Perceptual Issues in Multi-Display Environments

Viktoria Witka
Universität Passau
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme
Innstr. 43
94032 Passau, Germany
witka01@stud.uni-passau.de

ABSTRACT

Nowadays, the use of multiple display environments is getting very common in many different fields, may it be the stationary display of large data on multiple large screens (e.g. in conference rooms) or an interaction between multiple mobile devices and mobile devices with multiple displays (e.g. dual-display gaming consoles) respectively. The purpose of this paper is to present perceptional challenges and to evaluate their relevance for mobile and stationary multi-display environments. Furthermore an overview over several experimental studies that have a relevance to this topic is given.

Keywords

Multi-display environments, perceptional issues, visual perception, visual attention, body-proximate environments

1. INTRODUCTION

In our time user interaction with computing devices is not longer limited to only a single desktop PC. It is not uncommon for a person in today's environment to own multiple devices, such as a laptop, tablet, smartphone, music player, Google glasses or a smart watch. This provides the opportunity for people who own different devices to use them simultaneously for different or the same task, be it watching videos on the laptop while chatting on the smartphone or using a second display at work.

These kinds of environments where the data or task is spread across multiple displays is called a multi-display environment. Multi-display environments consisting of multiple different devices have the advantage, that the devices can compensate for each others drawbacks. Imagine combining a mobile phone with a large display screen. The phone itself has only a small display and cannot show large data, while the screen itself has no mobility or option to interact locally. When those devices interact, the large screen to display a great amount of data and the mobility made possible by interacting directly via the mobile phone are both available.

When combining displays in Multi-display environments, there are many aspects that can play a role. Considering the properties of the human visual system is of great importance to effectively design the interaction of displays in a multi-display environment. For example, when multiple displays are physically separated, it is not possible for the eye to focus on all of them simultaneously, which leads to switches in attention and may affect the performance in completing tasks. One has to think about what data is represented on which screen and how to enable a fluid interaction with multiple displays.

In this work an overview about the human visual system and perception will be given in the first two sections. Next their relevance for mobile, stationary and hybrid multi-display environments will be evaluated in section 3, followed by an overview over several experimental studies that have a relevance to this topic. Lastly, an outlook on potential future challenges and experiments will be presented.

- Viktoria Witka is a master's student at the University of Passau, Germany
- This research report was written for *Masterseminar Embedded Interactive Systems*

2. VISUAL PERCEPTION

When combining multiple displays, sometimes of different devices, of course, a number of challenges and questions arise. For example: 'How to efficiently map information between displays?' or 'How does the use of multiple display affect performance?'. To answer these questions and ensure a fluid interaction and maximized performance one has to take the properties of the human visual system into consideration.

Therefore, in this first section, basic fundamentals about the processes taking place in the eye and visual perception will be presented. A horizontal section of the human eye can be seen in figure 1.

The imaging process in the human eye works by refracting light using the two lenses, the cornea and the lens [25] (chapter 2 page 77 ff). To be able to switch between looking at objects in the distance and objects close to the observer, the focus of the lens can be adjusted with the ciliary muscle. The image is then projected onto the retina. The retina contains receptors, cones for color perception and rods for perception of brightness.The receptors convert light into nerve signals, which are collected and directed to the brain via the optic nerve.

A short introduction to the most important visual properties is given in the sections below.

2.1 Color

As mentioned in 2, receptors in the retina, the cones, are responsible for the perception of colors [25] (chapter 15 page 663 ff). Out of ca. 100 million receptors in the retina, only about 5 million are used for color perception, the rest are

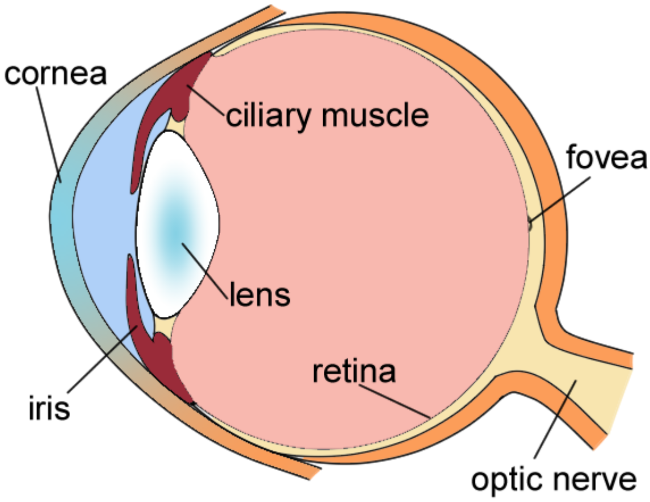

Figure 1: Horizontal section of the human eye

used for perception of brightness. Cones are mainly located in the center of the retina, the fovea. They need a relatively high light intensity to work, which is the reason that we cannot see colors at night.

How color plays a role in multi-display environments is shown in the sections 4.1.1, 4.2.1 and 4.3.1.

2.2 Brightness

The receptors, which are responsible for the brightness are called rods [25] (chapter 13 page 545 ff). Rods make out the biggest part of receptors in the retina. That is why it is easier for humans to detect changes in brightness, than it is to detect changes in color. To fully understand the concept of brightness one has to consider two more factors of importance: luminance and lightness [1].

Luminance is the measurable amount of light coming from a region of space. Unlike brightness and lightness, luminance can be measured using tools. The unit in which lightness is measured is Candela per square meter (Cd/m^2).

Brightness refers to the perceived amount of light which is emitted from a self-luminous source. Brightness is perceived non-linear, following Stephen's power law: $Brightness = Luminance^n$, where n depends on the size of the patch of light. The perception of brightness for one object always depends on ambient lighting, the brightness of the surrounding space.

The perceived reflectance of a surface is called **lightness**. Other than brightness it depends on the overall luminance of a scene and is perceived differently by each human.

When the brightness perceived by the eye changes, a process called adaptation takes place in the eye. Adaptation works by expansion and contraction of the iris, as well as by regulation of neurotransmitters. When the brightness changes from dark to bright, the process only takes a few seconds. On the other hand, when the brightness changes from bright to dark, it can take up to 45 minutes.

How brightness plays a role in multi-display environments is shown in the sections 4.1.2, 4.2.2 and 4.3.2.

2.3 Contrast

Contrast [1] [25] (chapter 14 page 630) is the ability of our eye to precisely distinguish between neighboring objects that have different properties (color or luminance). For better recognition of borders, the contrast between surfaces with different luminance is enhanced by a process called lateral inhibition.

Lateral inhibition enhances these borders by making the bright patch directly next to a dark one seem even brighter and the dark one darker. This can lead to several optical illusions such as, for example, the Mach Band Effect.

How contrast plays a role in multi-display environments is shown in the sections 4.1.2, 4.2.2 and 4.3.2.

2.4 Focus

The human eye can change the focus from near to far objects by adjusting the lens with the ciliary muscle [25] (chapter 10 page 411 ff). This process is called Accommodation. The power of a lens is about 1/f, with f being the distance to the focus point in meters (called diopter). The maximal diopter that the eye can adapt is 10-12.

The inability of the human eye to focus on multiple things that are distributed in space simultaneously is one factor leading to attention switching (see section 3.2).

How focus plays a role in multi-display environments is shown in the sections 4.1.3, 4.2.3 and 4.3.3.

2.5 Field of vision

The field of vision is the total field which a human is able to perceive when focusing on a single point [27]. It typically has a span of ca. 200° horizontally (see figure 2) and ca.120° vertically. The field of vision which is perceived by both eyes simultaneously is the field of binocular vision.

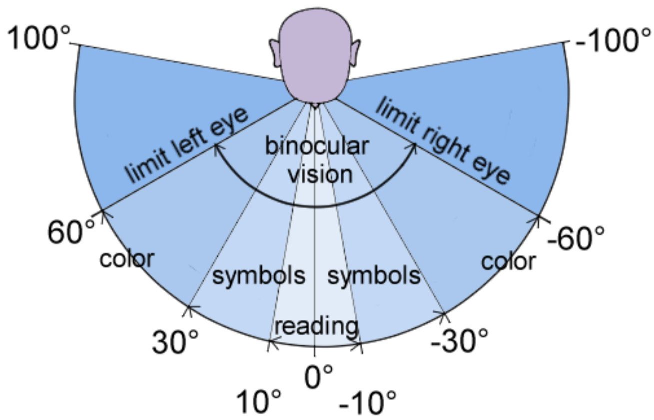

Figure 2: Horizontal field of vision

The visual field is affected by the distribution of rods and cones [25] (chapter 15 page 663 ff). The cones are located in the center of the retina, so we can only see colors there. The most densely packed location is called the fovea. In the fovea the vision is sharpest. However, the highest resolution of foveal vision is only about 2°. The peripheral vision is the part of the visual field which is not in the center of vision but where humans are still able to perceive motion.

The area in which it is possible to extract information with only a single look is called the "Useful Field of View" [30, 27].

The range of this field can vary depending on the task that is handled. In the horizontal field the ability to read ranges from ca. $-10°$ to $10°$. Symbols can be recognized from ca. $-30°$ to $30°$ and color can be perceived in ca. $-60°$ to $60°$. Vertically color can be perceived from ca. $-30°$ to $30°$. The age of a person also matters. Elderly people often have more difficulties solving unknown peripheral tasks than younger ones, as shown in [30], but when familiar with a task, their experience can lead to better results.

Differences in distance of objects in the visual field or switches between peripheral and foveal vision are factors leading to switches in visual attention (see section 3.2).

How the field of vision plays a role in multi-display environments is shown in the sections 4.1.4, 4.2.4 and 4.3.4.

2.6 Depth perception

As mentioned before, the human visual system works by projecting the scene onto the retina [19]. Since it is a projection from a 3-dimensional to a 2-dimensional space, information is lost in the process. But humans can still perceive depth and space through focusing one one specific point and analyzing the relative distance to other points in space as well as the comparison between the different retinal images of both eyes in binocular vision.

In the perception of depth, the size of objects and visual angle plays a role as well [24], [11]. For example, same-sized objects can seem closer, when they are surrounded by smaller objects than bigger objects.

How depth perception plays a role in multi-display environments is shown in the sections 4.1.3, 4.2.3 and 4.3.3.

3. ATTENTION

The part of the human memory, in which the currently viewed objects are stored is the visual working memory. But our this memory is limited in its capacity [20, 38, 23, 7]. We can only process about 3 to 5 objects in our visual working memory at a certain point in time. However, in our normal environments the scenes we view are usually composed of a multitude of different objects with different properties. Somehow we have to choose which objects and properties are of importance.

"Attention is the cognitive process to selectively interpret information subsets while ignoring others" [35, 36]. This means that attention is the focus on one single task at a point in time.

Visual information is not perceived continuously, but in distinct 'snapshots' [20, 38]. For each snapshot the objects are scanned sequentially after initial identification. Some objects need more attention than others (Low-Level vs. High-level-attention).

How attention plays a role in multi-display environments is shown in the sections 4.1.5, 4.2.5 and 4.3.5.

3.1 Selective attention

Multiple stimuli have to processed to select which parts of a scene are of importance [23, 7, 31]. Those stimuli can be biased by sensory driven (bottom up) or knowledge-driven mechanisms (top-down). Important aspects of the processed scene are seemingly enhanced while unimportant ones are filtered out. This is called selective attention.

3.2 Divided attention

Divided attention [6] is the division of a person's attention between multiple tasks or objects, when trying to do multiple tasks that require attention simultaneously. To perform those tasks in parallel, attention switches between those tasks have to be performed. When, for example, observing a number of displays distributed in the visual field or depth (see figure 3), one has to split their attention between those displays, when not able to focus on them simultaneously (see sections 2.4 and 2.5). This leads to gaze and attention switches between the objects. Since the capacity to process information is limited, the performance declines when we try to do more than one task at a time.

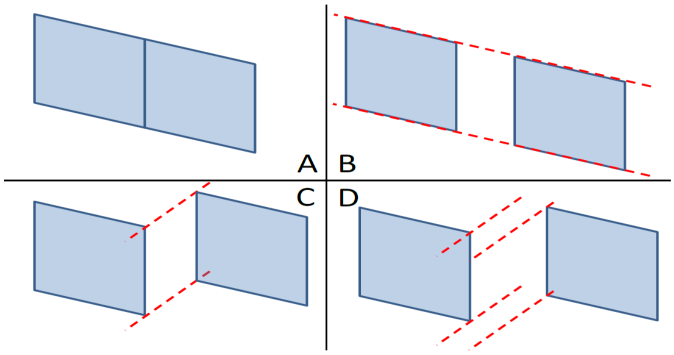

Figure 3: Display contiguity factors:[29, 27]

3.3 Sustained attention

Sustained Attention, or vigilance is "a fundamental component of attention characterized by the subjects readiness to detect rarely and unpredictably occurring signals over prolonged periods of time" [31]. Basically a person is in a state in which he is waiting to react to a certain signal. Sustained attention influences the efficiency of other parts of attention like selective and divided attention.

There are several variables that influence the effectiveness of sustained attention. These are the successive presentation of signal and non-signal features, the high frequency of occurring signals, the uncertainty about the location of the occurring event, the demands on working memory and the use of signals with conditioned or symbolic significance.

3.4 Change blindness

When looking at a scene in which a change occurs slowly over a certain period of time, humans have difficulties perceiving this change. This phenomena is called change blindness [20, 38]. The reason for change blindness is the limited capacity of our visual working memory. Past scenes which are not interesting are immediately forgotten so we don't notice a change over time.

3.5 Inattention blindness

Humans cannot keep more than 3-5 individual objects of an observed scene in the visual working memory[20, 38]. Only the most important objects are actually perceived, the rest of a scene is completed by information in the long term memory. When focusing attention on specific parts of a scene, one does not perceive information or changes about other parts. This is called inattention blindness.

4. VISUAL ISSUES IN MULTI-DISPLAY ENVIRONMENTS

A multi-display environment is a computer systems that present output to more than one physical display [27].

It can be differentiated between single-device and multi-device environments. Single-device environments usually consists of multiple output screens that are connected to only one computing device, while multi-device environments consist of a composition of multiple computing devices where each one has its own display.

One can also make a distinction between stationary and mobile multi-display environments. Stationary user interfaces usually consist of a number of large display screens that are fixated in one place. Mobile user interfaces consist of a number of portable or worn devices that are interconnected with each other. When those devices are located in a certain perimeter around the user, they are called body-proximate [14, 26]. Additionally, there is the possibility of combining mobile and stationary displays in a hybrid multi-display environment.

The usage of multiple displays for presenting information is getting more and more common. Multi display environments can have several advantages. When combining multiple devices or displays one has the possibility to make use of the distinct advantages of different devices. By using a smartphone as an input device for a large display [27, 2, 32, 9], the large display can compensate for the limited display size of the phone, while the mobility of the phone can compensate for the immobility of the stationary display. Multi-Display Environments in e.g. conference rooms can also contribute to "collaborative problem solving and teamwork by providing multiple display surfaces for presenting information" [21].

4.1 Stationary multi-display environments

Stationary multi-display environments consist of environments with usually one or multiple large display screens connected to other computing devices. Since they provide further usable space, they give the possibility to display a larger amount of data across those screens. Usually they can be found in meeting rooms, conference rooms, and mission control centers [21]. Figure 4 shows an example of a conference room.

When displaying data across multiple large displays, many different perceptional issues can arise. The following paragraphs evaluate the relevance of the perceptional properties introduced in section 2 and 3 on stationary multi-display environments.

4.1.1 Color

The use of color (see 2.1) can be of great importance when displaying data. Rather than the choice of color, in multi-display environments, it might be more important to consider that each display might use a different color model [33]. A color that seems light green on one device might look cyan on another. One has to make sure that a color displayed across devices is always perceived as the same. Otherwise, it might lead to confusion, performance drops and errors.

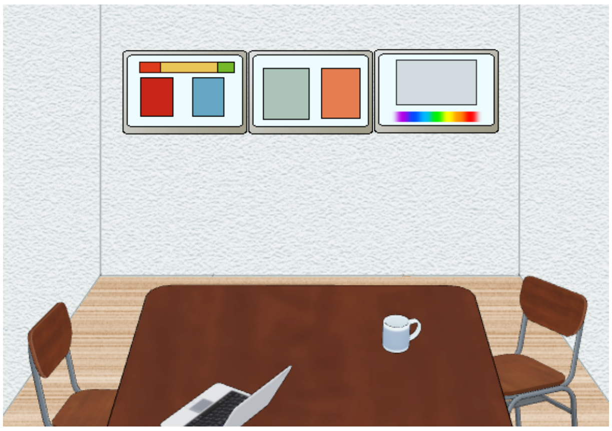

Figure 4: Sketch of a conference room with multiple displays

4.1.2 Brightness and contrast

It is important that displays are sufficiently bright (see 2.2) , so the content is clearly visible to the user. One also has to take ambient lighting in consideration, the higher the ambient light is, the brighter must be the displays. In the context of stationary multi display environments, it has to be ensured, that every display has a sufficient brightness. One has to take into consideration, that some displays have a higher luminance than others [33]. They have to be regulated in a way, that the perceived brightness from each device is similar, so the eye won't have to adjust (see section 2.2) when switching from one display to another.

Ambient Lighting conditions in the environment also have to be considered. When one display is closer to a source of light (e.g. a lamp) than another, the luminance of the display has to be corrected accordingly.

For the data to be clearly visible one also has to make sure that the contrast (see 2.3) is sufficient. Contrast depends on brightness and ambient lighting.

4.1.3 Focus and depth perception

Large displays in e.g. conference rooms usually cover the walls, so for stationary environments depth (see 2.6) and focus (see 2.4) do not have as much impact.

4.1.4 Field of vision

In a system consisting of multiple displays one has to decide how the displays are arranged and what information is shown where. In this context the field of vision (see 2.5) has to be taken into consideration. Stationary multi display environments usually include one or multiple large displays. As already explained, the foveal vision only make out about 2° of the visual system. This is usually not enough to cover the entire span of the displays, so one can make use of peripheral vision [18]. The arrangement of displays and information in space has to be done accordingly. Critical information should be displayed in the center, while secondary information is available in the peripheral vision. Viewing distance, size and display resolution also have to be taken into consideration.

4.1.5 Attention

As mentioned in section 3, the capacity of humans to focus their attention on tasks or objects is limited. In the context of multi-display environments, visual attention encloses for example, that the user is only able to focus his attention efficiently on display at a time.

Selective attention: When using multiple displays the effects of display properties on selective attention have to be taken into consideration. If one display stands out from the others (for example because it is bigger) it will be identified as the main display [35, 36]. In that case more attention will be used to focus on this particular screen, so it should be used to display the core information.

Divided attention: When there are multiple displays showing information distributed in space, the attention will be divided between them. This leads to attention switches and gaze shifts between the displays. In an environment with multiple displays one has to be aware, that the positioning in space is a matter that influences attention.

As mentioned in 4.1.3, in stationary multi display environments the displays are usually mounted in a depth contiguous (see figure 3) [29, 27] manner. In stationary environments the impact of visual field discontiguity (e.g. through bezels or physical separation of displays) on performance might be more significant.

In stationary multi-display environments the angular coverage [29, 27] is usually field-wide, covering the whole visual field, or even panorama, when the user is surrounded by displays. This leads to visual attention switches when a task (e.g. reading) only covers a certain angle (see2.5) but the information is spread over the whole visual field or even further (requiring centering the gaze or even head turns).

Sustained attention: The use of multiple displays might put a strain on sustained attention. The more displays are used, the higher the demands on the visual working memory and the more possible locations for events to occur.

4.2 Mobile multi-display environments

Mobile multi-display environments consist of multiple mobile devices that interact with each other. Environments solely consisting of mobile devices can also be called body proximate display environments [26] since the user usually wears them or holds them close to his body. Examples for such devices are smartphones, tablets, smart watches or head-mounted displays (Figure 5). Compared to a stationary environment, there are more factors that have to be considered [4, 13], due to their mobility, the variable size of mobile displays, their diverse methods of control and the challenge of adding or removing them flexibly from multi-display environments.

The following paragraphs evaluate the relevance of the perceptional properties introduced in section 2 and 3 for mobile multi-display environments.

4.2.1 Color

Same as for stationary devices, see section 4.1.1.

4.2.2 Brightness and contrast

For brightness (see 2.2) and contrast (see 2.3) mainly the same aspects have to be considered as for stationary environments, see section 4.1.2. For mobile devices the adapting to ambient lighting might be of bigger importance than for stationary devices. Since the devices are mobile, they can be used indoors as well as outdoors and such, it has to be made sure that they can adapt to changes in the surrounding brightness efficiently and in the same way.

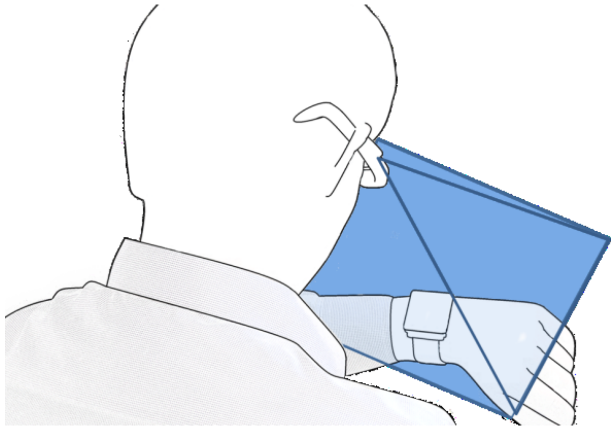

Figure 5: Combination of google glasses and a smart watch: [13]

4.2.3 Focus and depth perception

Our eyes cannot focus on near and far objects at the same time (see 2.4). Since mobile devices can take flexible positions in space, focus is an issue. Additionally, "optical see-through displays (e.g. Google Glass) often employ optical techniques to generate images at distances which are easier for the eye to accommodate" [26]. That means that when looking at data through a Google Glass and trying to simultaneously see the display on another device, this can cause problems with focus when the image of Google glass is generated at another distance than the other display is.

Another factor that should be considered are the diverging display sizes and resolutions of different mobile devices. The depth perception(see 2.6) of augmented reality changes with the display size of handheld displays [8, 4]. Depth compression is lesser when using a smaller display. This can cause visual separation effects and lead to divided attention issues (see 4.2.5). Therefore, it should also be taken into consideration when combining mobile displays with different screen sizes.

4.2.4 Field of vision

In mobile devices with smaller display, the foveal vision (see 2.5) and UFOV can be used more effectively, since the displays of mobile devices are usually smaller. Since the devices are mobile they can also be moved to take different positions in the field of vision, according to what task the user is occupied with.

4.2.5 Attention

For mobile multi-display environments, attention (see 3) is also of importance, maybe even more than for stationary devices, since they are more flexible.

Selective attention: Just as for stationary displays the distribution of information is important.

Between different mobile devices often exist differences regarding the way and the purpose for what they are used (e.g. google glasses provide more display space, but have a less comfortable input system while a smartphone can be handled more intuitively but has a smaller display screen). A mobile multi-display environment gives the opportunity to partition tasks between different displays [4]. So for example a Google glass can be used to show the data, a smart watch for navigating and a smartphone for displaying more detailed information. When doing this the attention can be focused on the display that corresponds to the current task and shows the currently interesting information.

Divided attention: As for stationary displays, the attention of the user is divided between multiple displays.

In a mobile environment displays can be moved at will, so they can be placed both depth and visual field discontigous (see figure 3) which can lead to visual attention switches. Since they are mobile devices, they can be moved to positions, in which the distances of gaze switches are minimal. But this will not work in all cases, since, as mentioned in 4.2.3 optical see through devices display their information at a generated distance which is different to the actual distance.

Angular coverage in mobile multi-display environments is mostly fovea-wide due to the relatively small displays of mobile devices. In case of head-mounted displays this is extended to field-wide coverage. Due to this and the possibility to move the displays to the viewed positions, the impact of gaze switches might be smaller than for stationary devices.

Since the devices are mobile, the attention is not only limited to the devices. A part of the attention also has to be directed towards the environment, for example street traffic.

Sustained attention: As for stationary environments (section 4.1.5), more displays mean a bigger strain on sustained attention. Since the number of displays in a mobile environment can be flexible and a part of the attention also has to be divided to the environment, one has to adapt to a constantly changing environment which might make the strain on sustained attention even bigger.

4.3 Hybrid multi-display environments

Hybrid multi-display environments consist of one or multiple stationary large displays that are interacting with one or multiple mobile devices. There is a possibility to use smartphones as an input device for stationary large displays [32, 2]. It has the advantage of combining the displaying of large data on a large screen with the mobility and intuitivity of remote input. There are approaches in which one can use private mobile devices to interact with public large displays. Dix [9] evaluated the possibilities of an interaction between public large displays like in airports or bus shelters, with a personal mobile device.

The following paragraphs evaluate the relevance of the perceptional properties introduced in section 2 and 3 for mobile multi-display environments.

4.3.1 Color

Same as for stationary devices, see section 4.1.1.

4.3.2 Brightness and contrast

Same aspects as for stationary and mobile devices, see sections 4.1.2 and 4.2.2.

4.3.3 Focus and depth perception

As explained in section (see 2.4), it is not possible to focus on near and far objects at the same time. This has to be taken into consideration when a local display is combined with global displays (depth-discontinuous [29, 27]), since there can be a larger physical distance between the displays of a large screen and the mobile device, than in the pure stationary or mobile environments. When using a global display as output as well as show (a partition of) the data on a local display, one can't focus on both of them simultaneously. This leads to attention switches which might cost time and performance.

4.3.4 Field of vision

In a hybrid environment, both the foveal vison for small-sized mobile devices (see section 4.2.4) and the peripheral vision for the large display screens (see section 4.1.4) can be used.

When using mobile devices to display a part of the perceived scene (or stationary large display) it can come to the dual-view problem [5]. This means that the devices field of view (see 2.5) is different for the observers, because of a camera screen offset.

4.3.5 Attention

Similar as for stationary (see section 4.1.5) and mobile (see section 4.2.5) multi-display environments, attention (see section 3) is a factor that also has to be considered in the hybrid environment.

Selective attention: In the hybrid multi-display environment, the stationary large screens usually function as the main output while the mobile device usually is used as an input device [32, 2]. As for stationary environments, one has to take the property of selective attention into consideration when deciding on the layout of the large screens. But one must also decide what kind of information the mobile device should show [12, 29, 27], that is if it should show additional information or a copy or subset of the data on the stationary device. If there is more than one large display one must decide what information from which display is shown on the mobile device and if it should be preserved when switching from a large display to another or leaving the environment completely.

Divided attention: Similar as in a pure mobile environment (see section 4.2.5), hybrid multi-display environments the displays can be placed both depth and visual field discontigous (see figure 3). But in a hybrid environment the distance from the stationary screen to a mobile device can become quite large, so visual attention switches between the screens might take more time. One also has to consider that due to the distance the relative size of mobile and stationary display one has to adapt to the differences in resolution.

In hybrid environments angular coverage can range from fovea-wide, when focusing on the mobile device (see section 4.2.5) to field- or even panorama-wide for the stationary devices (see section 4.1.5).

Also varying size of workspace could have effects on the performance [16] as well as the social setting in which the interaction takes place [15, 17].

Sustained attention: Most factors are the same as for mobile multi-display environments (see section 4.2.5). But when dealing with hybrid environments, physical fatigue can play a role as well [12]. Large display screens, are usually mounted at eyesight or higher. When using a mobile device to interact with them (e.g. trough pointing), one might need to hold up one's arms and remain in this position for a extended period of time. The arms tire and in result one might not be able to continue with his task.

5. EXPERIMENTAL STUDIES ON PERCEPTIONAL ISSUES

There are several experiments on human interaction with multi-display environments considering properties of the human perception. In this section the setup and results of the seemingly most relevant ones will be briefly summarized.

Most of the experiments are mainly regarding the effects of visual field and depth discontiguity (see figure 3) and the resulting switches in visual attention on task performance. One is Rashid's experiment in 5.1, where he evaluated the tradeoff between an input technique requiring pointing and one requiring attention switches from a large output to a mobile input display. Rashid's second experiment in section 5.2 compared a hybrid UI configuration to a mobile and stationary one, particularly pointing out the effects of visual attention switches in the hybrid configuration on task performance. Vatavu (section 5.3) evaluated the effects of layout and display number on the participants visual attention. In section 5.4 experiment on how visual field separation through bezel presence and width affect a visual search task is summarized.

5.1 Proximal and distal selection of widgets for mobile interaction with large displays

This Experiment was conducted by Rashid [27, 28] to evaluate the tradeoff between the effects of attention switching and the imprecision of pointing when using a smartphone as a remote control for large displays. For this reason he compared two different techniques: The " Distal Selection (DS)" is a no-attention-switch technique, where the selection is done via pointing. The second technique is an attention-switch technique called "Proximal Selection (PS)", where the selection is shown on the mobile device and selected by touch.

The Apparatus consisted of a Nokia smartphone attached to the circuit board of a Nintendo WiiTM remote control and a large display screen with a resolution of 1920x1080px. The participants were seated at an approximate distance of 2.5 meters from the screen. 20 people (17 males and 3 females) in an age group of 3045 participated in this experiment. All had normal or corrected-to-normal vision. Their task was to select clustered circular widgets in a two-step approach: first they had to zoom in the region by pointing and secondly, they had to select each widget by the DS- or the PS-technique.

This experiment had the independent variables interaction technique (DS and PS), widget quantity (2, 4, 6 and 8 widgets) and widget size (small and large), so the task consisted of 2 techniques x 2 widget sizes x 4 widget quantity levels x 5 repetitions = 80 trials per participant.

The experiment showed, that PS was significantly faster than DS and also outperforms DS when the widget quantity increases. The completion time increased linearly with widget quantity and there was an interaction effect between widget size and the widget quantity. The error rate was calculated as missed clicks per widget. Over 2/3rds of the tests were completed without errors. It was found, that the DS technique was more accurate than the PS technique (assumably due to the "fat finger problem"), this effect depended on the widget-size (only significant for small-sized widgets). The time spent for attention switches was calculated to be 0.64x0.36 seconds. In the subjective evaluation, the users preferred the use of PS, rather than DS, and regarded a big widget-size more positively. Overall 75% of participants selected PS over DS as their favorite technique, since the tasks were easier to accomplish. On the other hand, they disliked the switching of visual attention between the mobile device and the large display.

5.2 Visual search with mobile, large display and hybrid distributed UIs

Another Experiment by Rashid [27, 28] was to compare mobile, large display and hybrid distributed UIs by testing their usability and performance in three different visual search tasks, particularly considering the impacts of gaze shifts in the hybrid configuration.

The Apparatus consisted of a smartphone with a 480x800px screen connected to a large display screen with a resolution of 1920x1080px. The participants were seated at a distance of approximately 120cm from the large display. 26 people (19 males and 7 females), with an age ranging from 19 to 33, participated in this experiment. All had normal or corrected-to-normal vision.

There were three UI configurations used in this experiment. In the mobile configuration only the mobile device was used for input and output. In the large display configuration the mobile device was used only as an input device and the output was shown only on the large display. In the third, the hybrid configuration, the mobile device was used for input and output like in the mobile configuration, but the output was also shown on the large display, while the mobile device only showed a partial view.

In this experiment the independent variables were UI Configuration (Mobile, Large Display, Hybrid) and data size (small or large). The task consisted of 8 trials(4 small data, 4 large data) x 3 UI configuration x 3 blocks = 72 trials per participant.

The UI configurations were compared for three different visual search tasks. In a map search task, participants had to find a location on a map based on given criteria and tap on the corresponding marker. It was found, that for task performance on small data mobile and large display perform equivalent and better than hybrid. For large data the large display performed better than hybrid and mobile. The hybrid configuration is performing worst, because of the required gaze shifts (cost ca. 1.8 seconds).

The second task was a text search task. The participants had to find specific text fragments of in informational texts and tap on these. In task the mobile and large displays performed similarly and the hybrid configuration was the worst, but no relationship between gaze-shifts and completion time was found.

In the third task, a photo search, the participants had to find a specific photograph among other photographs of faces. In this task the mobile and large displays performed equally in both large and small data conditions. The hybrid option performed worst in both conditions.

5.3 Visual attention for multi screen TVs

Radu-Daniel Vatavu evaluated the effects of layout and number of multiple TV screens on users visual attention [35, 36].

In this experiment the TV screens were part of a large image projected on a wall with a standard projector. The participants were seated at 2.3 meters from the projection.

10 people (9 males and 1 female), with a mean age of 27,9 years, participated in this experiment. All had normal or corrected-to-normal vision. The participants were asked to watch one-minute long movies separately and after that to take tests to collect workload subjective ratings and fill questionnaires to evaluate their understanding of the content they were watching.

In this experiment the independent variables were the TV-Count (2,3 and 4 screens) and the Layout seen in figure 6. For Layout there are three possibilities Tiled(equal sized screens, compact layout), Primary (one larger screen is the main screen) and Arbitrary (screens in arbitrary sizes with a random layout). There were 3 TV-count x 3 Layout= 9 trials per participant.

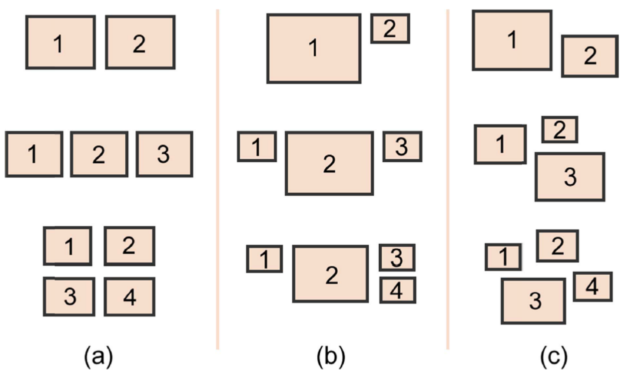

Figure 6: TV layouts of multiple TV screens experiments [35, 36]

Regarding the distribution of visual attention this experiment showed that the discovery time varied between 0.1 and 15.5 seconds. A significant effect of TV-count on discovery time was found, but no effect of layout. In case of discovery sequence, for n screens there are n! possible sequences. The experiment showed that the layout has a mayor impact on the discovery sequence. For primary the users are first attracted by the middle screen, and the sequence follows a counter-clockwise pattern in the absence of a primary screen. As for screen watching time, there were differences for tiled and primary layouts for three and four screens. Only the arbitrary layout had an effect for two screens. There were significant effects for both TV-count and Layout on the gaze transition count, with no significant distance between tiled and primary for layout. It was found that more screens determine more transitions during the first minute of watching. The arbitrary layout led to significantly less transitions. For the distance that an eye gaze travelled was no significant effect of screen number, but of layout found. Also, there was a significant effect of TV-count on switch time.

For cognitive load and the perceived comfortability, participants perceived no effect of layout on the cognitive load, but it increased with the number of screens. The Participants were most comfortable with 2 screens.

Concerning the capacity to understand content and perceived screen watching time, there was no effect of either layout or screen number on the content understandability. The participants were able to estimate how much they watched each screen surprisingly accurately.

5.4 Effect of bezel presence and width on visual search

In [37] Wallace, Vogel and Lank evaluated the effect that bezel presence and width have on a visual search task.

The utilized display measured 2m x 1,5 m and was projected at a resolution of 1024x768. The participants were seated 3 meters from the display. 20 people (16 males and 4 females), with an age between 21 and 40 years, participated in this experiment. Each participant was asked to search for a target in a field of randomly positioned detractors and then decide if the target was present or not.

This experiment had the independent variables Bezel Width (0, 0.5, 1, 2, 4 cm), Target Presence (present, absent) and Bezel Split (if a target crossed a bezel or not). The experiment consisted of 5 Bezel Widths x 2 Target Present/Absent x 2 Split Present/Absent x 6 Repetitions= 120 trials per participant.

It was found, that there was a significant effect of the absence or presence of targets on the error rate. Bezel width had no effects, but when data crossed a bezel line, the error rates were consistently lower. For visual search time, there were differences in time based on whether targets were absent. Again, no effect of bezel width was found. Whether data crossed a bezel also had no effect on visual search time.

5.5 Further experiments

Jonathan Grudin in [18] made an experiment that showed how users would arrange information when they had a large amount of available space.

Forlines, Shen, Widgor and Balakrishnan conducted an experiment in [10] on how the size of a group and the number and distribution of displays affect visual search tasks.

Wallace, Vogel and Lank evaluated in [37] how bezel presence and bezel width can influence magnitude judgment.

Bi, Bae and Balakrishnan conducted a series of experiments in [3] to evaluate how bezels affect tasks like visual search, tunnel steering and target selection.

Tan and Czerwinski investigated in [34] how visual separation and physical discontinuities affect the distribution of information across multiple displays.

Huckauf, Urbina, Böckelmann, Schega, Mecke, Grubert, Doil and Tümler [22] conducted a series of experiments on how perceptual issues in optical-see-through designs can have an effect on visual search, dual task and vergence eye movements.

Cauchard [4] examined the effects of visual separation on mobile multi-display environments.

Stone in [33] evaluated how differences in color and brightness can be hindrances when trying to make tiled displays interact seamlessly.

6. WHAT COULD BE DONE NEXT?

Most of the experiments in section 5, especially those concerning stationary and hybrid multi-display environments, concentrated on the effects of visual separation of displays in depth and visual field on attention switches. It can be noticed that the visual properties like focus and the field of vision have an impact on attention.

On the other hand, visual properties like color of brightness could be further evaluated the context of multiple displays. For example, how differences in color or brightness of multiple displays might affect performance or lead to errors may be a topic that could be explored.

The field of mobile and hybrid multi-display user interfaces is still very young. There are still many possible issues that can be worked with.

One could research on how the ambient lighting can influence mobile multi-display user interfaces. Since those devices are mobile they have to adapt to brightness changes in the same way, for example, when exiting from a dark building into a bright outdoors and vice versa.

It might also be interesting to research the effects of divided attention. When using multiple mobile devices that require attention, how much declines the attention we pay to our surroundings in comparison to when using only one mobile device. This might be important to evaluate the usefulness in a natural environment.

Another issue that might be worth addressing is how, in environments containing mobile devices, the variety and flexibility in display size, display number, distances and position can affect attention and performance.

More comparisons between stationary, mobile and hybrid multi-display environments might be interesting as well. For example, which one has a bigger strain on sustained attention, or which one leads to more attention switches etc.

7. CONCLUSION

In this work an overview about the human visual system and visual attention was presented. The relevance of these properties in the context of stationary and mobile multi-display environments were evaluated. Afterwards a short summary of experiments conducted by different researchers which had a relevance to perceptional issues was given, followed by an overview of open points and interesting topics that could be further examined.

8. REFERENCES

[1] L. E. Arend and B. Spehar. Lightness, brightness, and brightness contrast: 1. illuminance variation. *Attention, Perception, & Psychophysics*, 54(4):446–456, 1993.

[2] R. Ballagas, J. Borchers, M. Rohs, and J. G. Sheridan. The smart phone: a ubiquitous input device. *Pervasive Computing, IEEE*, 5(1):70–77, 2006.

[3] X. Bi, S.-H. Bae, and R. Balakrishnan. Effects of interior bezels of tiled-monitor large displays on visual search, tunnel steering, and target selection. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 65–74. ACM, 2010.

[4] J. R. Cauchard, M. Löchtefeld, P. Irani, J. Schoening, A. Krüger, M. Fraser, and S. Subramanian. Visual separation in mobile multi-display environments. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, pages 451–460. ACM, 2011.

[5] K. Čopič Pucihar, P. Coulton, and J. Alexander. Evaluating dual-view perceptual issues in handheld augmented reality: device vs. user perspective rendering. In *Proceedings of the 15th ACM on International conference on multimodal interaction*, pages 381–388. ACM, 2013.

[6] M. Corbetta, F. M. Miezin, S. Dobmeyer, G. L. Shulman, and S. E. Petersen. Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *The Journal of Neuroscience*, 11(8):2383–2402, 1991.

[7] R. Desimone and J. Duncan. Neural mechanisms of selective visual attention. *Annual review of neuroscience*, 18(1):193–222, 1995.

[8] A. Dey, G. Jarvis, C. Sandor, and G. Reitmayr. Tablet versus phone: Depth perception in handheld augmented reality. In *Mixed and Augmented Reality (ISMAR), 2012 IEEE International Symposium on*, pages 187–196. IEEE, 2012.

[9] A. Dix and C. Sas. Mobile personal devices meet situated public displays: Synergies and opportunities. *International Journal of Ubiquitous Computing*, 1(1):11–28, 2010.

[10] C. Forlines, C. Shen, D. Wigdor, and R. Balakrishnan. Exploring the effects of group size and display configuration on visual search. In *Proceedings of the 2006 20th anniversary conference on Computer supported cooperative work*, pages 11–20. ACM, 2006.

[11] W. C. Gogel and D. W. Eby. Measures of perceived linear size, sagittal motion, and visual angle from optical expansions and contractions. *Perception & psychophysics*, 59(5):783–806, 1997.

[12] J. Grubert, R. Grasset, and G. Reitmayr. Exploring the design of hybrid interfaces for augmented posters in public spaces. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, pages 238–246. ACM, 2012.

[13] J. Grubert, M. Heinisch, A. J. Quigley, and D. Schmalstieg. Multifi: multi-fidelity interaction with displays on and around the body. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*. ACM Press-Association for Computing Machinery, 2015.

[14] J. Grubert, M. Kranz, and A. Quigley. Design and technology challenges for body proximate display ecosystems. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pages 951–954. ACM, 2015.

[15] J. Grubert, A. Morrison, H. Munz, and G. Reitmayr. Playing it real: magic lens and static peephole interfaces for games in a public space. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, pages 231–240. ACM, 2012.

[16] J. Grubert, M. Pahud, R. Grasset, D. Schmalstieg, and H. Seichter. The utility of magic lens interfaces on handheld devices for touristic map navigation. *Pervasive and Mobile Computing*, 18:88–103, 2015.

[17] J. Grubert and D. Schmalstieg. Playing it real again: a repeated evaluation of magic lens and static peephole interfaces in public space. In *Proceedings of the 15th international conference on Human-computer interaction with mobile devices and services*, pages 99–102. ACM, 2013.

[18] J. Grudin. Partitioning digital worlds: focal and peripheral awareness in multiple monitor use. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 458–465. ACM,

2001.
[19] D. A. Hanes, J. Keller, and G. McCollum. Motion parallax contribution to perception of self-motion and depth. *Biological cybernetics*, 98(4):273–293, 2008.
[20] C. G. Healey et al. Perception in visualization. *Retrieved February*, 10, 2007.
[21] T. Heider and T. Kirste. Usable multi-display environments: concept and evaluation. In *Universal Access in Human-Computer Interaction. Ambient Interaction*, pages 93–102. Springer, 2007.
[22] A. Huckauf, M. H. Urbina, J. Grubert, I. Böckelmann, F. Doil, L. Schega, J. Tümler, and R. Mecke. Perceptual issues in optical-see-through displays. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, pages 41–48. ACM, 2010.
[23] S. Kastner and L. G. Ungerleider. Mechanisms of visual attention in the human cortex. *Annual review of neuroscience*, 23(1):315–341, 2000.
[24] D. McCready. On size, distance, and visual angle perception. *Perception & Psychophysics*, 37(4):323–334, 1985.
[25] C. Oyster. *The Human Eye: Structure and Function*. Sinauer Associates, 2006.
[26] A. Quigley and J. Grubert. Perceptual and social challenges in body proximate display ecosystems. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pages 1168–1174. ACM, 2015.
[27] U. Rashid. *Cross-display attention switching in mobile interaction with large displays*. PhD thesis, University of St Andrews, 2012.
[28] U. Rashid, M. A. Nacenta, and A. Quigley. The cost of display switching: a comparison of mobile, large display and hybrid ui configurations. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, pages 99–106. ACM, 2012.
[29] U. Rashid, M. A. Nacenta, and A. Quigley. Factors influencing visual attention switch in multi-display user interfaces: A survey. In *Proceedings of the 2012 International Symposium on Pervasive Displays*, pages 1–6. ACM, 2012.
[30] E. Richards, P. J. Bennett, and A. B. Sekuler. Age related differences in learning with the useful field of view. *Vision Research*, 46(25):4217–4231, 2006.
[31] M. Sarter, B. Givens, and J. P. Bruno. The cognitive neuroscience of sustained attention: where top-down meets bottom-up. *Brain research reviews*, 35(2):146–160, 2001.
[32] J. Seifert, A. Bayer, and E. Rukzio. Pointerphone: Using mobile phones for direct pointing interactions with remote displays. In *Human-Computer Interaction–INTERACT 2013*, pages 18–35. Springer, 2013.
[33] M. C. Stone. Color and brightness appearance issues in tiled displays. *Computer Graphics and Applications, IEEE*, 21(5):58–66, 2001.
[34] D. S. Tan and M. Czerwinski. Effects of visual separation and physical discontinuities when distributing information across multiple displays. In *Human–Computer Interaction*, volume 3, pages 252–255, 2003.
[35] R.-D. Vatavu and M. Mancas. Visual attention measures for multi-screen tv. In *Proceedings of the 2014 ACM international conference on Interactive experiences for TV and online video*, pages 111–118. ACM, 2014.
[36] R.-D. Vatavu and M. Mancas. Evaluating visual attention for multi-screen television: measures, toolkit, and experimental findings. *Personal and Ubiquitous Computing*, 19(5-6):781–801, 2015.
[37] J. R. Wallace, D. Vogel, and E. Lank. Effect of bezel presence and width on visual search. In *Proceedings of The International Symposium on Pervasive Displays*, pages 118–123. ACM, 2014.
[38] C. Ware. *Information visualization: perception for design*. Elsevier, 2012.