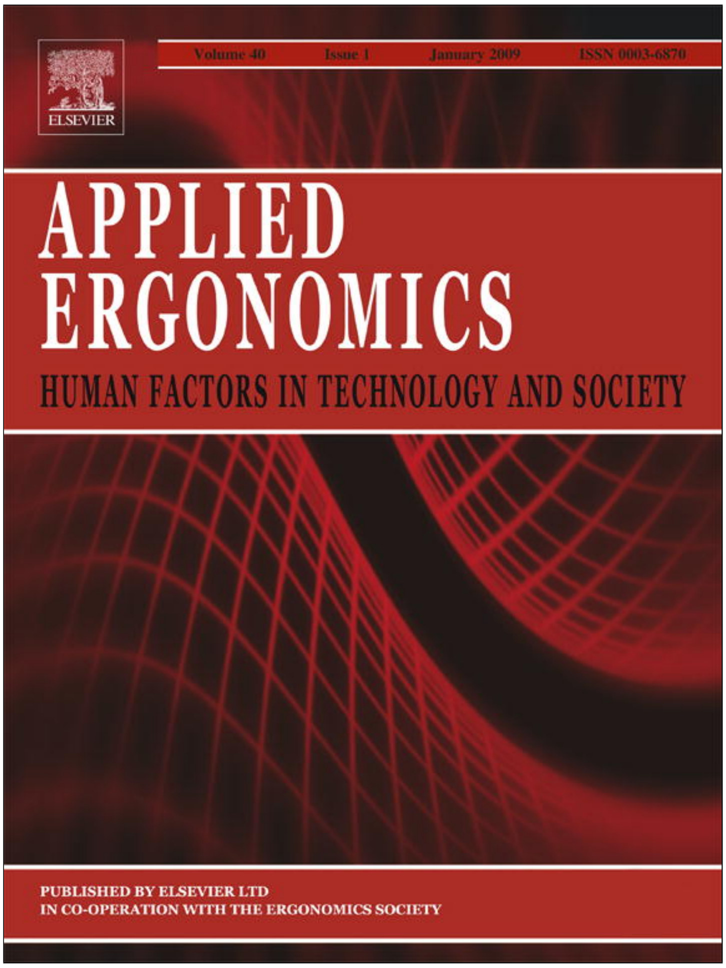
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A visual ergonomic evaluation of different screen types and screen technologies with respect to discrimination performance

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Abstract

An increasing demand to work with electronic displays and to use mobile computers emphasises the need to compare visual performance while working with different screen types. In the present study, a cathode ray tube (CRT) was compared to an external liquid crystal display (LCD) and a Notebook-LCD. The influence of screen type and viewing angle on discrimination performance was studied. Physical measurements revealed that luminance and contrast values change with varying viewing angles (anisotropy). This is most pronounced in Notebook-LCDs, followed by external LCDs and CRTs. Performance data showed that LCD's anisotropy has negative impacts on completing time critical visual tasks. The best results were achieved when a CRT was used. The largest deterioration of performance resulted when participants worked with a Notebook-LCD. When it is necessary to react quickly and accurately, LCD screens have disadvantages. The anisotropy of LCD-TFTs is therefore considered to be as a limiting factor deteriorating visual performance.

Keywords: Notebook-LCD; Discrimination Performance; Anisotropy

1. Introduction

The private and public need for electronically displayed information has increased considerably and continuously for a fairly long time. In order to assure high productivity, it should be focused on the visual quality of electronic displays and the ease with which they allow visual information to be processed. Improvements in screen technology lead to a considerable change of the quality of electronic displays and display types. Nevertheless, the underlying ergonomic questions did not change: How can it be assured that working with electronic screens is possible without difficulty and that efficient visual processing of information is facilitated?

Visual ergonomic studies were concerned with the evaluation of electronic displays and aimed at identifying possible shortcomings of current display design. The criteria for the suitability of displays for presenting information were users' productivity in terms of speed and accuracy of visual processing as well as the emergence of visual strain (e.g. Gould et al., 1987a, b; Dillon 1992, 2004; Schlick et al., 2007; Sheedy and Bergstrom, 2002; Ziefle, 1998; Ziefle et al., 2005). Even though the studies yielded a solid visual ergonomic knowledge with respect to the displaying of electronic information, technical developments and improvements necessitate the need to continuously evaluate new technologies with respect to their actual benefit for human performance. This regards, for example, the impact of different text factors (e.g. structure, format, and breadth of electronic information) as well as display factors (e.g. contrast, resolution, image quality) (e.g. Dillon et al., 2006; Farrell, 1987; Oetjen and Ziefle, 2004, 2007; Qin et al., 2006; Sheedy et al., 2003; Vaughan and Dillon, 2006; Ziefle et al., 2003). Also, the impact of visual and cognitive demands that are imposed by different task types and the effects of prolonged on-screen reading still receive attention (e.g. Gröger et al., 2005; Schlick et al., 2007; Stone et al., 1980; Ziefle, 1998).

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Another prominent research issue refers to the question, which screen type benefits or disadvantages visual performance. The comparison of different display types received special attention lately as screen technology changed. While a few years ago, the cathode ray tube (CRT) was the state-of-the-art technology and was excessively studied (Schlick et al., 2007), the liquid crystal displays (LCDs) are replacing CRTs more and more. LCDs with thin film transistor technique (LCD-TFTs) seem to overcome many disadvantages of the CRTs. Beyond others, the most significant advantage is their suitability for mobile devices. For this reason, they are not only used in small screen devices like digital cameras and mobile phones, but also play an important role in computer notebooks. Notebook computers are continuously replacing stationary desktop computers and should be focused in the ergonomic evaluation of electronic displays (Kirsch, 2004).

Although distribution and purchase rates of notebook computers are increasing (BITKOM, 2007), to our knowledge no visual ergonomic study was concerned with the visual quality of Notebook-LCDs so far. Whenever notebooks are considered in ergonomic studies, mostly the specificity of hardware components (e.g. input devices, Sutter and Ziefle 2005; Armbrüster et al., 2007) or the specificity of users' sitting posture and characteristics of work places received attention (e.g. Harbison and Forrester, 1995; Saito et al., 2000). As the trend is heading towards a steady increase in mobility, there is a considerable need to learn about the suitability of the visual conditions that are present in Notebook-LCDs. This is the topic of the present study.

To achieve valuable results, a two-step procedure was realised: the first step was to physically measure the visual quality of different screen types and screen technologies. To do so, a standardised measurement procedure was applied that allows the objective, replicable and reliable comparison of the physical features of different screen types. The second step in the analysis of the suitability of Notebook-LCDs was to determine the visual discrimination performance of normal screen users. Here three screen types were compared: the screen of a Notebook-PC, an external LCD and a CRT.

2. Characteristics of the screens and electronic displaying

From a visual ergonomic perspective, the CRT and LCD screen technologies have different advantages and disadvantages. This results in different display-specific performance benefits and drawbacks. These are summarised in the following section.

2.1. Cathode ray tube displays

A characteristic visual feature of CRT screens is a flicker sensation caused by low refresh rates. Many studies have examined the impact of refresh rates and screen flicker, and revealed that it is a major source of performance decrements (e.g. Menozzi et al., 1999, 2001) and visual fatiguing (e.g. Jaschinski et al., 1996). It can even be responsible for the emergence of migraines (e.g. Boschman and Roufs, 1994; Küller and Laike, 1998). A screen flickering at 50 Hz leads to a significant disturbance and a deterioration of visual performance compared to 100 Hz-screens. The performance decreases even more, when the time on task is prolonged. However, increased refresh rates lead to an increase in performance and it can overall be stated that rates of about 100 Hz facilitate a reasonably good performance (e.g. Ziefle, 2001). A second important disadvantage of CRT displays is the bulky format and relatively high weight. These characteristics also have an impact on visual performance, because the admeasurements and space restrictions on conventional computer and office desks (about 80 cm depth) do not allow users to change the position of their screen easily and flexibly. Thus, it is impossible to adjust the viewing distance to the screen and meet individual accommodation needs of the users (users differ considerably in their personally preferred viewing distances and their optimal focal distances, e.g. Heuer et al., 1991; Ziefle, 2003). Beyond visual characteristics, it should be mentioned that CRTs also have a certain amount of radiation, what may be especially important when more than one CRT is used in a small space.

2.2. Liquid crystal displays

The LCD technology seems to elegantly overcome the disadvantages of the CRT screens. LCDs are lightweight and small, and can therefore be individually positioned on computer desks. Further important advantages are that LCD screens run flicker free, provide higher luminance levels than CRTs, and that they can be used in mobile devices. Notebook-LCDs have a lower threshold voltage than their external counterparts. This leads to less complicated electronics, the possibility to use smaller components and an even lower weight and footprint. Furthermore, the energy consumption can be reduced and the operation time of the batteries can be extended. Lower threshold voltages can be realised because the liquid crystal mixtures in Notebook-LCDs are slightly different from the ones used in conventional external LCDs (Heckmeier et al., 2002).

Apart from these advantages, the main drawback of LCDs is that the visibility of information depends upon the viewing angles. Information cannot be seen perfectly when it is not displayed in the centre of the screen or when the user is not sitting directly in front of the screen but looks at it from aside. Under off-axis conditions, the light from the display has a different direction and the users can perceive rays of light that should not be seen. In physical terms, the distribution of luminance over the screen's surface is not constant but differs depending on the point of view. This specific property of LCD screens is called anisotropy. According to ISO 13406-2 (ISO, 2001), a display is called anisotropic when it shows a deviation of luminance of more than 10% depending on the target location or the viewing angle. Recent studies show that anisotropic effects have to be taken rather seriously because the visual performance when working with LCD-TFT screens deteriorates when users are looking from 10° to 50° off-axis (e.g. Gröger et al., 2003; Hollands et al., 2001, 2002; Oetjen and Ziefle, 2004, 2007; Oetjen et al., 2005; Ziefle et al., 2003).

It could be argued that off-axis viewing conditions are artificial and that normally users are sitting directly in front of the screens. However, in real life many situations are present in which anisotropy may play an important role. For example, in traffic controlling environments or stock exchanges, several displays are placed in parallel and/or upon one another and have to be surveyed simultaneously by one operator. Also, in medical contexts like radiology or patient monitoring, often more than one screen has to be used by one person or more than one person has to work with the same screen. Another example are school contexts, where it is frequently the case that several pupils are sitting in front of one screen, and naturally extended or off-axis viewing angles are present. In mobile contexts, the probability of extended viewing angles is also high especially when taking into account that mobile computers increasingly replacing stationary desk top computer systems (Kirsch, 2004). In a recent large research project funded by the German Government (BMBF, 2002; www.bmbf.de/press/670.php), the feasibility of "notebook universities" and the learning and teaching with mobile computing was under study. Although, it is certainly an advantage to be able to learn and teach mobile and flexible, the visual effects of electronic reading should also be considered. While visibility problems of LCD screens are well known by computer notebook users, whenever viewing angles are off-axis, up to now no research study was concerned with the visual effects of anisotropy in notebook devices. The present study aims at clarifying the effects of anisotropy on visual performance when notebook devices are used. Furthermore, the present research introduces a methodology to quantify anisotropic characteristics of LCD screens and relate these to visual performance. A Notebook-LCD was compared to an LCD and a CRT. The outcomes contribute to the understanding of how LCD's anisotropy influences visual performance.

3. Methodology to quantify the extent of anisotropy

There were only a few approaches so far which proposed a specific rationale for a precise and reproducible measurement of anisotropic effects. A promising technique was recently proposed by Qin et al. (2006). They fixed an LCD in a holder and rotated it horizontally and vertically. Their participants should indicate at which rotational angle they perceived changes in the image (due to anisotropy) and at which angle these image changes became unacceptable. Thus, visibility thresholds were distinguished from acceptability thresholds. The biggest advantage of this method is the direct involvement of users' perceptions. However, it is not capable of exactly relating these angle rotations to performance variations. Apart from physical variations of screen visibility, we should also learn about the impact of physical variations on performance, as this is a central interest of successfully interacting with electronic devices in terms of productivity. Therefore, our measurement rationale implicates several demands:

1. It should allow a reliable expression of anisotropy in terms of single components. Thus, the luminance of bright (background) and dark areas (letters) should be known for different screen positions and result from a standardised procedure, which allows comparisons between several screens.
2. Anisotropy occurs on the complete surface of the screen and is not necessarily symmetrically. The measurement rationale should be small-grained and detailed, and include different screen positions and viewing angles.
3. Any experimental evaluation can only consider a limited number of screens. It therefore has to be assured that the features under study are not limited to the selection of screens used in the present experimental study but rather reflect typical and general characteristics of each screen type.

To meet these demands, a measurement setup was developed in our workgroup that enabled us to quantify the changes of photometric measures for different viewing angles and relate these to visual performance (Gröger et al., 2003; Ziefle et al., 2003). In order to refer to replicable screen locations, the screen was virtually divided into 63 black and white fields (nine lines and seven rows). The ambient lighting was according to ISO 13406-2 (ISO, 2001) set to 300 lx during measurement and testing. The luminance of the background (luminance of the bright areas) was standardised (100 cd/m^2, according to DIN-ISO 9241-3; ISO, 1992). It was taken as a standardisation criterion because it was found that mainly the background luminance influences anisotropy based performance decrements (Gröger et al., 2003). All 63 screen locations were measured with a photometer (Luminance Meter Type 1101 by Bruel & Kjaer® with a minimum flare angle of 1/3°).

It is of crucial impact for the understanding of anisotropy that the outcomes in photometry depend on how the measurements are carried out. In the measurement procedure that is normally used by the industry, the photometer is placed in front of the screen and displaced gradually from field to field. Thus, it always has a right angle to the screen surface. These conditions result in luminance values that are quite homogeneous, but do not reflect the actual extent of the divergence of luminance values over the screen surface. The procedure is highly artificial because users do not displace themselves in front of the screen. They rather turn their head and view, and viewing angles change remarkably depending on where users are looking at. To simulate the behaviour of users, the standard measurement procedure was altered. In our measurements the photometer adopted two basic viewing angles: in the central 0° position, the lens of the photometer was turned to all 63 screen locations just as it is the case when users are working with the screens. For the 50° off-axis sitting position, the photometer was placed in the off-axis position and its view pointed to all 63 fields of the screen surface from the left and right side. Both the 0° and the 50° position are shown in Fig. 1.

This measurement rationale was applied to different screen types to learn if anisotropy has to be considered as restricted to single screens or rather as a general characteristic of LCDs. These screens included various LCD-TFTs (all with TN technology) as well as CRTs. Different screen sizes (15 and 17 in.), brands and fabrication times (from 2000 to 2004) were studied with respect to their extent of anisotropy. The outcomes of the photometric measurements are shown in Fig. 2. On the left side, the results for the luminance of bright areas in different screens are illustrated; the right side shows the luminance values for dark areas.

It is obvious in Fig. 2 that photometric measures change dramatically as a function of the photometer's viewing angle. These changes are less pronounced for the two CRT-screens that were tested (Sony S200PS and Elsa Ecomo Office) than for all LCDs. Characteristically, with increasing viewing angles the luminance of the bright areas is less bright (Fig. 2, left side). The luminance of the dark areas (Fig. 2, right side) does not vary monotonically with increasing viewing angle but shows that each screen has an individual luminance profile at the different screen positions. The most prominent anisotropic effects were observed for the two Notebook-LCDs (Dell 8100 and IBM Thinkpad). Overall, it has to be concluded that anisotropy is a general characteristic of LCDs and almost independently of brand and production time.

As experimental displays, an Elsa Ecomo Office (100 Hz)-CRT, a Vobis CF-L15-LCD and a Dell 8100 Notebook-LCD were used. In order to get a deeper insight into the photometric measures of the three experimental screens, Fig. 3 shows their photometric parameters. These include the luminance of bright and dark areas as well as the contrast (Michelson contrast, see for example Bjørset and Brekke, 1980). The measures are comprised for the 0° and 50° sitting position. On the left side, the CRT is visualised where luminance and contrast differ by about 20% when the central 0° sitting position is compared to the 50° off-axis condition. The LCD is shown in the centre of Fig. 3 and luminance and contrast drop by about 80%; this drop averages 90% when the Notebook-LCD is focused (shown on the right side of Fig. 3).

4. Experimental study to determine visual performance

The following sections describe the independent and dependent variables, the viewing conditions, the experimental procedure and participants.

4.1. Independent and dependent variables

Two independent variables were examined. The first one was the screen type. Three different screens (and three different extents of anisotropy) were examined: (1) CRT: Elsa Ecomo Office; (2) (LCD-TFT): Vobis CF-L 15 and (3) Notebook-LCD from the Dell 8100. The second independent variable was the viewing angle. Participants worked

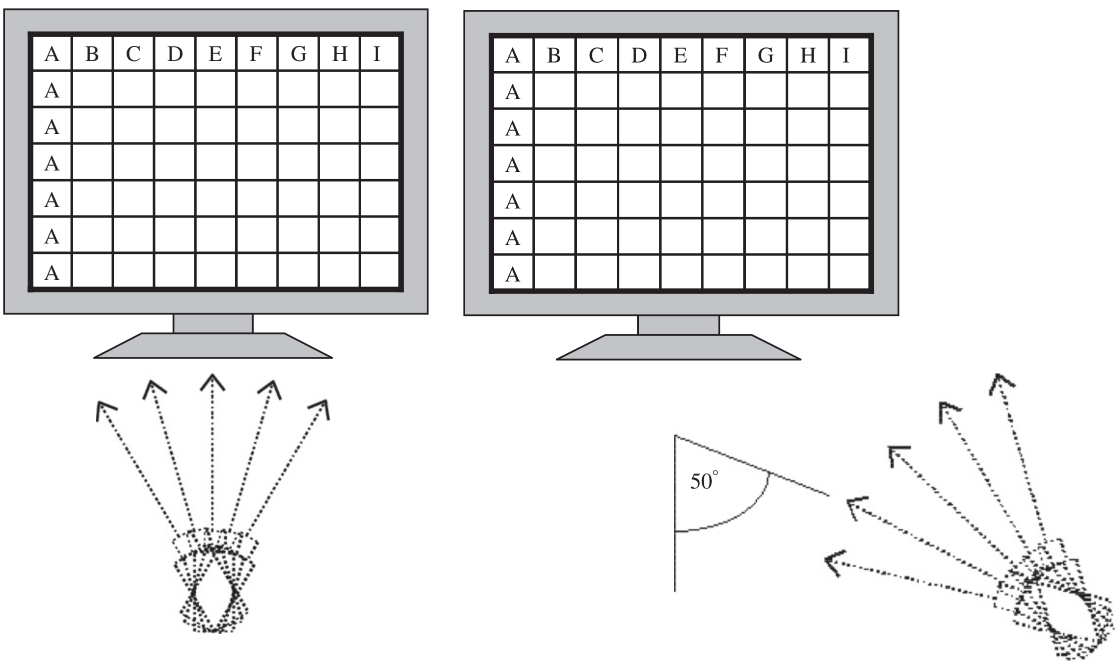

Fig. 1. Photometric measurements for all screen locations (black and white areas). Left side: 0° sitting position, right side: 50° off-axis sitting position.

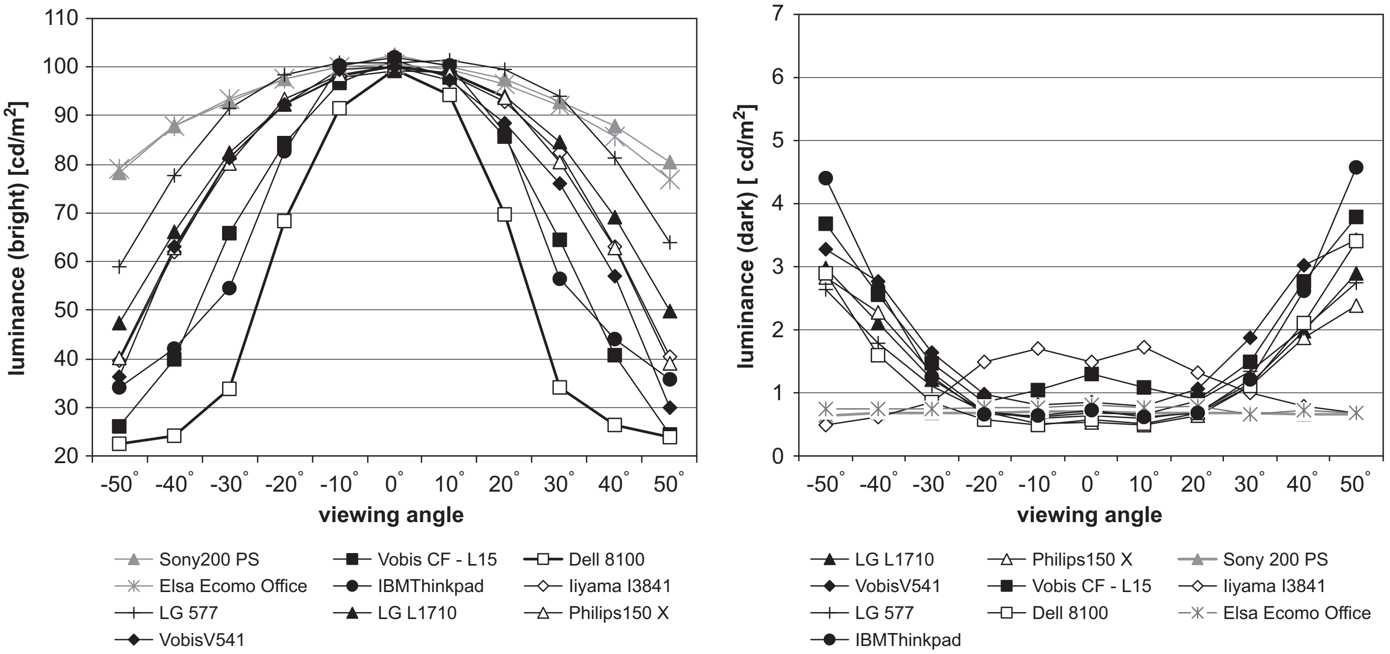

Fig. 2. Outcomes of the photometric measurements for different screen types. Left side: luminance of bright areas (background), right side: luminance of dark areas (targets).

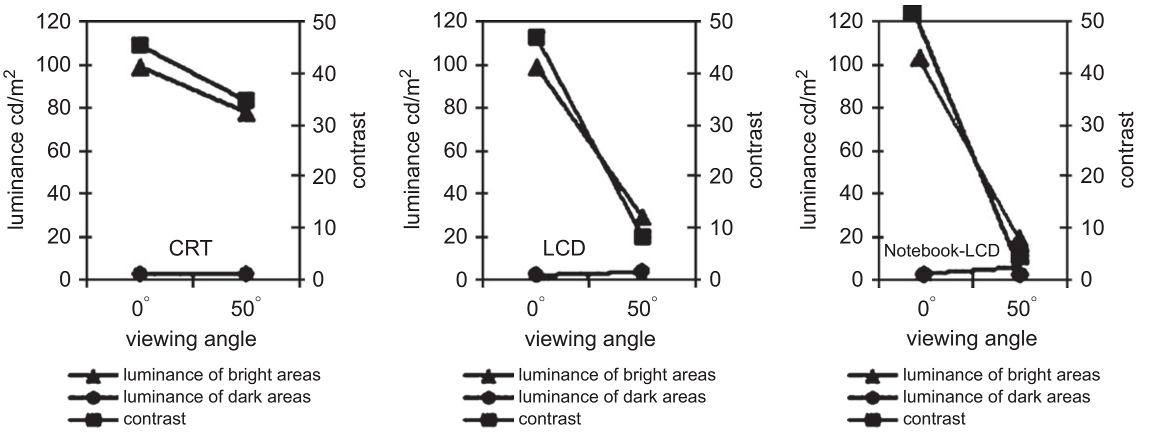

Fig. 3. Photometric values of luminance of the bright and the dark areas and contrast levels for the CRT (left side), the LCD (centre) and the Notebook-LCD (right side) used in the present experiment.

with the screens from two different sitting positions: a 0° central sitting position was compared to a 50° extended position. In the 50° off-axis sitting position, half the participants worked from the left and the other half from the right side. On the basis of the two sitting positions, five different viewing angles were extracted. This was achieved by virtually dividing the screens into three equally large sections and comprising the performance outcomes within these sections (see Fig. 4). For the central sitting position, two viewing angles were distinguished: 0° in the centre of the screen and 11.3° on the left and right side. When the participants sat in the 50° off-axis position, viewing angles for the section closer to the participant were smaller than those for the section that is farther away. Therefore, three viewing angles result: 41.4°, 50° and 56.4°. Overall, this leads to five viewing angles, two of them having their origin in the central sitting position and three of them originating from the 50° sitting position.

Dependent variables were the speed of visual performance (discrimination times in ms) and accuracy (errors).

4.2. Experimental task

The experimental task was a visual discrimination task. This simple task was chosen because it is visually demanding and can reflect the differences in the extent of anisotropy in the screen types. It was moreover of methodological impact to present the targets on all of the

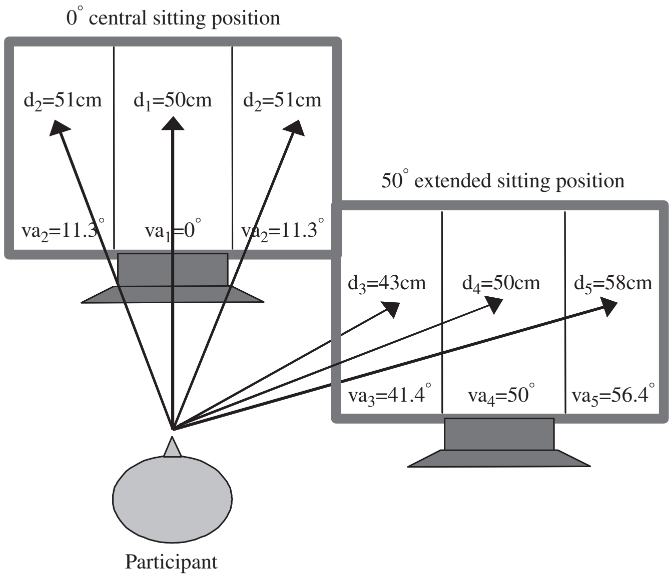

Fig. 4. By virtually dividing the experimental screens into three equally large sections, five different viewing angles (va) result. Viewing distances (*d*) to the screen sections are also depicted.

63 screen positions that had previously been measured. Targets were quadratic stimuli similar to Landolt C's with a gap either at the top, the bottom, the right or the left hand side. The size of the targets was equalised in all screen types, reaching 1.5 mm (this equals a font size of 10 pt in a common word processor document). The size of the gap was 0.38 mm. The viewing distance to the screen was 50 cm in all conditions. Background luminance was 100 cd/m^2 in the centre of the screens; the targets had a luminance of 0.85 cd/m^2. The targets were presented randomly on the complete surface of the screen (on all 63 screen locations). Participants had to detect the direction of the gap as fast and accurately as possible and indicate the chosen answer on a reaction keyboard. The keyboard was specifically built for experimental purposes and consisted of five buttons. One central button to let the target appear and four buttons at the top, the bottom, the left and the right side to indicate the chosen answer. To let the target appear on the screen, participants had to push the central button and rest with the finger on that button until he/she could see where the gap was. Then the button had to be released, this led to the disappearance of the target. After that the chosen answer had to be detected by pushing the appropriate one of the four direction buttons. The software recorded two different reaction times. The first one (the time in which the target was visible) was referred to as visual discrimination time, because the gap could be visually encoded. The second time comprised the motor reaction and covered the time until participants pressed the key for the gap's direction. As encoding and motor reaction times were recorded separately, it could be distinguished whether anisotropy affects the encoding process, the motor reaction, or both.

4.3. Experimental design and procedure

The study was based on a 3 (screen type) $\times$ 2 (sitting position)—experimental design with repeated measurement on both factors. Thus, the main experiment consisted of six independent conditions with 504 reactions in each of these: (1) CRT with a sitting position of 0° (central condition), (2) CRT with a sitting position of 50° (extended sitting condition), (3) LCD with a sitting position of 0°, (4) LCD with a sitting position of 50°, (5) Notebook-LCD with a sitting position of 0° and (6) Notebook-LCD with a sitting position of 50°. The order of experimental conditions was balanced via a Latin Square.

In order to avoid confounding effects from non-foveal fixation, the screen position, on which the next stimulus would appear, was indicated by a fixation cross. By this, a foveal presentation and fixation was assured for each trial.

At the beginning of the experiment visual acuity of participants was assessed. To familiarise with the experimental task, 50 training trials were completed. Then the six experimental conditions were executed. Each condition consisted of 504 reactions (63 fields $\times$ 4 gap directions $\times$ 2 repetitions = 504 trials). After each condition, a short break could be taken in which the experimenter changed the condition and prepared the experimental software and the displays for the next steps. One experimental session lasted approximately 90 min.

4.4. Apparatus and material

Near visual acuity of the participants was tested with the Titmus Vision Tester®.

In order to provide maximum control with respect to the visual quality of the displays (apart from the extent of anisotropy), all screens were connected to and driven by the notebook (Dell Inspiron 8100, with an Intel Mobile Pentium® III processor). The displays had a resolution of 1024 $\times$ 768. The CRT had a screen size of 17 in., the external LCD and the Notebook-LCD had a size of 15 in. These screen sizes are comparable, because the effective screen size of a 17 in. CRT is approximately equivalent to that of a 15 in. LCD. A chinrest was used to stabilise the viewing distance of 50 cm and to assure that the extended sitting position of 50° was kept constant throughout the experimental conditions.

4.5. Participants

Thirty participants between 20 and 33 years of age ($M = 23.83$ years, SD = 3.04 years) were tested in the present study. They were recruited from the university campus and fulfilled a course requirement. Twelve participants were male, the other 18 females. All had a normal or corrected to normal visual acuity (14/12 Snellen). Eye diseases were not reported; corrective lenses could be worn while completing the experimental task. All participants were frequent computer users with a mean frequency of

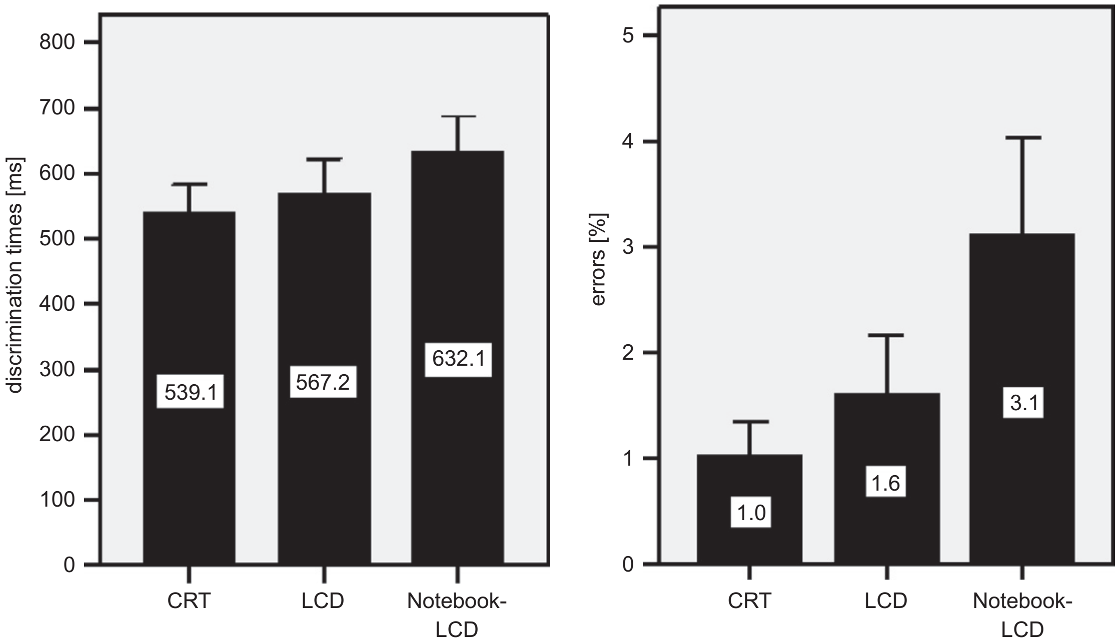

Fig. 5. Left side: mean discrimination times (ms) for CRT, LCD and Notebook-LCD. Right side: mean error rate (%) for CRT, LCD and Notebook-LCD.

usage of almost 20 h per week ($M = 19.53$ h per week, SD = 14.80). Fifty-seven percent of the participants used to work with a CRT, the others used either an LCD or both screen types in their homes and offices.

5. Results

Discrimination times and accuracy were analysed by an ANOVA for repeated measurements; Levene tests were carried out to control homogeneity of variances, and it was given for both speed and accuracy measures. The significance level was set at $p = 0.05$, the p-levels were adjusted when multiple testing was carried out. Whenever discrimination times are reported, only correct responses were taken into account.

In the following section, the main effects of screen type and viewing angle will be presented, followed by the analysis of the interaction effects.

5.1. Effects of screen type

For the discrimination times, a significant main effect of screen type was found ($F_{(2,58)} = 10.44$; $p = 0.00$). Visual discrimination was fastest when a CRT was used with a mean time of 539.13 ms (SD = 119.50). The slowest discrimination times were found for the Notebook-LCD condition with a mean time of 632.05 ms (SD = 150.98). This equals a performance decrease of 17.3%. The external LCD ranked between the CRT and the Notebook-LCD with a mean discrimination time of 567.23 ms (SD = 150.05). Post-hoc tests revealed that the discrimination time for the CRT differs significantly from the discrimination times for the Notebook-LCD ($t_{29} = -4.38$, $p = 0.00$). Also, the external LCD differed significantly from the Notebook-LCD ($t_{29} = -2.81$, $p = 0.01$). The difference between CRT and external LCD missed the significance level ($t_{29} = -1.46$, $p = 0.16$). Thus, participants needed considerably more time to detect targets on the Notebook-LCD than on the CRT and the external LCD. Fig. 5 (left side) shows the mean discrimination times for the three screen types.

When discrimination accuracy is focused, a similar picture occurs (Fig. 5, right side). Again, a significant main effect of screen type was observed ($F_{(2,28)} = 19.08$; $p = 0.00$). When a CRT was used, a mean of 4.9 errors (0.9%, SD = 3.9) occurred. When the task was completed with an LCD, error rates increased to 1.42% (SD = 6.83, this equals a mean of 7.17 errors out of the 504 reactions). Finally, when the Notebook-LCD is in use, a mean of 13 errors occurred (2.59%, SD = 11.02). Follow-up t-tests showed significant differences between CRT and LCD ($t_{29} = -2.46$, $p = 0.02$), between CRT and Notebook-LCD ($t_{29} = -4.90$, $p = 0.00$), as well as between LCD and Notebook-LCD ($t_{29} = -4.41$, $p = 0.00$). Although, there were significant effects for detection accuracy, the total amount of errors was rather small. This hints at a very accurate and careful working style of participants.

The correlation between speed and accuracy (between discrimination times and errors) did not reveal significant results ($r = 0.09$, $p = 0.62$).

5.2. Effects of viewing angle

As a first step in this section, the results of visual performance with respect to the two sitting positions 0° and 50° will be described. Here the ANOVA revealed a

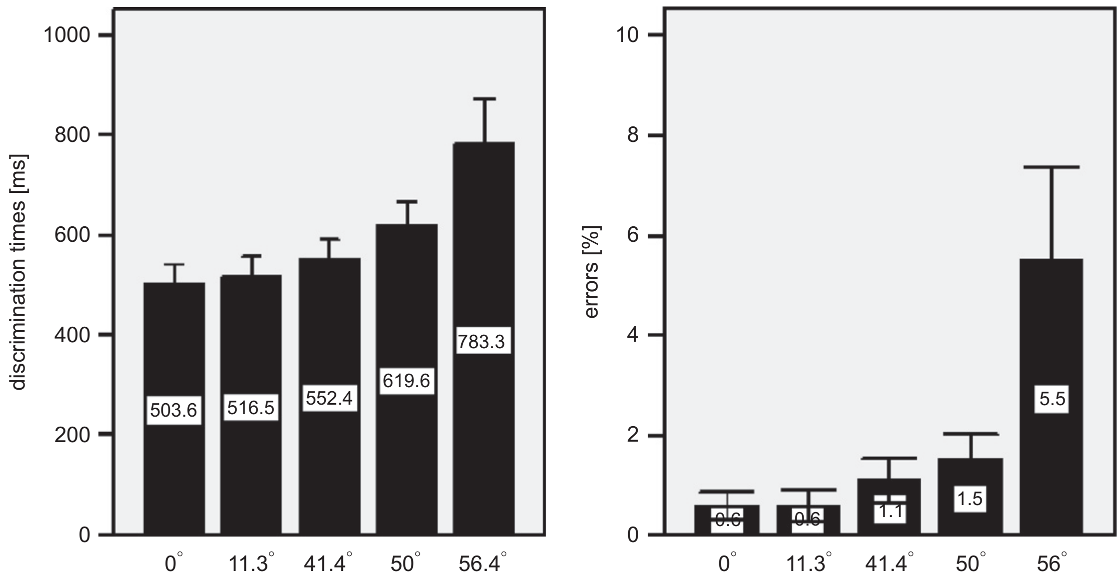

Fig. 6. Left side: Discrimination times (ms) for the five viewing angles. Right side: error rates (%) depending on the five different viewing angles.

significant effect on the speed of performance ($F_{(1,29)} = 85.48$; $p = 0.00$). The mean discrimination time for the central (0°) sitting position was 512.16 ms (SD = 107.21). In the 50°-condition (extended viewing angle), discrimination took a mean of 647.32 ms (SD = 149.80). This equals a performance decrement of 6.3%. When the errors are focused, the same picture emerges ($F_{(1,29)} = 33.86$; $p = 0.00$). More errors were made when extended viewing angles were applied. 4.13 errors (0.55%, SD = 4.07) occurred for the central conditions while 20.53 errors (2.72%, SD = 16.98) were made in the extended viewing angle condition.

As a second step, the five different viewing angles (see Section 4.1) were analysed in order to achieve a deeper insight into the performance function for different levels of anisotropy. Regarding the speed of visual discrimination, a significant main effect of viewing angle was observed ($F_{(4,116)} = 59.71$; $p = 0.00$). The discrimination times vary between 503.62 ms for the 0° viewing angle and 783.26 ms when a viewing angle of 56.4° is applied. This equals an increase of 36% (0°: $M = 503.62$ ms, SD = 102.63; 11.3°: $M = 516.54$ ms, SD = 109.72; 41.4°: $M = 552.36$, SD = 104.30; 50°: $M = 619.64$, SD = 127.72; 56.4°: $M = 783.26$, SD = 244.15). Fig. 6 (left side) depicts the outcomes for the discrimination times as a function of viewing angle. Post-hoc *t*-tests revealed that all single comparisons between the five viewing angles are significantly different from each other, as it is shown in Table 1.

The same pattern of results was received for discrimination accuracy. The ANOVA showed a significant difference between the viewing angles ($F_{(4,116)} = 28.22$; $p = 0.00$). Fig. 6 (right side) shows the results.

Post-hoc *t*-tests demonstrated significant differences between all pair-wise comparisons, apart from the comparisons between 0° and 11.3° and between 41.4° and 50° (see Table 2).

Table 1
Post-hoc comparisons between the discrimination times of the five different viewing angles

	df	*t*	*p*		df	*t*	*p*
0–11.3°	29	−6.53	0.000	11.3–50°	29	−8.92	0.000
0–41.4°	29	−6.91	0.000	11.3–56.4°	29	−8.07	0.000
0–50°	29	−10.09	0.000	41.4–50°	29	−8.78	0.000
0–56.4°	29	−8.39	0.000	41.4–56.4°	29	−7.20	0.000
11.3–41.4°	29	−4.92	0.000	50–56.4°	29	−6.09	0.000

All pairs differ significantly from each other.

Table 2
Post-hoc comparisons between the error rates of the five different viewing angles

	df	*t*	*p*		df	*t*	*p*
0–11.3°	29	0.32	0.749	11.3–50°	29	−4.65	0.000
0–41.4°	29	−2.59	0.015	11.3–56.4°	29	−5.70	0.000
0–50°	29	−4.05	0.000	41.4–50°	29	−1.71	0.099
0–56.4°	29	−5.50	0.000	41.4–56.4°	29	−5.17	0.000
11.3–41.4°	29	−2.93	0.007	50–56.4°	29	−5.40	0.000

5.3. Interaction of screen type and viewing angle

The crucial question is now whether the performance deterioration differs for the screen types when the viewing angles are considered. While it is rather probable that performance decrements in extended viewing angles are less when the CRT is used, it is also of main impact for the question here whether the Notebook-LCD performs significantly lower than the external LCD. Again, the outcomes of discrimination times are presented first and are followed by the description of the error rates.

5.3.1. Discrimination times

The ANOVA shows a significant interaction effect ($F_{(2,58)} = 18.72$; $p = 0.00$). Mean discrimination times are illustrated in Fig. 7 (left side). It becomes obvious that the negative impact of presenting large viewing angles is not equal for all screen types. Using a 50° sitting position increases the discrimination times far more when the participants work with the Notebook-LCD than when a CRT is used. Follow-up analyses proved that discrimination times did not differ significantly in the 0°-conditions ($F_{(2,58)} = 1.44$; $p = 0.25$). But the discrimination was statistically different when the 50°-conditions were focused ($F_{(2,58)} = 16.12$; $p = 0.00$). But not only the two different sitting positions are of interest here. It is also important to analyse visual performance in the five different viewing angles with respect to the different screen types. The ANOVA revealed a significant interaction effect ($F_{(8,232)} = 16.52$; $p = 0.00$). For the 0° viewing angle, performance for the three screens did not differ significantly from each other ($F_{(2,58)} = 1.42$; $p = 0.25$). Also, for the 11.3° viewing angle the screens did not differ from each other ($F_{(2,58)} = 1.41$; $p = 0.25$). Then the discrimination times for the different screens in the 41.4°-condition were analysed and a significant difference was found ($F_{(2,58)} = 9.61$; $p = 0.00$). The same was true for the 50°-condition ($F_{(2,58)} = 17.84$; $p = 0.00$) and the 56.4°-condition ($F_{(2,58)} = 17.13$; $p = 0.00$) (see Fig. 8, left side).

5.3.2. Errors

The same results were achieved for the mean percentage of discrimination errors. The ANOVA for the three screen types and two sitting positions revealed a significant interaction effect ($F_{(2,58)} = 18.04$; $p = 0.00$). As Fig. 7 (right side) shows, the discrimination errors for the 0°-conditions did not differ between the screen types ($F_{(2,58)} = 1.62$; $p = 0.21$), but they are different in the 50° sitting position ($F_{(2,58)} = 21.13$; $p = 0.00$). After that, the five different viewing angles were analysed and a significant effect was revealed (ANOVA: $F_{(8,131)} = 17.93$; $p = 0.00$). Follow-up analyses showed that discrimination errors did not differentiate between the screen types for the 0° viewing angle ($F_{(2,58)} = 3.98$; $p = 0.02$), the 11.3° viewing angle ($F_{(2,58)} = 0.30$; $p = 0.74$) and the 41.4° ($F_{(2,58)} = 1.66$; $p = 0.19$). Then the 50° viewing angle was analysed and a significant difference occurred ($F_{(2,58)} = 10.65$; $p = 0.00$), this was also the case for the 56.4°-condition ($F_{(2,58)} = 24.14$; $p = 0.00$). These results are shown in Fig. 8 (right side).

5.4. Motor reaction times

Even though it was not the central focus of the present study, motor reaction times were also considered. It was suggested that the effects of anisotropy do not affect motor reaction times, because anisotropy is assumed to influence the visual rather than the motor system. Statistical analysis showed that this assumption was not correct. As found, the screen quality and the extent of anisotropy also significantly affected motor reaction times ($F_{(2,58)} = 4.02$; $p = 0.02$). This is shown in Fig. 9. Further analyses showed the difference between the fastest motor reaction time (CRT: 157.89 ms) and the slowest motor reaction time (Notebook-LCD: 170.19 ms) to be significant ($t_{29} = -2.94$, $p = 0.01$).

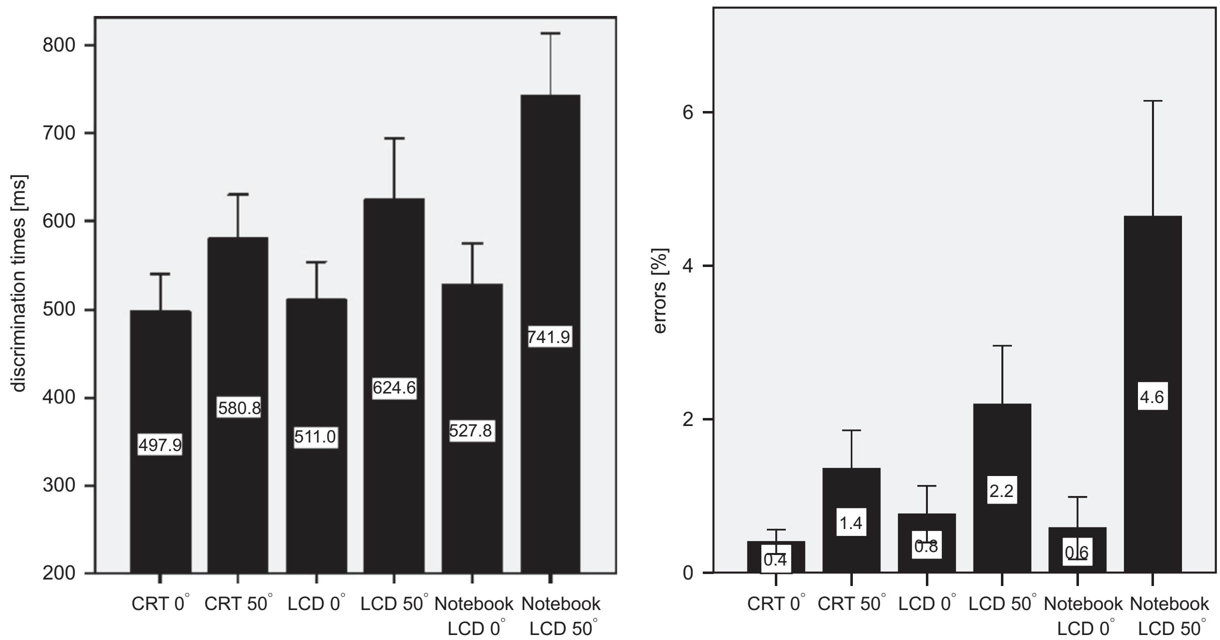

Fig. 7. Interaction between three screen types and two sitting positions for the discrimination times (ms) (left side) and errors (%) (right side).

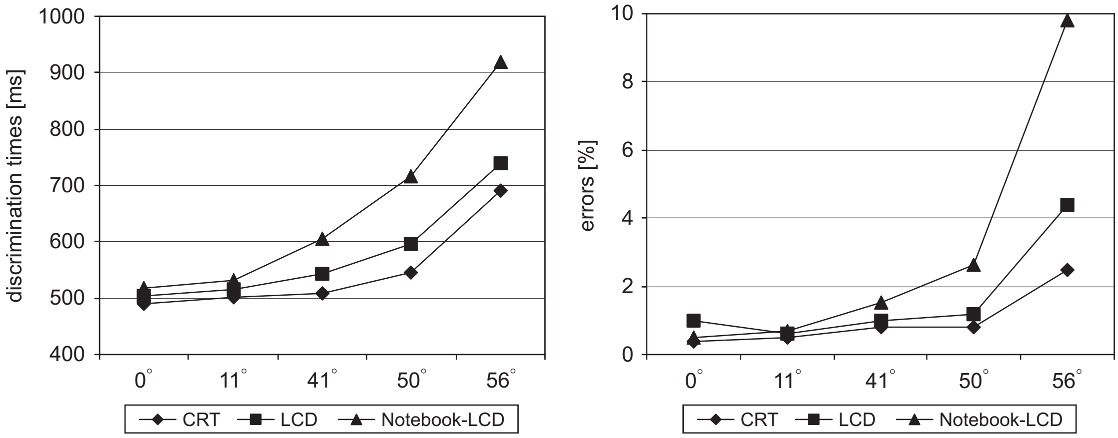

Fig. 8. Interaction effects between the three screen types and the five different viewing angles for the discrimination times (ms) (left side) and errors (%) (right side).

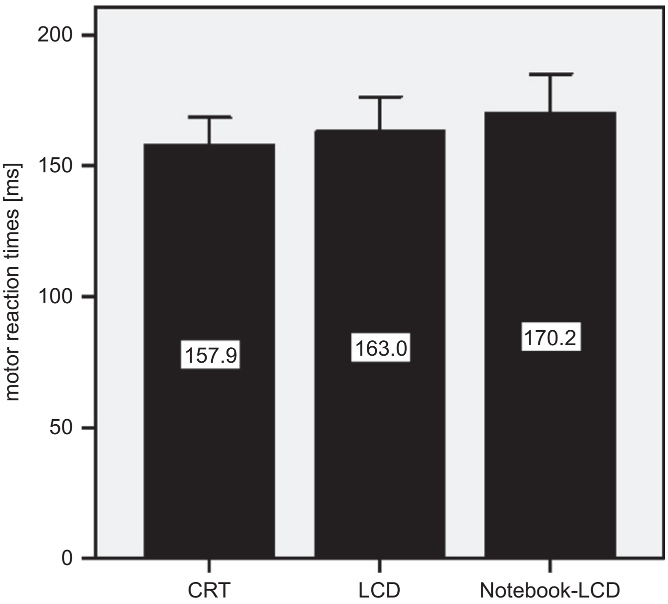

Fig. 9. Motor reaction times (ms) for the three screen types.

6. Discussion

The present study was concerned with the ergonomic evaluation of visual performance in different screen types. A CRT was compared to the increasingly upcoming LCD-technology. A special research focus was placed upon the evaluation of the visual quality of computer notebooks. Notebook-PCs are replacing the stationary desktop computer systems more and more, because of increasing demands for mobility. The study simulated real working situations where several users are viewing onto one screen or where one operator has to survey several screens at the same time. The participants of the study worked from two sitting positions (a 0° central position where the user was placed directly in front of the screen and an off-axis condition in which the user was placed 50° to either the right or the left side). Five different viewing angles were distinguished and related to performance outcomes. In the following sections, the key results will be summarised and the impact of the outcomes will be discussed with respect to ergonomic demands of visual display work settings. Also, the optimised usage of different screen types will be a topic, focusing mainly on visual aspects. Finally, an outlook to future research issues is undertaken.

In accordance with outcomes of recent studies (e.g. Gröger et al., 2003; Hollands et al., 2002; Oetjen and Ziefle, 2004, 2007; Ziefle et al., 2003), the present study corroborated anisotropy as a major shortcoming of LCD screens. Although LCDs have many advantages, one disadvantage is that luminance measures are not homogenous over the screen surface, but vary distinctly as a function of viewing angle. Physical measurements revealed the strongest fluctuation of luminance parameters for Notebook-LCDs, followed by external LCDs. The CRT technology on the other hand was not affected by anisotropy. Performance data mirror these differences although the extent of performance deterioration is smaller than the deterioration of luminance measures. Apparently, human perceptual processes are modulating or compensating suboptimal physical conditions.

When the discrimination performance of all screen positions is comprised, using the CRT led to the best performance and the Notebook-LCD to the worst. Over all screen positions, the mean difference was about 6% when CRT and external LCD were compared, and it increased to even 18% between CRT and Notebook-LCD. The strong susceptibility to off-axis viewing becomes still more evident, when only the off-axis conditions are focused. In the 56.4°-condition, the speed of visual discrimination decreased by 33% when the Notebook-LCD was compared to the traditional CRT. Nevertheless, it should be taken into account that any comparison of a Notebook-LCD and external LCDs must be "unfair" by nature, if only one dimension (visual quality) is focused. Other aspects of working contexts are also of importance in real life applications. It has to be considered that the major advantage of Notebook computers is the possibility to be mobile and to change work settings. With respect to their visual quality of screens, however, Notebook computers do not lead to the best visual performance possible. Besides these negative effects of restricted viewing angles, it should also be mentioned that for privacy reasons the effects are sometimes highly welcome (e.g. in automated teller machines (ATMs) or mobile phones).

Effects of anisotropy were found in both parameters of visual performance, speed *and* accuracy. That reveals that both performance facets are sensitive for anisotropic effects. However, it should be noted that overall error rates were rather small, and that participants adopted a very accurate working style. From a methodological point of view, the high accuracy is especially important because the results are not affected by a speed-accuracy trade-off, which could have limited the interpretation of the effects.

The procedure to record reaction times allowed the separation of two processes. The first process (reflected by discrimination times) was assumed to be mainly visual, because only in this period the target was visible. Nevertheless, it cannot be excluded completely that motor preprogramming processes are also included in the discrimination times. Anyway, at this stage encoding should be finished and the second process should indicate the pure psychomotor component. Here participants had to move the finger to one of the reaction buttons to indicate the direction of the gap. This segregation of the two reaction times could contribute to our understanding of anisotropy in LCD screens. To do so it has to be examined if anisotropic effects primarily affect the encoding system or if they also influence motor reactions. The results showed a small but significant difference between the motor reaction times for the three display types and extents of anisotropy, respectively (about 12 ms between the fastest and the slowest motor reaction time). It is unclear at this point of research if these small differences can be interpreted as visual carry-over effects. Especially as differences in visual discrimination times reached much larger amounts (up to about 430 ms). It can therefore be summarised that anisotropy mainly affects visual processing during the encoding stage (discrimination of targets). Future research will have to deal with a more precise separation of these two components.

It could critically be objected that performance decrements in the off-axis viewing conditions are predominantly caused by geometric distortion effects instead of anisotropy. This objection is based on the fact that viewing objects from an extended viewing angle leads to a smaller size than viewing them from a central position. However, this argument can be ruled out. Even when geometric distortion effects cannot be excluded completely, their relative impact should apply for all screen types likewise and can be disregarded. Moreover, the influence of geometric distortion should be equally large for all screen-type comparisons. The results showed that this is not the case. The difference of discrimination times between the 0° central viewing condition and the 56.4° off-axis viewing condition differs considerably for the three screen types. The increase equals 37% for the CRT, 43% for the external LCD and even 71% for the Notebook-LCD. Thus, we can generally assume that performance decrements in the off-axis conditions are in fact caused by anisotropy.

Anisotropic characteristics of screens and their visual evaluation had previously been addressed with visual search task types (Gröger et al. 2003; Hollands et al. 2002; Oetjen and Ziefle 2004, 2007; Yeh et al. 1999; Ziefle et al. 2003). The characteristics of this task type implicate that limitations in visual performance can be expected whenever early stages of visual processing are involved. Even though this procedure is appropriate and proves that anisotropy is a limiting factor whenever time-critical visual encoding is of interest, a cautionary note has to be taken into account. The task demand in the present study was rather simple and reflected pure visual discrimination. But it is still unknown if and to what extent anisotropy affects visual encoding and processing when cognitively more complex comparison and decision task demands are present. Such tasks are frequently necessary in traffic control contexts (air and rail environments). If, for example, an air traffic controller has to decide quickly and accurately whether two or more planes are going to collide, the task is no longer driven purely by bottom-up processes (as anisotropic effects are). This task also has a considerable cognitive component (complex comparison and decision processes and a high responsibility of the operators). It is not easy to predict how higher task complexities are modulating performance. On the one hand, the additional cognitive load present in more complex tasks could result in even stronger performance decrements. On the other hand, it is also reasonable to assume that the visual effects of anisotropy are masked by the high task complexity. In this case, task complexity would have a stronger impact on performance than visual characteristics. This should be pursued in future studies. Moreover, as it is a rather frequent task demand in real life to control several screens at the same time, future studies also have to show if performance changes when more than one screen is used simultaneously.

Another important research issue for future studies is the impact of the usage of glasses in combination with anisotropic screen effects. A first investigation should address the use of conventional corrective lenses. In addition to displays' anisotropic effects, visual performance could be further degraded when users are viewing through peripheral portions of corrective lenses or reading glasses, what might be a rather frequent viewing condition in real working contexts. Furthermore, a second experiment should focus on specific working conditions as, for example, the avionics context. To avoid anisotropic effects and to provide good visibility of the information displayed on the primary display from the other crew station across the cockpit, air crew members wear certain polarised sun glasses. Even if these kinds of glasses may help to avoid colour reversals due to anisotropy, further visual degradations could emerge from interactions between the polarised glasses with the polarisation on the LCD.

The LCDs used in the present study were equipped with TN-technology. In order to extent the knowledge of the impact of different display technologies, other techniques should also be scrutinised. Two other technologies are fairly widespread and should be mentioned here. One is the MVA (multiple vertical alignment)-type, which is predominately used for screens larger than the conventional office displays. This technology is more expensive but expected to provide wider viewing angles, even though brightness losses also have to be expected within this technology. The other technology is the IPS (in-plane-switching)-type. Due to high contrast and brightness levels, it is a promising technique for office work displays. However, here slow response times (about 35 ms) are present, the displays are still fairly expensive and therefore mainly used for professional large screen displaying (Artamonov, 2004).

A final consideration is concerned with application issues of the present research. Visual ergonomic approaches and results do not allow to recommend one screen type as finally and definitely better than the other one. This is because any technology has benefits and disadvantages. Recommendations for screen types should therefore be related to the specific task context they are to be used for. As human performance in off-axis viewing conditions were of central interest in the present study, there is a clear ranking of screen types for this kind of task demand. CRTs, although they have many negative characteristics, lead to the best visual performance. Considerable performance decrements have to be expected when LCDs are used, time-critical tasks have to be completed, the whole display surface is used to display the stimuli and/or extended viewing angles are present. The decrements are most pronounced in Notebook-LCDs, because their LCD technology is very susceptible to off-axis viewing conditions.

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