Lightbar Design: The Effect of Light Color, Lightbar Size and Auxiliary Indicators on Tracking and Monitoring Performance

C. S. Ima and D. D. Mann

Department of Biosystems Engineering, University of Manitoba,
Winnipeg, MB R3T 5V6, Canada
Tel: (204) 474-7149; Fax: (204) 474-7512; Email: Danny_Mann@umanitoba.ca

ABSTRACT

The purpose of this paper is to determine the effect of light color, the presence of auxiliary indicators, and lightbar size on the tracking and monitoring performance of the operator of an agricultural machine while using a lightbar as a guidance aid. Five lightbar displays varying in light color, presence of an auxiliary indicator, and lightbar size were evaluated by twenty-four volunteer test subjects. The simulation consisted of a tracking task and three choice reaction time tasks. Subjective workload ratings were completed following each driving session.

The effectiveness of the lightbar in transmitting guidance information can be improved by replacing the presently used red LEDs with blue LEDs and by increasing the size of the lightbar. A blue-colored display reduced the steering error and the reaction time by 16 and 13%, respectively, compared with a red-colored display of the same size. Similarly, a large lightbar reduced the steering error and the reaction time by 10 and 4%, respectively. Auxiliary indicators reduced steering error by 6%, but increased reaction time by 7%. These results suggest that ergonomic factors should be considered when designing a lightbar display.

Keywords: lightbar, guidance, color, indicator, size, performance

INTRODUCTION

Deviation of a farm implement from its predetermined path results in skipping (i.e., zero application) and overlapping (i.e., double application). Skips and overlaps can cause yield losses, excessive cost of crop inputs, environmental pollution, groundwater contamination, and reduced crop growth. Davis (1977) estimated the crop losses during sugar beet harvesting due to skips and overlaps to be about 13% of the total input. This loss ranked second highest out of ten factors and represents about 400 kg of beets per hectare (Davis, 1977). Palmer and Fischer (1985) reported a lateral overlap of about 10%. Hanson (1998) estimated the loss due to skipping

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and overlapping to be about 7% of the total input. Input costs are high in farming. As such, even a 7% overlap represents a significant economic loss to the farmer. Therefore, further reduction of skips and overlaps will improve the economic viability of agriculture.

To help the farmer reduce tracking error, various types of guidance systems have been developed. Although some auto-steer systems are now becoming available, the majority of these systems can be classified as guidance aids. A guidance aid provides tracking information to the operator, but steering corrections are initiated by the operator. The most common method for displaying tracking information is with the use of a horizontal array of light emitting diodes (LEDs), which illuminate according to the corrective steering action required. Such devices are known as 'lightbars' (Fig. 1).

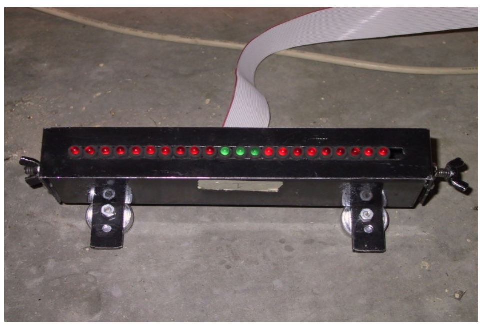
Figure 1. A lightbar with a horizontal array of 23 LEDs.

Several ergonomic factors, relating to human physiological limitations, affect the ease with which the operator can obtain the required guidance information from the lightbar. Among several others, these factors include light color, the presence of auxiliary peripheral indicators, and lightbar size. Conditions which improve the salience of the lightbar should be selected.

Some related works have been reported on light color (Ancman, 1991; Dudek and Colton, 1970), peripheral displays (Vallerie, 1968), and stimulus size (Virsu and Rovamo, 1979; Ogle, 1961) especially in the aviation industry. However, limited or no work has been done on the effects of these factors with specific application to the lightbar or the task of guiding agricultural equipment. Therefore, the purpose of this paper is to determine the effect of light color, the presence of auxiliary indicators, and lightbar size on the tracking and monitoring performance of the operator of an agricultural machine while using the lightbar as the guidance aid. Ultimately, the knowledge developed from this study can be used to produce more efficient agricultural guidance aids, which will both reduce the amount of stress the operator experiences in trying to acquire information from the systems and improve the precision of agricultural operations.

MATERIALS AND METHODS

Subjects

Twenty-four volunteers (20 male and 4 female) drawn from the population of students and staff at the University of Manitoba were recruited as test subjects. The subjects were between 18 and 50 years of age and ranged in height from 1.52 to 1.93 m. The subjects were predominantly right –handed. Thirteen of the subjects wore corrective lenses during the experiment: 10 for far-sightedness and 3 for near-sightedness. All but one subject had car-driving experience, twelve had previous tractor driving experience, and six had previously participated in experiments with the driving simulator described below.

Simulator

A tractor-driving simulator (Fig. 2) previously developed by Young (2003) was used during the experiment. The operator 'steered' the simulator in response to signals displayed on a lightbar mounted on the front windshield of the cab. Rocker switches on a joystick were used to respond to three identical monitoring displays located outside, and surrounding, the simulator (Fig. 3). Both the steering and the monitoring components were controlled by a computer program.

Figure 2. Interior view of the operator's station of the simulator showing the locations of the lightbar, steering wheel, and joystick in relation to the seat.

To simulate the field situation, these secondary displays were located a distance of 6 m from the operator's position. The center display was placed directly in front of the operator and at eye level. Monitoring this display represents the condition where the operator is required to look forward to ensure the tractor is moving towards the target. The side displays were placed rearward on either side, 15° behind a line directly to the side of the operator, and below eye level. Monitoring these two displays represents the rear-monitoring task of the operator during actual field operation. Each monitoring display was 480 mm wide, 640 mm high, and 170 mm deep, and consisted of a level bar (Fig. 4), which moved vertically away from a center position at random and on a delay sequence.

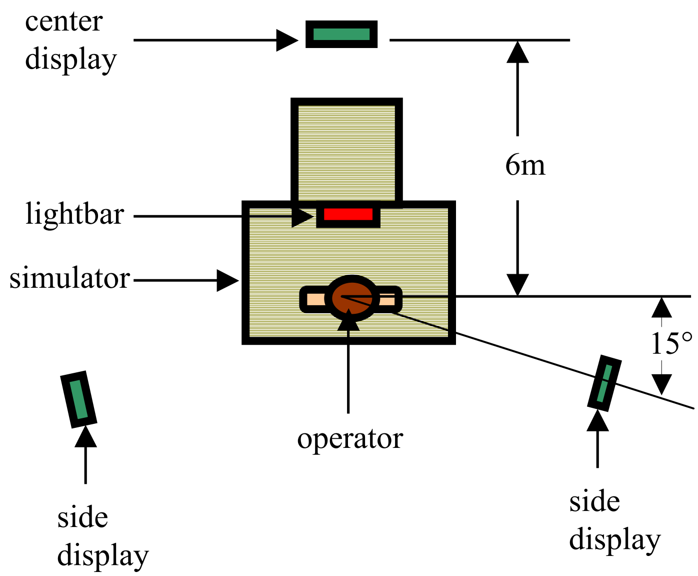

Figure 3. A schematic diagram of the simulator showing the positions of the lightbar and the monitoring displays in relation to the operator.

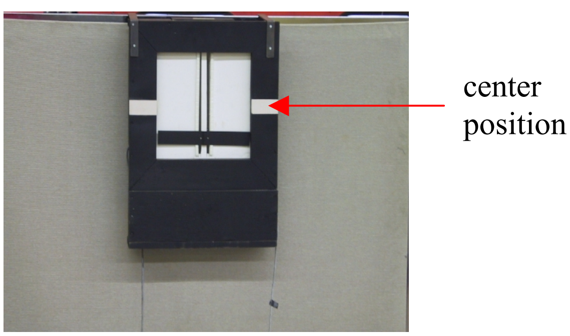

Figure 4. Monitoring display showing the condition with the level bar below the centered position. An appropriate response on the joystick is required to move the level bar back to the centered position.

Lightbar Displays

Five lightbar displays (RR, BB, BY, BY-A, and BY-L) (Table 1) were evaluated in this experiment. During the experiment, each of the displays was placed at the same spot on the front windshield of the cab corresponding to an angle of approximately 15° below eye level. This position is in agreement with the recommendation for vertical location of visual targets given by Woodson (1981). The viewing distance (i.e., distance between the driver's sitting position and the front windshield of the simulator) was kept constant at 880 mm throughout the experiment.

Display RR was 210 mm wide (180 mm between the outer extremities of the LEDs), 34 mm high, and 52 mm deep, and consisted of 23, 5 mm diameter Lumex Poly light-emitting diodes (LEDs) spaced at equal intervals; 3 green LEDs (marked G) at the center of the unit and 10 red LEDs on either side of the center (Fig. 5). Display RR is referred to as a conventional lightbar display because most commercially available lightbars consist of red and green LEDs possibly because red and green colors are primarily used for the purpose of giving dichotomous information; red for warning and green for safety. Displays BB and BY had the same dimensions and also contained the same type and number of LEDs as display RR. The only difference between the three displays was in LED color (Table 1).

Table 1 Details of the five lightbar designs tested.

Lightbar Design	Width (mm)	LED Color (# of LED units)			Type of LED unit
		left	center	right	
RR	180	red (10)	green (3)	red (10)	individual
BB	180	blue (10)	green (3)	blue (10)	individual
BY	180	blue (10)	green (3)	yellow (10)	individual
BY-A	180	blue (10)	green (3)	yellow (10)	individual*
BY-L	410	blue (4)	green (1)	yellow (4)	cluster of 24 LEDs

* Lightbar BY-A had an additional cluster of 24 blue LEDs on the left and a cluster of 24 yellow LEDs on the right.

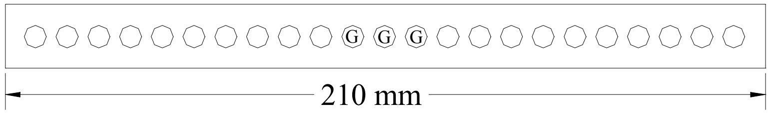

Figure 5. Representation of the lightbar used to test the effect of light color on tracking performance.

Display BY-A consisted of display BY (as the regular lightbar component) and two auxiliary indicators (Fig. 6) mounted on the left and right posts of the simulator cab during the testing at a distance of 1.20 m from the operator’s position and a visual angle of 37°. Each auxiliary indicator was 41 mm in diameter and consisted of circular clusters of 24, 5 mm diameter Lumex Poly LEDs.

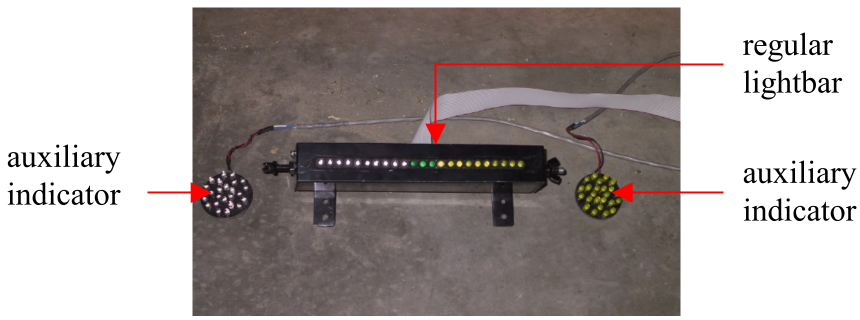

Figure 6. Display BY-A showing both the regular lightbar and the auxiliary indicators.

The auxiliary indicator on the left post of the simulator contained only blue LEDs to match with the blue-colored LEDs on the left hand side of display BY while the auxiliary indicator on the right post contained only yellow LEDs, which matched with the yellow-colored LEDs on the right side of display BY. The auxiliary indicators served as a source of additional guidance information to the operator, which should be detectable in the periphery.

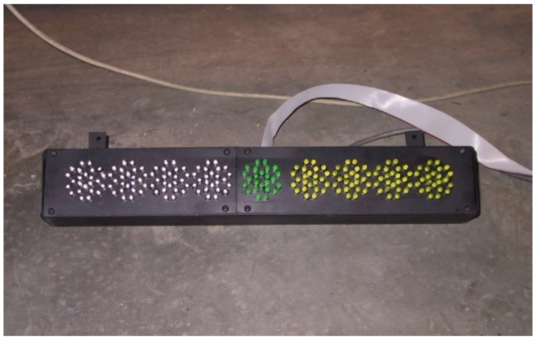

Figure 7. Display BY-L consisting of nine circular clusters of LEDs.

Display BY-L consisted of 9 circular clusters of LEDs; 4 blue clusters on the left, 4 yellow clusters on the right, and 1 green cluster at the center of the unit (Fig. 7). Each of the LED clusters was identical to the auxiliary indicators used in display BY-A. Consequently, the length of light source was approximately doubled and the height was increased by a factor of approximately eight compared with display RR.

Generally, all the lightbar displays had the same principle of operation. When the simulator was on track, the green LEDs at the center illuminated indicating that no steering correction was needed. When the simulator was off the track in either the right or left direction, a maximum of three LEDs illuminated laterally across the lightbar in the corresponding direction showing that a steering correction was needed in that direction. However, display BY-A had an additional response to the one described because of its auxiliary indicators. When a steering correction was needed in either direction, the auxiliary indicator located in that direction came on in addition to the illumination of the corresponding LEDs in its regular lightbar display component (display BY). The auxiliary indicator remained on until the simulator was back on track.

To obtain a fair comparison of the displays, the light intensity of the LEDs was measured using an L1-21O SA photometric sensor and an L1-1000 Data Logger. The light intensity of any three LEDs on displays RR, BB, and BY was found to be between 0.183 and 0.214 lx while the intensity of any three clusters of LEDs on display BY-L was found to be between 0.381 and 0.419 lx. Using a variable resistor, the light intensity of each of the auxiliary indicators in display BY-A was adjusted to match the intensity of any three LEDs in its regular lightbar component (display BY). Leibowitz et al. (1983) stated that peripheral vision operates over a large area of visual field. This implies that there could be situations where the operator could only be able to detect one auxiliary indicator. Therefore, matching the light intensity of each auxiliary indicator in display BY-A to that of any three LEDs on display BY would ensure that the operator would have the same amount of sensation when either one auxiliary indicator or three LEDs were detected. It is also necessary to mention that three LEDs were used in determining the baseline light intensity because there were always three LEDs illuminated during driving simulations at any instance.

The results obtained from the use of displays RR, BB and BY were compared for the effect of LED color on guidance performance. Similarly, the results achieved with the use of displays BY-A and BY-L were compared with that of display BY to determine the effect of auxiliary indicators and display size, respectively, on tracking and monitoring performance.

Simulation Tasks

The primary task of a tractor operator is to control the direction in which the vehicle is moving. In this experiment, subjects were required to follow, as accurately as possible, a programmed pseudo-random forcing function of the steering wheel movement generated by a sum of six sinusoids. At time intervals of 0.22 s, a computer recorded the required function movement, the subject's steering movement, the steering wheel deviation, and the index indicating which LEDs were illuminated. The computer also recorded the root mean square error (RMSE) in tracking at the end of each driving session using the values obtained for the steering deviations. The RMSE values were used to calculate the relative root mean square error (RRMSE) values, which is the primary performance measure used in this experiment. RRMSE is a ratio of the RMSE achieved by a subject to the RMSE that would have been obtained with no steering correction (Poulton, 1974).

The level bars in the secondary displays described previously moved vertically off the centered position at random. The task of the subject was to move the display bars back to their original (centered) position as soon as possible using a joystick (Fig. 8) located in the simulator cab. The time corresponding to the movement of the bar away from its centered position, the time the subject pressed the appropriate button on the joystick, and the time difference between the two times (i.e., reaction time) were recorded by the computer. At the end of each driving session, the computer also recorded the average reaction time, which was used as the secondary-task measure in this experiment. A lower reaction time indicates a better secondary-task performance.

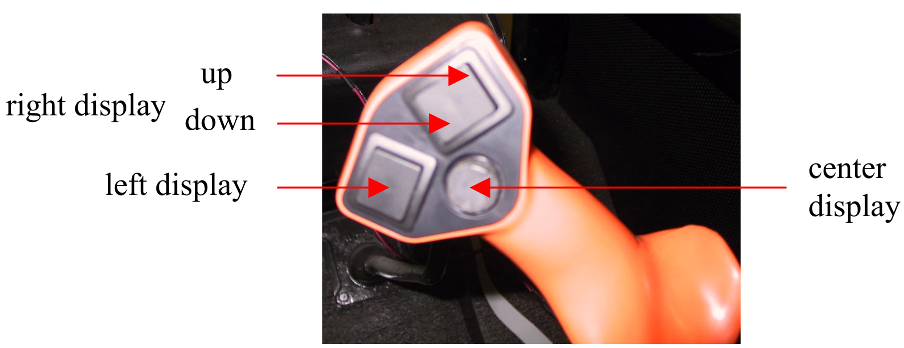

Figure 8. Joystick switches used for
controlling the monitoring displays

Subjective Measurement

The NASA-TLX (Task Load Index) (Hart and Staveland 1988) was the recording sheet used to collect subjective data. The TLX is a multidimensional scale having six subscales, which include mental demand, physical demand, temporal demand, effort, frustration, and performance. The TLX recording sheet consists of two components: a rating scale sheet and a weighting scale sheet. The information provided by a subject on both the rating and weighting scales for each task was used to obtain an overall workload assessment.

Experimental Procedure

Test subjects received a brief orientation explaining and demonstrating the basic functions and operation of the simulator, the controls, the displays, and the overall testing procedure to be followed. The subjects were instructed that the steering and the monitoring tasks were equally important. Actual testing occurred after the orientation session.

The driving sessions consisted of two test sessions, with the first being a training session. The second test session was simply a replicate of the training session and took place within 48 h (but not less than 24 h) of the training session. Each test session consisted of five driving sessions of 5-min duration each (i.e., one driving session for each of the 5 lightbar displays being tested). As stated previously, the root mean square error (RMSE) and the average reaction time were recorded during each driving session. After each driving session, the subjects completed a TLX subjective rating form, which indicated their experience of workload in that session. The subjects were also encouraged to record any other information or comments, which could be relevant in explaining the experimental results. Each test session lasted for approximately 1 h for each test subject. The lightbar displays were randomly assigned to the subjects within each test session to avoid any bias or favoritism.

Data Analysis

All data were analyzed using the analysis of variance (ANOVA) subprogram of the Statistical Analysis System (SAS 8.2) computer package. A further analysis of the results was performed using Duncan's multiple-range test for mean comparison. Error rate (α) was kept constant at 5% (0.05) throughout the analysis.

RESULTS AND DISCUSSION

Tracking Task Performance
The mean relative root mean square error (RRMSE) values for all the lightbar displays are summarized in Fig. 9. Analysis of variance performed on the steering task data showed a significant main display effect ($p < 0.0001$).

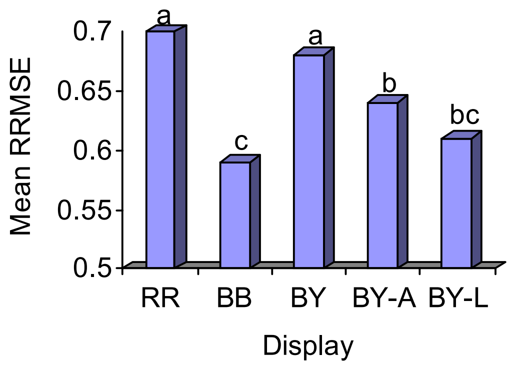

Figure 9. Tracking performance obtained with the different displays. Small letters at the top of the bars represent Duncan's multiple-means comparison results.

Monitoring Task Performance
The values of the mean reaction time for all the displays are summarized in Fig. 10. Analysis of variance showed no significant main display effect for the monitoring task ($p = 0.1021$).

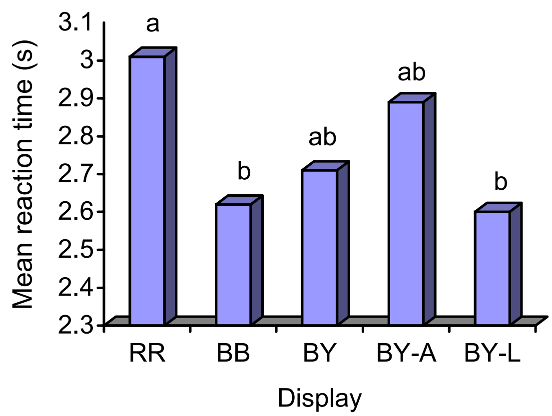

Figure 10. Monitoring performance obtained with the different displays. Small letters at the top of the bars represent Duncan's multiple-means comparison results.

Subjective Workload Rating

Analysis of variance performed on the subjective results showed significant main display effects for only mental demand and performance ratings ($p < 0.0001$, in each case). Figure 11 shows the observed relationship between the performance rating and the mental demand rating.

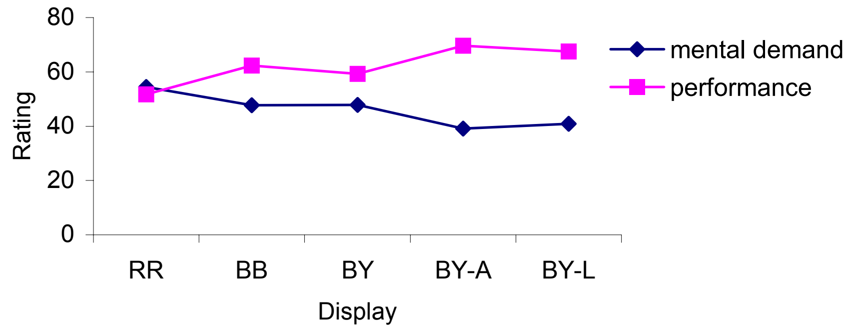

Figure 11. A graph showing the relationship between mental demand and performance scales.

Light Color

The tracking task results (Fig. 9) show that display BB (blue color) had a significantly lower steering error than display RR (red color), indicating better steering performance when display BB was used as opposed to display RR. Results obtained from both the monitoring task performance (Fig. 10) and subjective workload rating (Fig. 11) show that display BB also had a significantly better reaction time and subjective rating than display RR.

It had been hypothesized that display BY (blue-yellow color combination) would be significantly better than display RR in both the tracking and the monitoring task performance because of previous studies by Dudek and Colton (1970), which showed that both blue and yellow colors are perceived better in the periphery than red color. Contrary to this expectation, both the tracking and monitoring task results showed no significant difference between the two displays. However, display BY caused about 3% reduction in the steering error of display RR. Display BY also caused approximately 10% reduction in the reaction time achieved with display A. In addition, subjective scores (Fig. 11) showed that display BY had a significantly lower workload rating than display RR.

It is interesting to note that display BB is also significantly better than display BY. Display BB reduced the steering error of display BY by about 13%, indicating that blue color is better in tracking tasks than the blue-yellow color combination. In the monitoring task performance, display BB caused about 3% reduction in the reaction time of display BY even though the difference between them is not significant. Similarly, display BB had a lower workload rating than display BY (Fig. 11), indicating that subjects felt it was less difficult to get guidance information from display BB than from display BY.

The results on LED color obtained in this experiment are evidence that blue color is better than red in attracting the attention of subjects, and would, therefore, be better in the design of lightbars. These results support Dudek and Colton (1970) who concluded that for any given condition for background or environmental light level, blue test lights gave the best results for the greatest recognition of distance of color. The results also support Ancman (1991) who reported that blue color is the most easily detectable and the most reliable color in the periphery.

These results could be explained in terms of differences between rod and cone mediation of brightness. There are more rods in the peripheral visual field than there are cones (duplicity theory of vision) (Goldstein, 1989). Rods, which are responsible for peripheral vision, are more sensitive to short wavelength lights while cones, which are responsible for foveal vision, are more sensitive to long wavelength lights. A blue light reflects short wavelength while a red light reflects long wavelength. As such, a blue light is perceived more easily in the periphery than a red light (Moreland and Cruz, 1959). This could be the reason why display BB was significantly better than display RR in the tracking task, monitoring task, and subjective results. On the other hand, a yellow light reflects both medium and long wavelengths. Thus, a yellow light is perceived more easily in the periphery than a red light because of its medium wavelength component. However, there is still a possibility that a yellow light could be confused with a green light in the periphery since a green light reflects medium wavelength. This could explain why there was no significant difference between display BY and display RR in both the tracking and monitoring task performance.

Lightbar Size

Results of the tracking task performance (Fig. 9) showed a significantly lower steering error for display BY-L (large lightbar) when compared with display BY (smaller lightbar), indicating better steering performance with display BY-L than display BY. Also, the significantly lower subjective workload rating of display BY-L as opposed to display BY (Fig. 11) shows that test subjects preferred display BY-L to display BY. Although the monitoring task performance results showed no significant difference in reaction time between the two displays, display BY-L caused about 4% reduction in the reaction time of display BY.

Apart from the empirical results, ten of the test subjects commented that they felt more comfortable with display BY-L because it was much easier to obtain guidance information from it than all the smaller displays. This seems to imply that light stimulus from display BY-L produced much more stimulation of the retina (visual receptors) across a wider range of the visual field, thereby making information acquisition less difficult.

In general, the results discussed here indicate that increasing the physical size of the lightbar would improve guidance performance. These results agree with Virsu and Rovamo (1979) who reported that increasing stimulus size improved visual function and contrast sensitivity in the peripheral retina. The results also agree with Ogle (1961) who concluded that the threshold of visibility is lower for a large stimulus object than for a smaller stimulus object. In other words, it takes less visual energy and effort to detect light stimulus from a large object than from a smaller object 50% of the time. Moreso, Young (2003) reported that a larger display caused 11% reduction in the steering error achieved with the use of a smaller display. The result on physical size discussed here supports his conclusion too.

Auxiliary Indicators

The tracking task results (Fig. 9) showed a significantly lower steering error for display BY-A than for display BY. Unlike in the tracking task results where there was a clear distinction between displays BY-A and BY, monitoring task results showed no significant difference between the two displays. It was observed that the mean reaction time to the secondary displays was about 7% greater when display BY-A was used. However, subjective results (Fig. 11) showed a significant difference in the preference of the displays by the subjects. Subjects preferred display BY-A to display BY.

It seems that the use of display BY-A caused additional mental processing and more competition in the use of resources between the primary and secondary tasks, perhaps because of the auxiliary indicators. This assumption was confirmed by comments made by five subjects who stated that the auxiliary indicators increased the level of the workload they experienced and caused them to become more confused. The subjective rating on mental demand indicates otherwise (Fig. 11). Display BY-A had a lower mental demand rating than display BY. This discrepancy cannot be adequately explained based on our data.

The result on monitoring task performance between displays BY and BY-A is quite contrary to that expected and is similar to the result obtained by Leung (2002). It had been expected that the auxiliary indicators in display BY-A would transmit additional guidance information to the subjects, which should be easily detectable in the periphery and thereby result in a significantly lower reaction time and workload. Nevertheless, the result on steering task performance had been expected due to previous studies by Vallerie (1968) who reported that the use of peripheral displays resulted in a significant increase in tracking performance.

CONCLUSIONS

The results from this study indicate that the effectiveness of a lightbar in tracking tasks can be improved by using blue LEDs rather than the presently used red LEDs and by increasing the size of the lightbar. Even though auxiliary indicators improved steering performance, they increased reaction time considerably. Based on the data, it is not clear whether these auxiliary indicators increased or decreased the mental workload. Therefore, further research is needed before auxiliary indicators are implemented in the design of a lightbar.

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