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Effects of output display and control–display gain on human performance in interactive systems

I. SCOTT MACKENZIE and STAN RIDDERSMA

Department of Computing & Information Science, University of Guelph, Guelph, Ontario, Canada N1G 2W1;
email: mac@snowhite.cis.uoguelph.ca

Abstract. Human performance comparisons on interactive systems were drawn between output displays (CRT and LCD) across settings of control–display gain. Empirical evidence was sought in light of the common feeling in the user community that motor–sensory tasks are more difficult on a system equipped with an LCD display vs. a CRT display. In a routine target acquisition task using a mouse, movement times were 34% longer and motor–sensory bandwidth was 25% less when the output display was an LCD vs. a CRT. No significant difference in error rates was found. Control–display (C–D) gain was tested as a possible confounding factor; however, no interaction effect was found. There was a significant, opposing main effect for C–D gain on movement time and error rates, illustrating the difficulty in optimizing C–D gain on the basis of movement time alone.

1. Introduction

Since the advent of the graphical user interface (GUI), commands traditionally entered using a keyboard can be executed using a mouse, cursor, and a momentary switch (button). Iconic objects are selected by pressing and releasing the mouse button after positioning the cursor over the object. Consequently, the ability to make rapid, accurate target acquisitions is important in achieving optimal user performance.

While the GUI has changed the face of software, the pace of hardware change is even faster. In general, today's hardware is smaller in form and is produced at a lower cost. These factors, and others, have led to the emergence of two dominant output display technologies: the cathode-ray tube (CRT); and the flat panel, liquid crystal display (LCD). The pros and cons of each technology in consideration of the specific application determine the appropriate choice for a particular hardware platform.

In this study, we are concerned with the costs or benefits of these two technologies as they affect human motor–sensory performance. Since the speed of the cursor on the output display is set by the sensitivity of the input control, control–display (C–D) gain was introduced as a potential confounding factor. Specifically, we ask whether the choice of display technology, in combination with a particular C–D gain setting, compromises a user's ability to make quick and accurate target selections. These were tested in a routine target selection task using movement time, error rate, and bandwidth as criterion measures. Bandwidth is a motor–sensory measure which, if calculated using the method described later, reflects both the speed and accuracy of movements. We consider this somewhat analogous to efficiency in overall human performance. The next section introduces and compares CRT and LCD technology, and identifies the relevant ergonomic issues for human-computer interaction.

2. CRT technology

The CRT image is produced by bombarding a thin layer of phosphor material with an energized beam of electrons. The beam is activated while scanning past the visible portion of the image and deactivated when scanning where there is no image. The image must undergo periodic refreshing so that it remains stable to the eye of the user. Typical rates are 30 to 70 refreshes per second. In the absence of refreshing the image would simply fade away following a screen update. However, refreshing causes flicker which, although not usually noticeable for static images, is easily detected when motion is introduced. A rapid back-and-forth action of the hand holding a mouse is sufficient to demonstrate this: the cursor jumps about on the screen in an erratic pattern.

Although this is partly due to the sampling rate of the mouse, the refresh rate of the output display also contributes.

Green phosphor (P39) is often used because it has a long decay time, or persistence, and consequently produces relatively stable images (Shneiderman 1988: 256–258). Orange–amber phosphor (P38), preferred by many users, has an even longer decay time. This permits fewer refreshes with images presented in one scan persisting to the next, thus reducing flicker (Farrell 1986). An important property of phosphor is its low bloom, which is the degree to which the glow spreads to nearby points. Low bloom allows for sharp images.

The CRT remains the dominant display technology with sales about triple those for LCD displays. This can be attributed to its low cost, multi-colour high resolution, and grey-scale capabilities. However, a CRT occupies a large space, is heavy and bulky, consumes considerable power, and is difficult to read in bright sunlight. In addition, CRTs may produce x-rays and low frequency magnetic fields that are suspected as harmful to full-time computer operators; evidence is inconclusive, however (Smith 1987).

3. LCD technology

Through LCD technology, an image is created by a varying voltage that controls the transparency of tiny capsules of liquid crystals. These voltage changes turn capsules lighter or darker when viewed by reflected light. The LCD is free of flicker but the size of its capsules limits resolution and sharpness (Stix 1989).

Liquid crystal displays are proliferating. Laptop computers, considered the first generation of truly portable computers, were the first mass produced systems to employ LCD technology. More recent technological advances have witnessed the arrival of compact and portable computing systems known as notebooks and, recently, palmtops. These computers continue to capitalize upon LCD technology.

The main benefits of a liquid crystal display are its low weight, thin profile, and low power consumption. For these reasons, LCD technology is ideally suited to portable computers and other applications where low weight, thin profile, or low power consumption are important. However, it is commonly known that the LCD is slower than the CRT, because the capsules are slow to respond to a change in voltage. Furthermore, there are limitations in the future potential of the technology. An inherent cross-talk problem exists that worsens with the number of rows of crystals. The result is that resolution can only be improved by sacrificing contrast (Depp and Howard 1993). Consequently, CRT resolution is continually a step ahead of LCD technology. Form factors of 1024×1280 pixels, available for several years on CRTs, are only recently available for LCDs (Woodward and Long 1992).

The dominant LCD technology at present employs a 'passive-matrix' of crystals, so called because the light comes from a reflector or light source acting on an array of tiny electronically-controlled shutters (Depp and Howard 1993). Much of the promise for LCD displays lies in the relatively new 'active-matrix' technology, utilizing an array of thin-film transistors to address individual crystals. The resolution and response time are much improved; however, they are expensive to manufacture.

In 1991, several companies introduced (or announced) pen-based computers. These machines, which also use LCD technology, are suited to users who find the traditional computer keyboard too awkward or confusing. Data are entered by hand-printing alphanumeric characters or writing special marks directly on the computer screen with a pen or stylus. With market growth expected to exceed 900 000 units by 1995 (Rosenblatt 1992), the performance and user acceptance of pen-based systems will depend upon how well the technology addresses the ergonomic issues discussed in the next section.

4. Ergonomic considerations

Considerable anecdotal evidence has surfaced to suggest a user's ability to rapidly manipulate a cursor with a mouse is compromised when the output technology is an LCD display compared to a CRT display. This constraint may be due to a stimulus–response lag—a detrimental time interval between an action and feedback from that action. Response lag is known to cause longer task completion times and higher error rates in interactive systems (Hoffmann 1992, MacKenzie and Ware 1993). In MacKenzie and Ware's experiment, subjects manipulated a mouse in performing a routine target selection task (similar to that described later). Lag was controlled over several settings. At 75 ms lag, for example, task completion times increased by 16% and error rates increased by 36% compared to the zero-lag condition. A similar effect may occur with LCD output displays due to their inherently slow response to signal changes.

Previous research has compared several human performance measures when reading from paper vs. CRT. In a study of regular users of CRTs (Dainoff *et al.* 1981), 45% reported symptoms of visual fatigue; while, in another experiment (Wilkinson and Robinshaw 1987), fatigue resulted in fewer pages read and more proof-reading errors missed. Comparisons of reading speed on paper versus CRT show reading from CRT as much as 41% slower than from paper (Muter and Maurutto 1991), while reading speeds were at par when character fonts were of high quality and resembled those found on paper (Gould *et al.* 1987). Reading accuracy or comprehension was also much improved with similar character fonts.

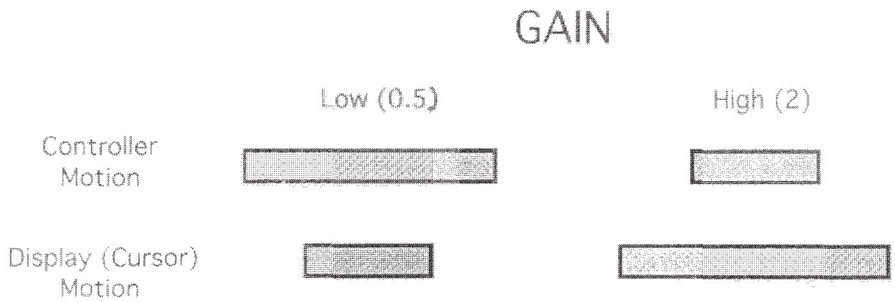

Figure 1. Control-display (C–D) gain: (*a*) under low gain a large controller movement is required for moderate cursor movement; (*b*) under high gain a slight controller movement yields significant cursor movement.

Due to the lack of flicker in LCDs, they may be the preferred technology for reading text. An empirical comparison of CRT vs. LCD reading speed has never been completed and remains to be investigated.

Another performance determinant is illumination. In an experiment considering several factors of CRT use (Stammerjohn *et al.* 1981), illumination suggested a trade-off. Proper illumination was required to read both the screen and the associated printed materials. Too much illumination made it difficult to see the CRT, while too little illumination made it difficult to see the printed materials. Glare occurs when reflected light makes the screen act as a mirror making reading difficult. This same experiment considered the distance from the user, and the height and angle of the CRT. Ninety-five per cent of users placed themselves 500 to 700 mm away from the CRT and 82% tilted the CRT at a 10 to 30° angle above eye level. The CRT technology does not unreasonably limit the user's seating position.

These human factors are all of direct relevance to LCD technology. Reading speed and accuracy, shown to depend upon font quality, resolution, illumination, and refresh rate, require that LCD resolution continue to improve. Excellent ambient lighting, required to provide enough contrast to make the display visible, may require back-lighting. This constraint is easily met, but at the expense of power consumption—obviously a problem when one considers that the market niche for LCD technology is the compact, battery-operated system. Other ergonomic issues are the screen angle and distance, which are restricted by the hinges on most portable computers, and the need in pen-based systems to combine a digitizing technology superimposed on or embedded in the LCD display. The latter introduces parallax which may further restrict display positions and readability. Goldberg and Goodisman (1991) tried to compensate for parallax by offsetting the cursor, but noted that subjects continued to have some difficulty in pointing tasks.

No empirical evidence has been presented comparing human performance on CRT and LCD technology. The present paper describes an experiment intended to compare these two technologies in a routine target acquisition task using a mouse input device.

5. Control–display gain

Since input/output movement and stimulus–response lag are central to the comparison, we felt that control–display (C–D) gain—the sensitivity of the mouse—may be a performance determinant, perhaps confounded with the display technology. C–D gain was also included as an experimental factor, therefore.

C–D gain expresses the relationship between the motion or force in a controller (e.g., a mouse) to the effected motion in a displayed object (e.g., a cursor). Low and high gain settings are illustrated in figure 1. Although a common criticism of research claiming to measure human performance on input devices is that C–D gain was not (properly) optimized, close examination reveals that the problem is tricky. Varying C–D gain evokes a trade-off between gross positioning time (getting to the vicinity of a target) and fine positioning time (the final acquisition), an effect first pointed out by Jenkins and Connor (1949). In a simplistic sense, the optimal setting is that which minimizes the combined gross and fine positioning times. However, this may be confounded with a potentially non-optimal error rate at the C–D gain setting yielding a minimal positioning time. Other factors, such as display size (independent of C–D gain setting), also bring into question of optimality of this common input device parameter (Arnault and Greenstein 1990).

The linear, or first order, C–D gain shown in figure 1 maps controller displacement to cursor (display) displacement. On many systems, the C–D gain function is non-linear or second order, mapping controller velocity to the square of cursor velocity. Examples include the Apple Macintosh mouse and Xerox Fastmouse. Figure 2 illustrates several first order (dashed lines) and second order (solid lines) C–D gains.

The second order gains are of the form,

$$V_d = k\ V_c^2 \qquad (1)$$

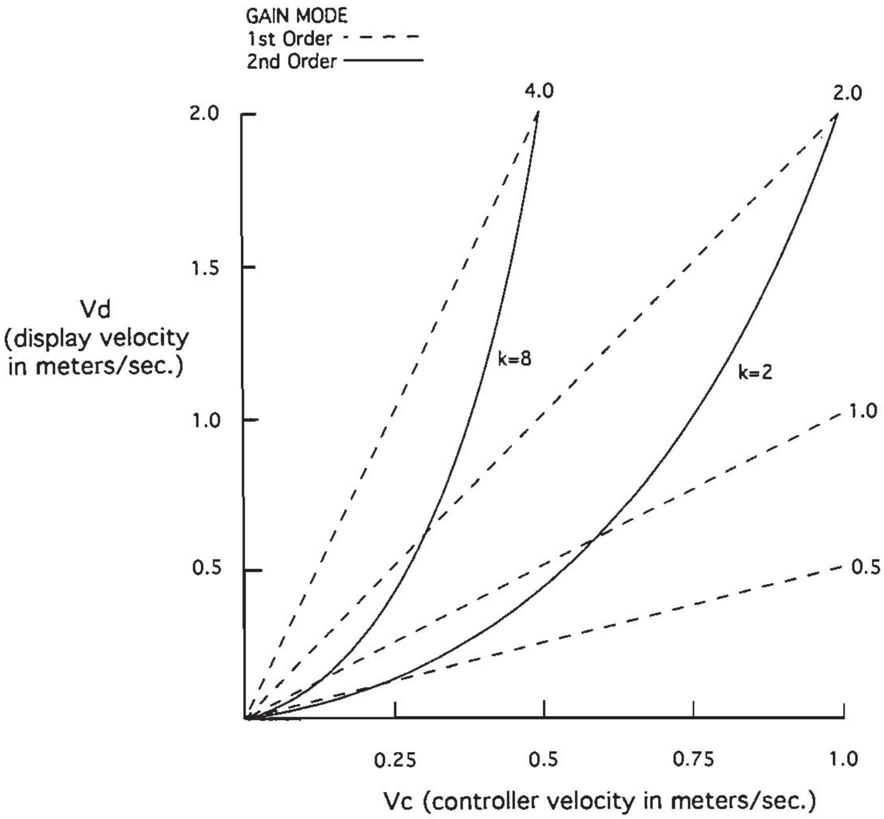

Figure 2. Linear (first order) vs. exponential (second order) mappings for C–D gain. Under exponential mapping, cursor velocity increases non-linearly by k times the square of the controller velocity.

where V_d is the display (i.e., cursor) velocity and V_c is the controller velocity. Note that the 2nd order functions cross several 1st order points as the controller velocity increases. This suggests that second order functions can be simulated using multiple first-order mappings, enabled using discrete thresholds to bump up k as the controller velocity increases. This relationship is

$$V_d = k\ V_c \tag{2}$$

where k increases by steps as V_c crosses pre-determined thresholds. The Apple Macintosh implements C–D gain this way using a table look-up method where cursor motion is a function of mouse motion in the current and previous sampling periods. The relationship cannot be described by simple displacement or velocity transfer functions. Although Apple has not published the implementation, it has been effectively reverse engineered (see Alley and Strange 1991).

Second order C–D gains have been explored as a means to boost user performance (Jackson and Roske-Hofstrand 1989, Rogers, 1970); however there is no evidence that performance is improved beyond the subjective preference of users. Jellinek and Card (1990) found no performance improvement using several second order C–D gain relationships with a mouse, and suggested the only benefit is the smaller desktop footprint afforded by a second order C–D gain. Similarly, Trankle and Deutschmann (1991) conducted a target selection experiment using a mouse with several settings of C–D gain. They found no main effect on positioning time, and noted that mouse distance moved (independent of C–D gain) is the primary determinant of task completion time.

6. Method

6.1. *Subjects*

Twelve computer users with previous mouse experience volunteered as subjects, eight from the authors' university and four from professional contacts. Subjects used their preferred hand.

6.2. *Equipment*

Tasks were performed using a Macintosh mouse on two machines, each with different display hardware. A Macintosh IIci computer provided the CRT display output technology. The display had an active viewing area of 235 mm horizontal and 176 mm vertical, with a resolution of 640 pixels horizontal and 480 pixels vertical. The centre-to-centre spacing of pixels was 0.37 mm measured on the horizontal or vertical axis. Screen images were black-and-white and were refreshed at a rate of 66.7 Hz.

A Macintosh Powerbook 100 provided the alternate output technology with a backlit, passive-matrix, black-and-white LCD display. The active viewing area was 190 mm horizontal by 120 mm vertical with a pixel resolution of 640 horizontal by 200 vertical. The centre-to-centre pixel spacing was 0.30 mm measured on the horizontal or vertical axis. The Powerbook trackball input device was not used.

Due to the smaller pixel size on the LCD display, a slightly closer viewing distance was used to keep the viewing angles constant across output displays. Subjects seated themselves comfortably in front of each system, with eye-to-display distances in the range of 600–650 mm for the CRT and 470–520 mm for the LCD.

The brightness and contrast of both displays were adjusted to nominal levels, consistent with common usage for these systems. Both Macintosh machines were running System 7.01 operating system software. The experiment software was written in C, optimized to minimize overhead (e.g., disk accesses were prevented during data collection).

6.3. *Procedure*

A routine target acquisition task was chosen. Six rectangular targets appeared on the screen, three on each side. The left and right targets were staggered vertically (see figure 3). Subjects selected targets by moving the cursor over the target and pressing and releasing the mouse button. They alternated between left and right targets moving down the screen and, upon reaching the bottom-right target, proceeded in reverse order until reaching the first target once again. Measurements began upon selecting the first target. Proceeding down and up the screen as just described constituted a block of ten trials. The 'next' target was always highlighted as an indication of where to move the cursor. A beep was heard when a selection was made outside the target. The target turned black when the mouse button was depressed inside the target. Due to the trivial nature of the task, practice effects were not deemed a major source of variation. However, a practice block of trials was administered for each condition prior to data collection.

6.4. *Design*

A 2×3 fully-within-subjects repeated measures design was used. Factors were output display (CRT & LCD) and C–D gain (low, medium, & high). C–D gain settings were the first (left), fourth, and sixth radio buttons on the Macintosh mouse control panel[1]. The targets were rectangles 32 pixels wide by 48 pixels high, separated by 256 pixels. The target separation corresponded to a viewing angle of 9° on both output displays.

The index of difficulty (*ID*) of the task was measured using Fitts' law as

$$ID = \log_2\left(\frac{A}{W} + 1\right) = \log_2\left(\frac{256}{32} + 1\right) = 3.2 \text{ bits} \qquad (3)$$

where *A* is the amplitude or distance between targets and *W* is the width of the targets (MacKenzie and Buxton 1992). Since Fitts' law tasks commonly range in difficulty from 1 to 6 bits (Fitts 1954), this corresponds to a 'medium' index of difficulty.

The output display and C–D gain factors were within-subjects—each subject performed the task at all three C–D gain settings on both displays. Prior to each new display/C–D gain combination, subjects were given a practice block. A rest was included between blocks, but subjects completed all trials on a display in a single sitting. Ordering of output displays was counter-balanced. Two sittings over two days, for a total of about two hours, were necessary to complete all conditions. During a sitting, each subject was presented with three C–D gain settings in seven sets of five blocks, distributed over the duration of the sitting. This resulted in a total of 350 trials for each display/C–D gain condition. A total of 1050 trials were collected on each display for each subject. The C–D

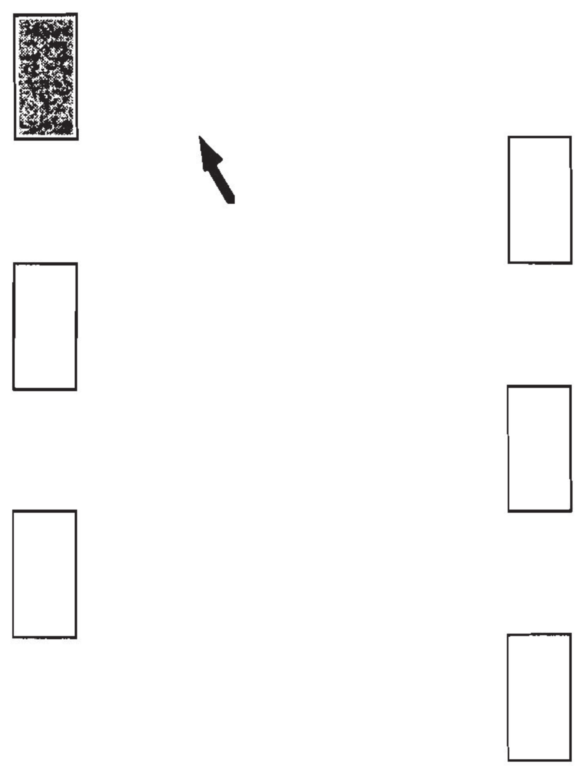

Figure 3. The experiment screen. Beginning with the highlighted target, subjects performed 10 target selections, proceeding back-and-forth down-and-up the screen, finising where they started. The target to be selected next was always highlighted in grey.

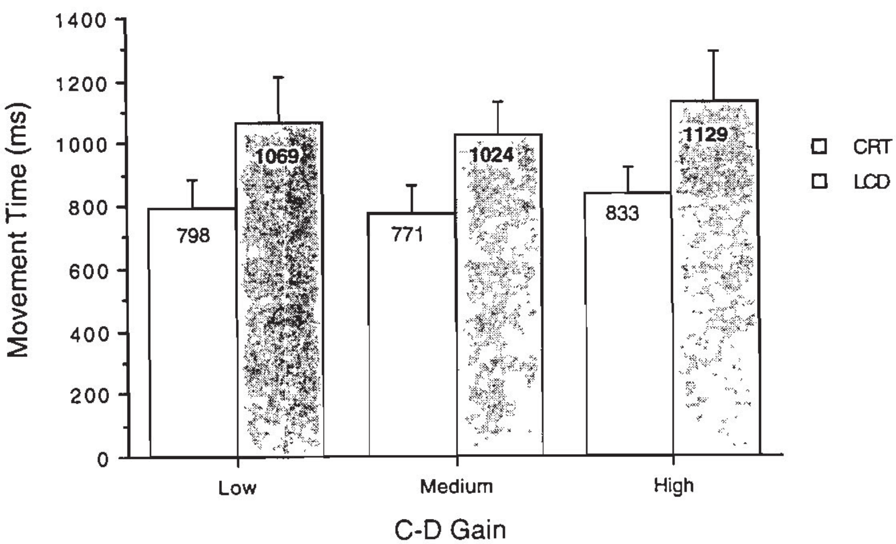

Figure 4. Mean movement times (with standard deviation bars) by output display and C–D gain.

gain setting was changed after each set by a random process without replacement over three sets.

On each button-down and button-up action, the time and *x* and *y* cursor co-ordinates were recorded. This allowed for several dependent variables to be analysed:

- Movement time: the time between successive button-down actions;
- Error rate: the percentage of trials where the button-down or button-up actions occurred outside the target;
- Bandwidth: (see below);
- Button-down time: the time between the pressing and releasing of the mouse button;
- Button-down error: pressing the mouse button outside the current target;
- Button-up error: releasing the mouse button outside of current target;
- Button down–up motion: computed using the Pythagorean identity as the distance (in pixels) between the mouse button-down and button-up actions.

If the mouse hand were held completely still between button-down and button-up actions, button down–up motion would be zero. This is a measure of stability in output motor control.

Bandwidth (BW, in bits/s) was calculated by dividing Fitts' index of difficulty, adjusted for errors (ID_e in bits), by the mean movement time (MT, in seconds) over a block of trials. Specifically, bandwidth was calculated as

$$BW = \frac{ID_e}{MT} = \frac{\log_2(A/W_e + 1)}{MT} \tag{4}$$

W_e is the effective target width, adjusted according to the spatial variability in selection co-ordinates[2]. Calculated in this manner, BW inherits both the speed (MT) and accuracy (W_e) of responses.

7. Results

7.1. *Movement time*

The mean movement times were 801 ms for the CRT and 1074 ms for the LCD, representing a 34% decline in performance for the LCD. This effect, which was statistically significant ($F_{1,11} = 107.0$, $p = < 0.0001$), is shown in figure 4 decomposed by output display and C–D gain. Movement time also differed significantly for C–D gain ($F_{2,22} = 26.01$, $p < 0.0001$). Mean movement times for low, medium, and high gains were 933, 897, and 981 ms respectively. The medium C–D gain produced the lowest movement times while the high gain produced the highest movement times. There was no significant interaction between output display and C–D gain ($F_{2,22} = 1.77$, $p > 0.05$).

7.2. *Errors*

Although error rates were higher than anticipated at 11.3% for the CRT and 10.8% for the LCD, the difference between output displays was not significant ($F_{1,11} = 0.23$). Error rates differed across C–D gain settings with means from low to high of 9.5%, 12.4%, and 11.3% respectively ($F_{2,22} = 11.80$, $p < 0.0001$). The decomposition by output display and C–D gain is graphically represented in figure 5.

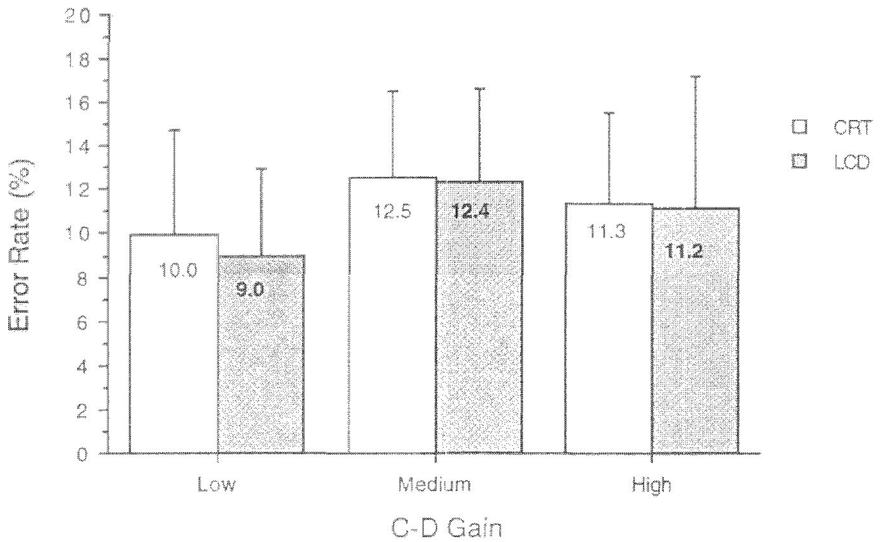

Figure 5. Error rates (with standard deviation bars) by output display and C–D gain.

Although the medium C–D gain produced the fastest movement times, it also produced the highest error rate. This result illustrates a speed–accuracy trade-off and shows that speed must be sacrificed for increased accuracy or *vice versa*. This throws into question the notion of an optimal C–D gain based solely on a movement time criterion. If a speed criterion is used, the optimal C–D gain setting is 'medium'; if an accuracy criterion is used, the optimal setting is 'low'. There was no significant interaction between display and C–D gain ($F_{2,22} = 0.28$) on error rates.

7.3. *Bandwidth*

Bandwidth is a composite measure reflecting both the speed and accuracy in responses (see equation 4). The movement time advantage for the CRT was also found on the criterion measure bandwidth, with mean rates of 3.6 bits/s and 2.7 bits/s for the CRT and LCD respectively ($F_{1,11} = 14.2$, $p < 0.0001$). This represents a performance drop of 25% for the LCD display. Although the display × gain interaction was not significant ($F_{2,22} = 0.49$), there was a significant main effect for C–D gain ($F_{2,22} = 28.11$, $p < 0.0001$). In figure 6, the CRT advantage is easily seen, as is the main effect for C–D gain where the high setting demonstrated a lower bandwidth than the medium or low settings.

The highest bandwidth was observed at the low C–D gain setting for both displays. The best error rates were also at the low C–D gain setting; so, on the basis of bandwidth, or overall efficiency in combining speed and accuracy in responses, the low C–D gain setting is the choice. This contradicts the same conclusion drawn on a movement time criterion where the medium C–D gain setting was best.

We should add that we do not consider bandwidth necessarily a superior criterion measure to movement time or error rate. The preference is highly qualitative, depending on the relative importance of speed vs. accuracy in the final application of the technology. Furthermore, the bandwidth figures cited herein were based on multiple trials at a single index of difficulty. Although the figures cited are consistent with those reported elsewhere (e.g., MacKenzie and Buxton 1992, MacKenzie and Ware 1993), a more comprehensive evaluation for bandwidth should include a range of task difficulties. The most important point, however, is simply that conclusions drawn purely on the basis of speed or movement time measurements are probably misleading, and jeopardize, at the very least, the external validity of the results.

7.4. *Other measures*

Button-down error rates were 8.1% for the CRT and 8.0% for the LCD. There was no significant main effect for output display. Button-down error rates for low, medium, and high C–D gains were 5.8%, 9.4%, and 9.1% respectively. Button-up error rates were 8.4% for the CRT and 9.2% for the LCD. There was no significant main effect for output display. Button-up error rates for low, medium, and high C–D gains were 7.5%, 9.7%, and 9.1% respectively. These results suggest that C–D gain was a more significant factor than output display, since output display error rates are much more similar. In general, button-up error rates are slightly higher, which suggests that subjects had significant button down-up motion.

Mean button-down times were 109 ms for the CRT and 118 ms for the LCD. Mean button-down times for low, medium, and high C–D gains were 110, 116, and 116 ms

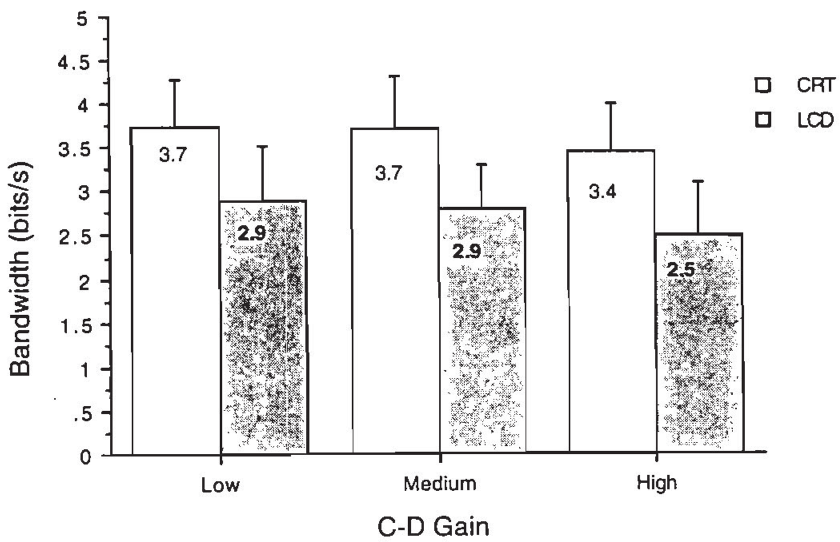

Figure 6. Bandwidths (with standard deviation bars) by output display and C–D gain.

respectively. Nothing can be concluded from the very similar mean button-down times.

Button down-up motion was 2.86 pixels for the CRT and 2.36 pixels for the LCD. Button down-up motion for low, medium, and high gains was 3.30, 2.53, and 2.01 pixels respectively. Since the button-up error rates were high and button down-up distances were relatively low, it appears subjects were hitting the targets very close to the edges.

7.5. *Ergonomic implications*

This experiment showed clear performance differences when comparing data collected from the two output displays, the CRT and LCD. Both the output display and the C–D gain of the mouse were found to be significant in portions of the results.

The experiment clearly showed that movement times were affected by the output display, with the CRT substantially out-performing the LCD on the criterion variable movement time. We feel the difference in movement times can be attributed mostly to subjects' difficulty in seeing the cursor on the LCD display. This is evident only when the cursor is set in motion, as common in icon selection and other target acquisition tasks. Several subjects strongly complained of this problem during the experiment. After particularly fast mouse movements on the LCD machine, it was not uncommon for the cursor to disappear momentarily (the 'submarine' effect). Under less abrupt motions, the outline of the cursor would blur and cursor movement would leave behind a trail of pixels (the 'comet's tail' effect). In either case, it became necessary to slow the movement, relocate the cursor, and proceed. This is consistent with MacKenzie and Ware's (1993) finding that stimulus–response lag increases task completion time. The response lag of the CRT is minimal, however, with no similar side effects apparent.

Since LCD displays are a rapidly changing technology, the findings above are somewhat tentative. The LCD display in the PowerBook 100 in our experience, is subject to considerable user frustration due the limitations described earlier. Our findings, therefore, may not generalize to all LCD displays, but only to certain 'low-end' examples. However, even the latest devices with improved LCD display panels, such as the Apple PowerBook models 145 and 160 are still known to suffer from response latency deficiencies such as the submarine effect (Martin 1992). The models 170 and 180 with active-matrix LCD panels are considered much better in their stimulus–response characteristics; so, we must exercise caution in generalizing our conclusions to other LCD technologies. The active-matrix LCD panels are complex to manufacture, however, costing several times as much to produce as passive-matrix LCD panels (Depp and Howard 1993).

Movement time was also clearly affected by C–D gain, with the medium gain yielding the lowest movement time. We did not, however, find the display × gain interaction anticipated. The higher times at the low C–D gain can be explained by the increased use of the forearm to move the cursor the longer distance required by a low C–D gain. Use of wrist action alone, observed with most subjects at the medium and high C–D gain settings, was no longer sufficient to move between targets in a reasonable time frame. This observation, combined with the non-optimal performance measured at the high gain setting, adds support to Jellinek and Card's (1990) finding that high gain settings are only advantageous due to the small desktop footprint they afford.

The longer movement times at the high C–D gain setting can be attributed to the high device sensitivity. Consequently, subjects became anxious or aggressive. On some occasions, subjects overshot the target and required additional time to reposition the cursor.

Error rates were very similar across output displays, but were significantly different across C–D gain settings in a pattern opposite to that for movement time. The lowest error rate was present during the lowest C–D gain setting. Forced to use the forearm, most subjects tended to achieve a smooth rhythm. Consequently, this 'slow but steady' approach resulted in fewer errors. The smooth rhythm was not as prevalent at the higher C–D gain settings.

8. Conclusions

Movement times were 34% higher and bandwidth was 25% lower with an LCD output display compared to a CRT display. This is the first empirical evidence of a phenomenon widely felt in the user community, but never supported experimentally. Consequently, more research and design effort are needed to improve LCD technology to support human performance levels comparable to or better than that for the CRT. These improvements will, no doubt, arrive in the near future. However, to ensure that claims advanced in glossy brochures and magazine ads are realized at the human–computer interface, thorough testing of human performance in controlled experiments should form the final verification of technological advances.

Acknowledgments

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Notes

[1]As noted earlier, the Macintosh simulates a 2nd order (velocity-to-velocity) C–D function using a table look-up scheme. We conducted informal tests to determine the 'equivalent' displacement-to-displacement mappings of mouse movement to cursor movement. We conducted multiple tests on each setting using constrained back-and-forth motion at a nominal mouse/arm velocity. The 'low', 'medium' and 'high' settings cited herein correspond roughly to C–D displacement ratios of 1 : 2, 1 : 5, and 1 : 7 respectively.

[2]W_e was calculated as 4.133 × SD where SD is the standard deviation in the Pythagorean distances between the points of selection and the target centre; see MacKenzie (1992) for a detailed discussion.

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