained above. After the participant had finished all tasks on all screen sizes, he was handed over a final questionnaire in order to get a comparative assessment from all the tasks and offer the possibility of comments.

# 4 Results

The following chapter will give a detailed insight of the data measured in the study. The chapter is divided in the sections quantitative results and qualitative results. In the section quantitative results we diagrammed mean and standard deviation of the data and tested for statistical significance.

## 4.1 Quantitative Results

The following section give a detailed insight about the quantitative results which contains data about TCT, ERR, perceived workload and satisfaction. A one-way Anova with repeated-measures was performed on the data of the quantitative results. Due to the small size of participants we performed a Greenhouse-Geisser correction on all of the data

### 4.1.1 Task-Completion-Time

Figure 4.1 shows the mean TCT for each of the tasks. The time is given in seconds. The inspection of Figure 4.1 suggest that the display sizes differed in TCT of the tasks. During the CSMT and the ICT the large display (CSMT: $M = 83$, $SD = 14$, ICT: $M = 65$, $SD = 18$) being the fastest, the small display (CSMT: $M = 154$, $SD = 57$, ICT: $M = 93$, $SD = 26$) being the slowest and the medium display CSMT: $M = 113$, $SD= 54$, ICT: $M = 69$, $SD= 22$) falling between these two extremes. In the LST the small display ($M = 71$, $SD= 23$) being the fastest, followed by medium display ($M = 88$, $SD= 25$) and large display ($M = 91$, $SD= 37$). A one-way Anova with repeated-measures was performed on these data. The Greenhouse-Geisser correction determined that in theCSMT ($F(1.996 , 33.927) = 18.260$ $p < 0.0005$) and the ICT ($F(1.678, 28.534) = 11.629$ $p < 0.005$) mean TCT differed statistically significantly between display sizes. Post-hoc tests revealed that during both tasks medium (CSMT : $p = 0.007$, ICT : $p = 0.009$ ) and large display (CSMT : $p < 0.0005$, ICT : $p = 0.003$) were significantly faster than the small display.

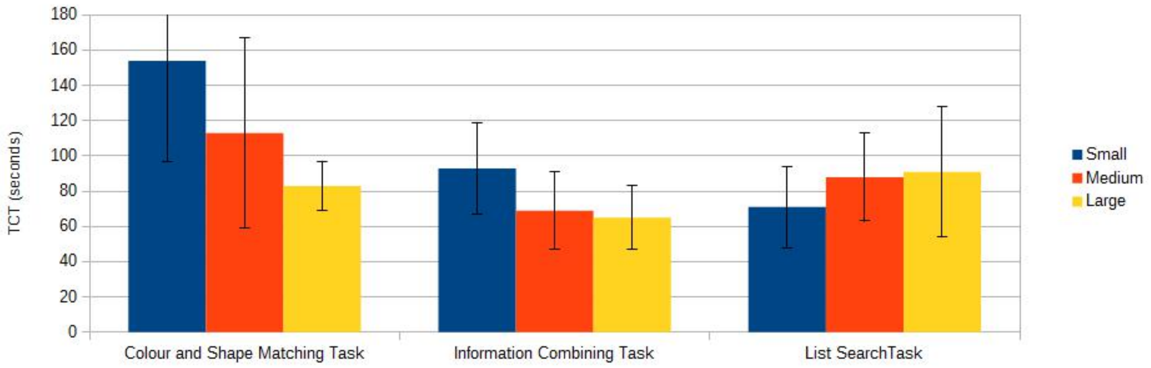



**Figure 4.1:** Effects of display size on the TCT

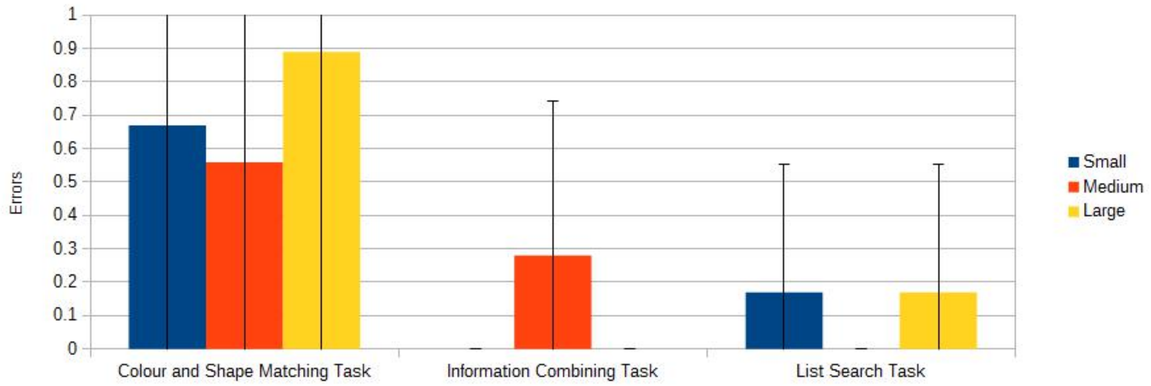



**Figure 4.2:** Effects of display size on the ERR

### 4.1.2 Error-Rate

Figure 4.2 shows the mean ERR for each of the tasks. During the CSMT the medium display (M = 0.56, SD= 0,948) causes the fewest errors, followed by the small display (M = 0.67, SD= 1.058). The large display (M = 0.98, SD= 1.568) causes the most errors. During the ICT the medium display (M = 0.28, SD= 0.461) being the only condition that causes errors. In the LST the small and the large display (M = 0.17, SD= 0.383) causes equal errors. The medium display causes none error. A repeated measures ANOVA determined that mean ERR did not differ statistically significantly between display sizes.

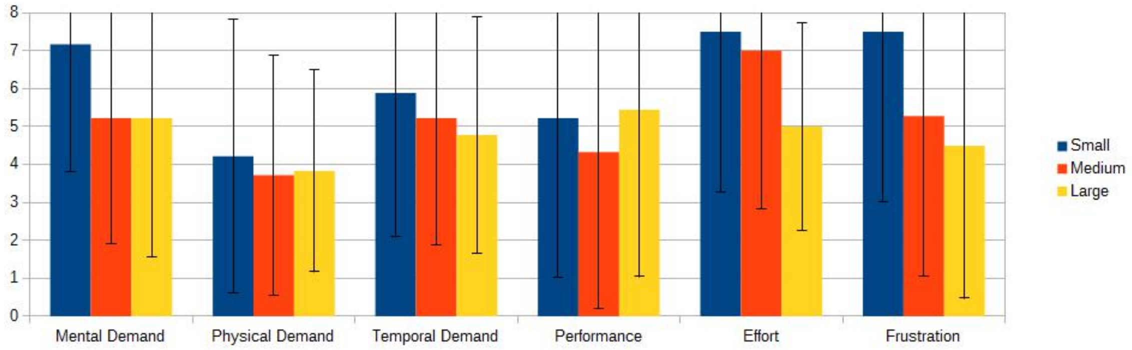



**Figure 4.3:** Effects of display size on the perceived workload

### 4.1.3 Perceived Workload

Figure 4.3 shows the mean perceived workload for each of the display sizes. The Figure suggests that the mean perceived workload using the large display being the lowest. Using the small display the perceived workload being the highest. The medium display falling between these two conditions. Related to the sub-scales of the TLX a repeated measures Anova with a Greenhouse-Geisser correction determined that only the mean of the Effort differed statistically significantly between display sizes ($F(1.872, 31.820) = 3.622$ $p = 0.041$). Post-hoc test showed that the large display significantly reduces the perceived effort compared to the small display ($p = 0.049$).

### 4.1.4 Satisfaction

Figure 4.4 shows the mean satisfaction using the different display sizes. Satisfaction metrics where recorded by using an adapted questionnaire, where the participants had to rate all screen sizes on a Lickert scale at the end of the experiment. Using the large display ($M = 4$, $SD= 1.03$) participants had the highest satisfaction, closely followed by the medium display ($M = 3.89$, $SD= 0.9$). The small display ($M = 1.61$ , $SD= 0.98$) reached the lowest score of satisfaction. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that mean satisfaction differed statistically significantly between display sizes ($F(1.802, 30.634) = 27.891$ $p < 0.0005$). Post-hoc test revealed that the participants were significantly more satisfied by using the medium ($p < 0,0005$) or large ($p < 0,0005$) display compared to the small display.

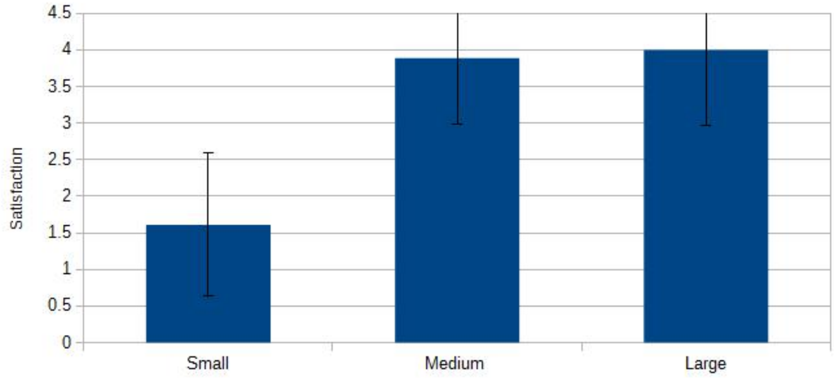



**Figure 4.4:** Effects of display size on the satisfaction

## 4.2 Qualitative Results

The qualitative feedback that was also collected with the concluding questionnaire but in form of comment fields, that allowed free text answers, points out that the participants like when they have enough space to visualize the needed information without switching windows. Therefore they especially liked the large display to perform the ICT, in which the needed information were distributed in different files. Then again some of the participants had difficulties to adjust to the unfamiliar large screen size. Participant 5 mentioned that he/she easily lost the focus. Furthermore participants mentioned the lack of privacy, low distance between screen and eyes and the physical demand as a result of the continues head movement as disadvantages of the large display. Using the medium display participants refer to facts like familiar display size, perfect size for desk in the office, protection of privacy and little head movement. On the other hand some of the participants said the screen is too small for daily work. Participant 15 criticized that it was hard to order multiple files parallel. Participant 9 felt it stressful to scroll to the requested sentence in the LST. The small display only received negative feedback. Participants criticized the small screen size that offers not enough space for the tasks. Especially the need for the continues switching of windows was considered as very annoying.

One question we asked in the questionnaire is: "which of the display sizes would you use for daily work in the office?". The results showed that 12 of the participant would use the medium display for daily office work and 6 participants would use the large display. None of the participants would use the small display.

# 5 Discussion

Earlier related work suggests that users are more efficient, make less errors and perceive less workload when performing office tasks with larger displays compared to smaller displays and that they almost unanimously prefer the largest display, so we assumed that the same would hold true in our study. While some of these assumptions were confirmed, surprisingly, task completion time can be inverse to the display size depending on the type of task. The largest display is also not the most preferred display overall in our study.

Our analysis of the quantitative data shows that participants complete the CSMT and ICT the fastest with the largest display and the slowest with the smallest display. They are statistically significantly faster with the largest and medium display compared to the smallest display. This result was expected since users benefit from being able to see all information at once in these tasks. Surprisingly, participants complete the LST fastest with the smallest display and slowest with the largest display. One possibility to explain this result is that people seem to often lose focus while scrolling a large list because their search for certain information requires very narrow focus and a lot of information is moving. The error rates in our quantitative results do vary, but not significantly statistically. As expected, the perceived mental workload is the lowest with the largest display and highest with the smallest display. This might be explained by our qualitative data that suggests that this is because users have to switch windows frequently and temporarily remember information during tasks where needed information is found in different windows. Similarly, perceived effort is significantly reduced with the largest display compared to the smallest display as indicated by our quantitative results. The overall satisfaction with the displays is the highest with largest display and only slightly higher than the medium display. Satisfaction was significantly higher for both larger displays compared to the smallest display. This is not surprising, as users complain that the smallest display affords too little space to efficiently manage a lot of information. Unexpectedly, the large majority of participants would prefer to use the medium display for daily office work even though they are most satisfied with the largest display. In addition to the complaints about having to move the head and reduced privacy with the largest display, we speculate that the unfamiliarity with the size of the largest display has also put the largest display at a disadvantage compared to the medium display, which is most familiar to users. We presume that familiarity may have a great effect on preference in the short term compared to other factors. Personal experience may also play an important role since some participants that routinely perform tasks that require multi-tasking clearly expressed that the largest display would help them perform such tasks more efficiently.

We observe that certain interactions are typical for certain display sizes. Participants always use full screen windows on the smallest display and switch between them when they need to work with multiple windows. However, participants generally try to position multiple windows next to each other on the medium and largest display. While this is always possible on the largest display with the tasks performed in our study, users of the medium display sometimes slightly overlap windows to see the most important information at once. Participants also make extensive use of zooming out to see more information at once even if that means that they have to sit closer to the display to be able to read the information. This shows that there is a clear preference for seeing information in parallel when multi-tasking, which large display allow without zooming out.

# 6 Conclusion and Future Work

Large high-resolution displays will be available soon due to recent advances in display technology and our study shows that office workers are significantly more productive and satisfied with larger displays when performing complex office tasks. We collected and analyzed both quantitative and qualitative data. Participants in our study complete tasks faster and are more satisfied with larger displays. All participants prefer a larger display and they were frustrated with the small virtual space of the smallest display. However, we observe that some participants are overwhelmed with the large virtual space of the largest display and do not make optimal use of all available space on the largest display. For example, some participants do not use all available space to layout their windows, or size and position windows on the largest display like on the next smaller display - simply ignoring the additional screen estate.

Earlier related studies mentioned here use much smaller displays or custom multi-projector systems that have unique usability issues such as uneven or lowered brightness. They also do not control for pixel density, color, brightness and contrast of the displays, which we do. However, their results are mostly consistent with ours. That is, users are either more productive, make less errors and are more satisfied with larger displays. The majority of users also prefer larger displays over smaller displays.

Since users in our study were not familiar with the largest display and did not always take advantage of the increased screen estate, future research can extend this study by examining whether and how users adapt to a very large display over a longer time frame, and whether this would lead to further increases in productivity and satisfaction of users when doing complex office work, or whether there is a natural limit to the size of displays that affects productivity and satisfaction like with other interactions [RJMR14]. Future research could also examine whether and how different input devices, for example hand and finger motion or eye tracking, improve interactions or remove certain limitations with large high resolution displays.

# A Appendix

The appendix contains all documents and questionnaires, that where used in the study. They are presented in the same order as they where presented to the participants.

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# Einverständniserklärung

**BESCHREIBUNG:** Sie sind hiermit dazu eingeladen an der **Studie** zur **Untersuchung des Einflusses von Bildschirmgröße und Auflösung auf die Arbeitseffektivität** teilzunehmen.

**ZEITAUFWAND:** Ihre Teilnahme dauert ungefähr **30 Minuten**.

**DATENERFASSUNG:** Für die Evaluation des Systems werden Zeiten und die Fehlerrate gemessen. Zusätzlich werden während der Studie Fragebögen ausgefüllt. In dieser Studie wird das zu testende System geprüft - nicht die Teilnehmer!
Bilder:
Ich bin damit einverstanden, dass Bilder von mir während der Studie gemacht werden.
Ich bin **nicht** einverstanden, dass Bilder von mir während der Studie gemacht werden.
Videos:
Ich bin damit einverstanden, dass Videoaufnahmen von dem Arbeitsprozess während der Studie gemacht werden.
Ich bin **nicht** einverstanden, dass Videoaufnahmen von dem Arbeitsprozess während der Studie gemacht werden.

**RISIKEN UND NUTZEN:** Mit dieser Studie sind keine Risiken verbunden. Die gesammelten Daten werden sicher und anonym gespeichert. Die gesammelten Daten werden aggregiert und anonymisiert in einem wissenschaftlichen Bericht veröffentlicht. Ihre Privatsphäre bleibt erhalten. Die Teilnahme an der Studie hat keinen Einfluss auf Ihr Arbeitsverhältnis. Die Daten werden nur in aggregierter Form und anonymisiert an Ihren Arbeitgeber weiter gegeben.

**RECHTE DER TEILNEHMER:** Wenn Sie dieses Formular gelesen und sich dazu entschieden haben an dieser Studie teilzunehmen, ist diese Teilnahme weiterhin **freiwillig** und Sie haben das Recht, jederzeit Ihre Zustimmung zurückzuziehen und Ihre Teilnahme jederzeit abzubrechen. Sie haben das Recht spezifische Fragen nicht zu beantworten. Die Ergebnisse dieser Forschungsstudie werden möglicherweise bei wissenschaftlichen Konferenzen oder Expertentreffen präsentiert oder in wissenschaftlichen Zeitschriften veröffentlicht.

**KONTAKT INFORMATIONEN:** Bei Fragen, Bedenken oder Beschwerden über diese Forschung, die Abläufe, Risiken und Nutzen, kontaktieren Sie bitte folgende Personen:
Lars Lischke (lars.lischke@vis.uni-stuttgart.de)
Miriam Greis (miriam.greis@vis.uni-stuttgart)

***Mit der Unterzeichnung dieses Dokuments stimme ich den oben genannten Bedingungen zu.***

*Name:* ________________________ *Unterschrift, Datum:* ______________________

**Figure A.1:** The consent form that was used in the study.

Eingangsfragebogen

Teilnehmer Nummer: ______________________________

Alter: __________________________________________________

Geschlecht: __________________________________________

Beruf: __________________________________________________

Bildschirmgröße:

**Figure A.2:** The introducing questionnaire queries demographic information.

Proband ID: ______________ Bedingung: _______________ Datum: ___________________

Mentaler Aufwand Wie geistig anspruchsvoll war die Aufgabe?

Sehr niedrig Sehr hoch

Körperlicher Aufwand Wie anstrengend war die Aufgabe?

Sehr niedrig Sehr hoch

Zeitlicher Aufwand Wie hastig oder gehetzt war das gesetzte Tempo der Aufgabe?

Sehr niedrig Sehr hoch

Performance Wie erfolgreich waren Sie im Lösen der Aufgabe?

Perfekt Gescheitert

Aufwand Wie sehr mussten sie sich anstrengen, um Ihre Leistung zu erreichen?

Sehr niedrig Sehr hoch

Frustration Wie unsicher, entmutigt, irritiert, gestresst, und verärgert waren Sie?

Sehr niedrig Sehr hoch

**Figure A.3:** The NASA TLX was used in German language.

1. Wie haben Ihnen die benutzten Bildschirmgrößen gefallen?

1.1 **klein**

schlecht gut

O O O O O

**1.2 mittel**

schlecht gut

O O O O O

**1.3 groß**

schlecht gut

O O O O O

2.Welche der Bildschirmgrößen würden Sie für den alltäglichen Bürogebrauch nutzen?

O klein

O mittel

O groß

3. Bitte notieren Sie Pro und Kontra der einzelnen Bildschirmgrößen. (Stichpunkte genügen)

| | Pro | Kontra |
|---|---|---|
| Klein | | |
| Mittel | | |
| Groß | | |

**Figure A.4:** In a final questionnaire the participants where asked to rate all screen sizes and leave comments.

| **Wert A** | **Wert B** |
|---|---|
| | |
| Mia | Bade |
| Emm | Ludw |
| Han | Mann |
| Luc | Calw |
| Jon | Stut |
| Fel | Ulmx |
| Jul | Pfor |
| Eli | Essl |
| Sop | Tübi |
| Ame | Kons |
| Lau | Aale |
| Joh | Sind |
| Cha | Offe |
| Maj | Lörr |
| Max | Böbl |
| Mil | Fild |
| Phi | Bruc |
| Osk | Wein |
| Dav | Weil |
| Len | Vaih |
| Pia | Mosb |
| Lis | Hass |
| Lot | Hoch |
| Leo | Ditz |
| Jam | Nago |
| Zoe | Schw |
| Pau | Dona |
| Van | Leim |
| Lin | Wald |
| Ben | Berl |
| Gab | Hamb |
| Tyl | Hann |
| Sam | Brem |
| Ale | Leip |

**Figure A.5:** The Information Combining Task list 1.

| **Wert B** | **Wert C** |
|---|---|
| | |
| Ludw | 1115 |
| Tübi | 0900 |
| Stut | 0815 |
| Vaih | 0830 |
| Kons | 1545 |
| Bade | 0945 |
| Calw | 1430 |
| Pfor | 1445 |
| Fild | 2015 |
| Offe | 2230 |
| Aale | 2315 |
| Sind | 0500 |
| Essl | 0730 |
| Ulmx | 1000 |
| Mann | 1330 |
| Böbl | 1345 |
| Lörr | 1625 |
| Bruc | 1719 |
| Wein | 2400 |
| Weil | 0100 |
| Hoch | 0330 |
| Wald | 1823 |
| Nago | 0947 |
| Leip | 1200 |
| Schw | 1639 |
| Ditz | 1835 |
| Mosb | 2239 |
| Leim | 1632 |
| Berl | 1121 |
| Dona | 2039 |
| Hamb | 1620 |
| Hass | 1449 |
| Hann | 1350 |
| Brem | 1355 |

**Figure A.6:** The Information Combining Task list 2.

| **Wert C** | **Wert D** |
|---|---|
| | |
| 1545 | Ball |
| 0830 | Feuerwerk |
| 1355 | Waffeleisen |
| 1115 | Magic Egg |
| 0815 | Skateboard |
| 0900 | Blumen |
| 1639 | Kuchen |
| 3333 | Porsche |
| 1430 | Pc |
| 0945 | Kerzen |
| 1625 | Fahrrad |
| 0500 | Bier |
| 1330 | Hund |
| 1345 | Katze |
| 0730 | Windeln |
| 1000 | Chips |
| 0947 | Schuhe |
| 1719 | Jeans |
| 0100 | Baumhaus |
| 2315 | Inliner |
| 0330 | Surfbrett |
| 2400 | Tetris |
| 1823 | Playstation |
| 1350 | Fernseher |
| 1449 | Kette |
| 2230 | Gutschein |
| 2015 | Lederjacke |
| 1835 | Messerset |
| 1632 | Urlaubsreise |
| 1620 | Nintendo |
| 1121 | Zigaretten |
| 2039 | Tennisschläger |
| 1445 | Smartphone |
| 1500 | Füller |

**Figure A.7:** The Information Combining Task list 3.

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All links were last followed on November 16, 2014.

**Erklärung**

Ich versichere, diese Arbeit selbstständig verfasst zu haben. Ich habe keine anderen als die angegebenen Quellen benutzt und alle wörtlich oder sinngemäß aus anderen Werken übernommene Aussagen als solche gekennzeichnet. Weder diese Arbeit noch wesentliche Teile daraus waren bisher Gegenstand eines anderen Prüfungsverfahrens. Ich habe diese Arbeit bisher weder teilweise noch vollständig veröffentlicht. Das elektronische Exemplar stimmt mit allen eingereichten Exemplaren überein.

Ort, Datum, Unterschrift