preferred hands; the difference in the strength of the stereotype for the compatible arrangement of display and control is about 18% (from figure 7 of Chapanis and Gropper).

In summary, these two-dimensional arrangements of controls and displays show a significant effect of the location of the hand relative to the control, specifically the rotation direction of the control is modified somewhat by an expectancy to rotate the control in the direction in which the thumb points to the index finger. This is a 'natural' or more comfortable direction of rotation of the wrist or fingers. Left-handers do not show a mirror image response to that of right-handers as they are also affected by the other principles that lead to the total stereotype strength (such as Warrick's principle and the scale-side principle). The response of left-handers is however modified from that of right-handed persons by the difference in the hand/control location effect.

(b) Three-Dimensional Display-Control Relationships

Hand/control location effects can be seen in two different three-dimensional display/control arrangements:

(i) *Using left and right hands for control:* In a display/control relationship when the right hand is used to rotate a control on the right hand side of a display, the natural tendency for movement is to move in the direction that the thumb points towards. This results in a clockwise rotation when viewed perpendicular to the control knob. When the left hand is used to rotate a control on the left-hand side of a display, the same tendency exists - motion is made towards the thumb direction. This results in an anti-clockwise direction when viewed perpendicular to the control knob.

(ii) *Using the same hand with controls in different locations:* When a top and bottom control location is used with the right hand, the top location may result in a clockwise rotation and the bottom control may yield an anti-clockwise rotation when viewed perpendicular to the control knob. In this case, however, the direction of rotation that results may be dependent on the position of the control knob relative to the body of the controller and this would need to be taken into account in investigating stereotype strengths. Thus it is necessary to include this natural or preferred direction of rotation for various locations of a control relative to the body.

In both of the above cases, the resulting motions are dependent on body factors rather than the usual relationships between control rotation and resulting movement of the indicator along the scale. They are thus defined as 'Hand/Control Location' effects as they occur purely due to the design of control location relative to the body. Two examples of the use of Warrick's principle and the HCL effect are given in the following:

(i) A three-dimensional rotary control with linear display

This case is illustrated in Fig. (**4**). Engineering students commonly mention an implied linkage for this situation, as illustrated in Fig. (**5**). Again, this implied linkage is a rack and pinion mechanism connecting rotation of the knob to the linear motion of the rack (Fig. **5**).

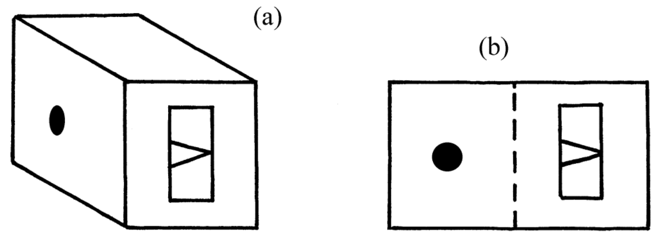


Fig. (4). (**a**) A three-dimensional display /control arrangement and (**b**) the 'unfolded' form used for analysis. This clearly shows the applicability of the Warrick principle in this case.

In the three-dimensional case of rotary controls with a linear display, the effect of the Warrick principle has been demonstrated in the data of [2]. In table 5 of that paper (page 211), data for three-dimensional control/display arrangements showed that Warrick's principle was the major contributor to the overall strength of the stereotype and the movements were reversible for decreasing scales. For scales that were on the front and top of the device and which were in the up and away directions, Warrick's principle accounted for 95% of the total stereotype strength. For scales that were on the front and top and which were in the left and right directions, it contributed 72% of the total stereotype strength.

When the control was on the right hand side of the device, Warrick's principle required a clockwise rotation of the control; when the control was on the left hand side, an anticlockwise rotation was required for the same indicator movement. Thus the left hand knob appeared to have a control reversal from the dominant clockwise rotation in order to move the indicator in the required direction. It was apparent that the W principle, being dominant, was the major factor in determining the direction of rotation of the control. In that case, subjects always used the right hand in control of the right-hand knob and the left hand when using the left-hand knob.

Two possible implied linkages are suggested for the case of a rotary control with linear display.

(a) *The 'Unfolded' control/display relationship.* Fig. (**4a**) shows a three-dimensional display/control device and (b) the same device where the system has been transformed into a two-dimensional arrangement by unfolding about the line dividing the planes of the control and the display. If the device is analysed in this form as a two-dimensional control/display relationship, it is seen that the Warrick principle is operational and that anticlockwise rotation is expected for the left-hand control and clockwise rotation for the right-hand control. This is fully in accord with the data of Hoffmann [2].

(b) *A three-dimensional linkage*. In a three-dimensional form, this 'implied linkage' may be viewed as a single shaft passing through the device, having a pinion attached to the shaft directly below the display (Fig. **5**). Attached to the indicator is a rack that meshes with the pinion. Again, this arrangement gives the anticlockwise rotation for the left-hand control and clockwise rotation for the right-hand control.

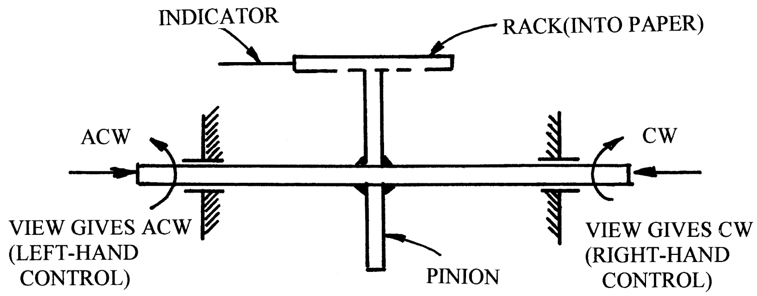


Fig. (5). A possible form of 'implied linkage' for the three-dimensional display/control arrangement shown in Fig. (**4**), when the rotary control is either on the left or right-hand side of the display (Front view).

For this display/control arrangement, the postulated HCL term, if written into an expression to determine component stereotype strengths [2] would yield a result identical to the inclusion of Warrick's principle when using the unfolded control/display arrangement. This is so, as all subjects when performing these tests used the right hand on the right-hand control and the left hand when using the left-hand control. The dominant hand movement was then in the direction pointed by the thumb to the first finger. Thus it is not possible with that data set to discriminate between these two possible explanations (HCL and Warrick) for the apparent reversal of control rotation (anticlockwise for the left hand and clockwise for the right hand).

(ii) A three-dimensional display control relationship. Rotary controls in top and bottom locations with a circular display.

Of particular interest are the recent results of Chan and Chan [11,12] who have experimentally established stereotypes for circular displays when there are controls in different planes. Here the case where there is a circular display on the front face of the device and controls located to the right and top [11] or left and bottom [12] of the device, are considered. A not-to-scale diagram of the relative location of display and controls is shown in Fig. (**6**). It should be noted that the subject groups were different in the two experiments reported in these two papers and hence there may be effects due to these different groups. The data are given in Table **1**.

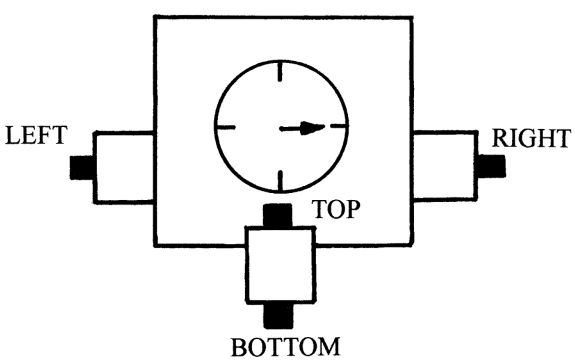


Fig. (6). Locations of the controls relative to the display in the experiments of [11,12]. Subjects sat in front of the CRT on which the circular display was presented. Top and right rotary controls are from [11]; Left and Bottom rotary controls are from [12]. Drawing is not to scale.

Table 1. Proportion of Clockwise Rotations for Instructed Clockwise Movement of the Indicator. Data of Chan and Chan [11,12]. Top, Bottom, Right-Hand and Left-Hand Refer to the Location of the Control Relative to the Display

Indicator Position (O'Clock)	Top [11]	Bottom [12]	Right-Hand [11]	Left-Hand [12]
12	.947	.474	.921	.158
3	.947	.342	.816	.158
6	.942	.237	.763	.237
9	.947	.342	.895	.316

There are several features apparent in these data:

(a) Top and right-hand controls give a strong clockwise response

(b) Bottom and left-hand controls give an anticlockwise response, which is not as strong as that for the other control locations.

(c) The differences in these columns of data suggest reinforcing or opposing effects of different principles.

These results are essentially in agreement with the data for engineering students mentioned earlier in that there appears to be a dominant form of response, which is clockwise or anticlockwise depending on the location of the control. The results are suggestive of the presence of a Warrick-type principle or one involving HCL. If it is a Warrick principle effect, the data may be biased due to the fact that engineering students were used as subjects; if an HCL effect, the data may be generalised to other subject groups.

This raises the question as to whether there is the possibility of an 'implied linkage' as found for the application of Warrick's principle in the two-dimensional and three-dimensional cases with linear scales. A possible linkage is shown in Fig. (**7**).

In this linkage, there is a single shaft passing through between the left and right-hand controls (or the top and bottom controls). This is as in the case of linear scales (Fig. **5**). Attached to the shaft is a bevel gear. This meshes with a bevel gear on the shaft carrying the indicator. In this case, an

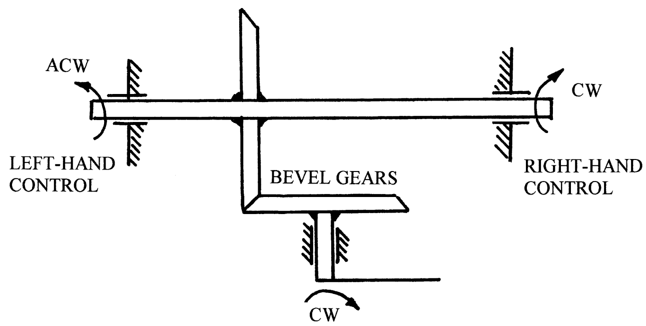


Fig. (7). A possible 'implied linkage' for the three-dimensional display/control relationship studied by Chan and Chan [11,12] with a circular display on the front face and rotary controls on the left and right-hand sides (Plan view).

anticlockwise rotation of the left-hand control produces a clockwise rotation of the indicator. Also, a clockwise rotation of the right-hand control produces the same clockwise rotation of the indicator. Similar reasoning produces the results found for the top and bottom control locations.

Thus, it appears that there may be three-dimensional equivalents to the two-dimensional case. It is therefore possible that biases are introduced into the data by testing only engineers who have a mental model of the way in which devices operate. This requires further investigation, as it is not known whether engineering subjects have any mental model of an 'implied linkage' in this more complex case. It should be noted that the data cannot be accounted for by the Clockwise-Clockwise (CC) principle suggested by Chan and Chan [11,12] as the principle does not account for the control reversal, but requires a separate set of relationships for each control location. Either of the implied Warrick linkage or the HCL effect may account for such a reversal. The case for HCL is presented in the following analysis. Here it will be seen that the Warrick effect is small and the dominant effect is that due to hand/control location effects.

The approximate locations of controls used by Chan and Chan [11,12] are illustrated in Fig. (**6**). Note that Chan and Chan [11] investigated the right and top control locations (as well as other locations) and Chan and Chan [12] reported data on the left and bottom control locations. In this analysis the 'unfolded' display/control arrangements for the top, bottom, left and right-hand controls have been used. Along with this unfolded arrangement the 'linearised' circular display (Chan, Courtney and So, [13]) is used in order to introduce the Clockwise for clockwise (CC), Scale side (SS) and Warrick (W) principles. An example of these for the 12 and 3-o'clock locations are shown in Fig. (**8**).

Expressions for the contribution of the various principles to the total stereotype strength have been developed by the method introduced by Hoffmann [2], which assumes that the effects of each of the principles are linearly additive [2]. For example, in Fig. (**8a**), in which there is a left-hand side control with the front face circular display and the indicator is at the 12-o'clock position (shown in the 'unfolded' arrangement), the scale-side principle would produce a clockwise rotation of the display along with the clockwise-for-clockwise principle. Here the HCL effect would be predicted to produce an anticlockwise rotation of the display, as on the left-hand side of the device, the 'natural' direction of rotation of the control is anticlockwise. Adding these components yields equation 1, with the further 0.5 being for the chance probability of a clockwise or anticlockwise rotation of the control [2]. The value .158 arises from the experimentally-measured total stereotype strengths given in Table **1**.

Table **2** gives the full breakdown of components of the stereotypes for each of the sixteen combinations of display position (12, 3, 6, and 9 o'clock) at each of the four control locations. As the direction of motion of the control is dependent on the grip of the knob used by the subjects, in this analysis the grip shown in Fig. (**9a**) has been assumed.

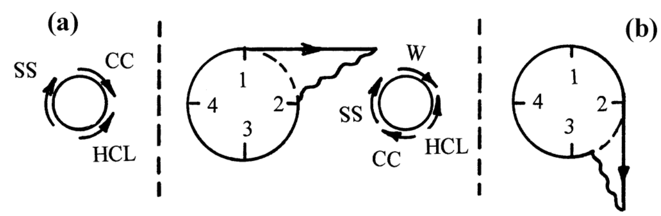


Fig. (8). The 'linearised' circular display for the unfolded left-hand control, front-face display arrangement. Arrows show the direction of control rotation predicted by the various principles and the hand/control location effect. (**a**) is for the display in the 12-o'clock position; (**b**) is for the display at the 3-o'clock position.

The equations 1 to 16 have been solved by the method of Hoffmann [2]. For example, for the case of left and right-hand controls, equations 1 to 8 can be simply added to solve for (CC+SS). Subtraction of equations 5 to 8 from equations 1 to 4 will yield a value for HCL, and so on. Note that the CC and SS components are always additive in these equations and the effects cannot be separated.

Left and Right-hand controls: Solution of equations 1 to 8 yields HCL = .316, (CC +SS) = .033 and W = -.02. This solution accounts for 74% of the stereotype. The dominant term is seen to be HCL, with, in this form of analysis, the W term being negligible. The maximum error of fit to the eight data results is .079, with an average error of .059.

Top and Bottom controls: Solution of equations 9 to 16 yields HCL = .299, (CC+SS) = .147 and W = .058. The sum of magnitudes in this case adds to .50, thus accounting for 100% of the stereotype strength. The maximum error of fit to the data is .068, with an average error of .032.

Table 2. Analysis of the Chan and Chan [11,12] Data for Stereotype Components Using the Hand/Control Location (HCL) Effect. Control Locations are as Shown in Fig. (6), Indicator Positions are Based on Clock Locations

Control Location	Indicator Position (O'Clock)	Describing Relationship	Equation Number
Left	12	-HCL +CC +SS + .5 = .158	1
	3	-HCL +CC +SS +W +.5 =. 158	2
	6	-HCL +CC+SS+.5 = .237	3
	9	-HCL +CC +SS-W +.5 =.316	4
Right	12	HCL +CC+SS +.5 =.921	5
	3	HCL+CC+SS-W +.5 =.816	6
	6	HCL+CC+SS+.5 =.763	7
	9	HCL+CC+SS+.5 =.895	8
Top	12	HCL +CC+SS-W+.5 =.947	9
	3	HCL +CC+SS+.5 =.947	10
	6	HCL+CC+SS+.5 = -.942	11
	9	HCL-CC-SS+.5 = .947	12
Bottom	12	-HCL-CC+SS-W+.5 = .474	13
	3	-HCL+CC+SSt.5 = .342	14
	6	-HCL+CC+SS-W+.5 =.237	15
	9	-HCL+CC+SS+.5 =.342	16

All cases: Here the fit to the sixteen equations gives HCL = .308, (CC+SS) = .09 and W = .019. These account for 83% of the total stereotype strength. The errors are however increased as there are differences between components of the stereotypes for the two cases of left/right and top/bottom controls (possibly due to the two different subject groups). The maximum error of fit is .173 and the mean error is .07.

DISCUSSION AND CONCLUSIONS

Much of the early research on handedness and hand used, as reviewed here, has been ignored in later literature. This is unfortunate as there are obviously features in these sets of data that show a significant effect on stereotype strength. Most of the later research has concentrated on using right-handed subjects in order to eliminate effects of handedness. All two-dimensional research has then been performed using the right hand for making control responses. It is usually only when three-dimensional arrangements are studied that the effects of handedness and hand used become strongly relevant to the researcher. In three-dimensional arrangements, it is more often necessary for the subject to use the non-preferred hand due to the location of the body relative to the controlled device.

This paper has investigated the hypothesis that there is an effect of the hand grip and the hand used on the component strengths of stereotypes for display-control relationships and, consequently, on the overall strength of the stereotype. Support for the hypothesis is found in data from two- and three-dimensional arrangements of displays and controls. In some arrangements, the HCL hypothesis produces results identical to the Warrick principle. In the most complex case investigated, the HCL effect is seen to outweigh the effects of the Warrick principle. The HCL effect is, however, more generally applicable than any of the principles affecting component strengths of stereotypes, as it is simply dependent on the hand used and grip used for moving the control knob.

The importance of the HCL *vs* Warrick effects lie in the consequences: if Warrick is dominant, there may be effects of the subject group as engineers, in particular through knowledge of mechanisms, have developed 'mental models' and 'implied linkages' that may bias the way in which they respond. Others, without this knowledge may respond quite differently. This difference is seen in the data of Hoffmann [2] for two-dimensional control-display arrangements.

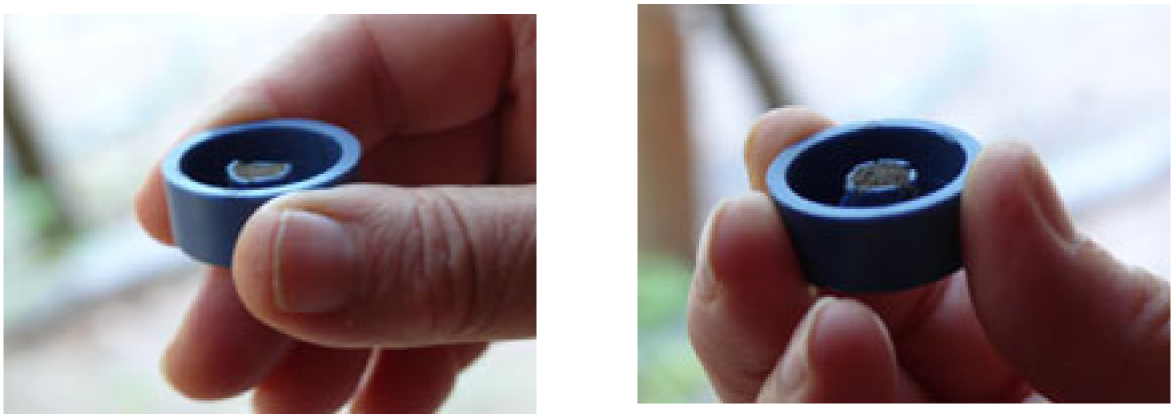
It appears from the analysis of this paper that, in the three-dimensional cases considered, the HCL effects may be dominant. In other words, the hand used and the posture of the hand in making the control action is of greater importance than the Warrick effect. The situation for the two-dimensional arrangements is quite different. Here there may be a significant effect of the HCL, but this is in competition with other principles that override the effects. When there is no display present (ie when turning a knob to increase brightness of a light) the hand-used effect is very strong.

The above analysis of the Chan and Chan [11,12] data has demonstrated two points:

(a) there is the possibility of 'implied linkages' in three-dimensional display/control relationships that may bias experimental results when engineering students are used as subjects. The research that has been reported for three-dimensional arrangements needs to be repeated with non-engineering subjects in order to see if the effects of Warrick's principle apply in those cases – and also if the HCL model may be applicable.

(b) it appears necessary to introduce a 'Hand/Control Location' effect in order to account for the data found for stereotypes in three-dimensional display/control arrangements. It is possible that these effects of hand and control location totally account for what may appear to be the Warrick components found in earlier research [2] on rotary controls with linear displays in three-dimensional arrangements.

Further experiments are required in order to separate the effects of the W and HCL in those arrangements where there is an apparent reversal of control rotation. These experiments would involve the use of the same hand when reaching to a control on the opposite side of a display or using the other hand when rotating a control that is either on the top or bottom of a display. In each case it would be necessary to record the posture of the hand in performing the control action. For example, in the case of the bottom control in Fig. (**6**), it is possible to hold the knob in two different hand postures (Fig. **9**). The more comfortable posture, requiring little wrist rotation, would be compatible with the HCL effect. The less comfortable hand posture, requiring considerable wrist rotation would not be consistent with the HCL effect used in developing the equations for component stereotype strengths. As the HCL effect postulates a 'natural'



(a) (b)

Fig. (9). Illustration of two different grips/hand postures that may be used for rotating a bottom knob as shown in Fig. (**6**). When viewed from the bottom of the knob (**a**), according to the HCL postulate, will produce an anticlockwise rotation; grip (**b**) would produce a clockwise rotation. The type of grip is likely to be dependent on the height of the knob relative to the body.

rotation towards the thumb pointing direction, the use of the left hand in the display/control arrangements used by Chan and Chan [11,12] is necessary to establish the validity of the HCL effect with top/bottom controls – and here the hand grip/posture to be used would need to be specified.

It was noted that the data from Chan and Chan was for two different subject groups. This is likely to have added some uncertainty to the number of clockwise responses for each of the control conditions. The fact that the HCL proposal comes out so strong in the analysis, even with different groups, seems to indicate that this is a valid concept.

ABBREVIATIONS

CC = The 'clockwise-for-clockwise' principle suggested by Chan and Chan [11,12] when there is a rotary control with a circular display. The expectancy with this principle is that a clockwise rotation of the control will produce a clockwise rotation of the indicator on the display

CR = The stereotype principle where a clockwise rotation of a rotary control is expected to produce a movement of the indicator to the right

HCL = The postulated physical principle developed in this paper, where there is an expectancy that a control will be rotated in a direction determined by the grasp of the control, but in a direction from the thumb to the tip of the index finger

SS = The scale-side principle of Brebner and Sandow [3]. This may be stated as the indicator will move in the direction of the side of the control that is on the same side of the knob as the scale is on the side of the display

W = Warrick's principle which states that the indicator is expected to move in the same direction as that part of the control nearest to the display

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