Movement Compatibility for Rotary Control and Digital Display

W.H. Chan and Alan H.S. Chan

***Abstract* — Using real mechanical controls, this experiment studied strength and reversibility of direction-of-motion stereotypes and response times for different configurations of digital display and rotary control. The effect of instruction of change of number direction (*I*) and control plane (*P*) on movement compatibility was analyzed with precise quantitative measures of strength and reversibility index of stereotype. A comparison between the results obtained in this experiment with that of rotary controls and circular display was made. There was similarity in the results of the two tests that both setups contain strong and reversible stereotypes. It was demonstrated that strong and significantly reversible clockwise-for-clockwise (CC) and anticlockwise-for-anticlockwise (AA) stereotypes were found with the use of circular display, and strong clockwise-for-increase (CI) and anticlockwise-for-decrease (AD) stereotypes were found with the digital display. Subjects' response times were found to be generally longer when there were no clear movement stereotypes. Nevertheless differences of results were observed in terms of variation in the stereotype strength and reversibility amongst different testing configurations in the two experiments, and the rotary control-digital display pair did not work as well as that of the rotary control-circular display pair. In the analysis of the contributions of component principles to overall stereotypes, the results were explained in terms of a number of common control operating principles. The results of this study provided significant implications for the industrial design of control panels used in man machine interfaces for improved human performance.**

***Index Terms*— movement compatibility, circular display, digital display, rotary control, stereotype reversibility**

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I. INTRODUCTION

The relationship between a control movement and its effect most expected by a population is known as a direction-of-motion stereotype, and such a relationship is said to be *compatible*. Research on control and motion relationships has been ongoing for more than fifty years. There were studies on linear indicator and translatory control [1], linear indicator and rotary control [2-3], and circular indicator and translatory control [4]. Nevertheless, no comprehensive research on movement compatibility for digital display and rotary control has been reported.

To determine whether or not any response preference or population stereotype exists, Chi-square tests are usually used to demonstrate statistical significance between proportions of different responses [5]. The majority proportion of responses (≥ 50%) for a testing condition is a measure of the strength of stereotype. A value of 50% indicates no choice preference while a value of 100% indicates a perfect stereotype.

Other than the strength of stereotype, reversibility of stereotypes is another important factor for consideration in industrial design for improved human performance. In the context of movement compatibility, reversibility is a term for describing the situation where, for example, a population that lifts a lever up to move a pointer up will also push it down to move the pointer down.

Some previous researches in movement compatibility showed that a person's expectations are not always *reversible*. In a study of operation of water taps, Hoffmann *et al.* [6] used a quantitative measure, Index of Reversibility (IR) "for measuring the likelihood that the response for closure of a tap is opposite to that used for opening the tap, independent of the expected direction of rotation of the tap for opening." So in this water tap example, the IR is evaluated from the sum of two products. One is derived from the proportion of anticlockwise responses for increasing the flow and the proportion of clockwise responses for decreasing the flow. The other product comes from the proportions of opposite pair of responses. With this formula, the index ranges from a value of zero indicating absolute non-reversibility to a value of unity for perfect reversibility, which occurs when the response to 'increasing the flow' is opposite to the response to 'decreasing the flow'. The existence of stereotype reversibility is obviously not always present but it is a very important concept when considering movement compatibility. Designers of man machine interfaces should use a stereotype with a reasonable degree of reversibility to reduce confusion and enhance efficiency and safety.

Since 80s, mechanical displays with pointers moving over printed scales have been increasingly replaced by electronic displays or solid-state devices. Digital display is frequently used in instruments nowadays due to its high precision and reliability. However, deviations from a normal operating condition are not readily detected as there are no analog indicators and mechanical movements with this type of display. The task of resetting or adjusting the monitored values may then cause difficulties in the manipulation of control devices for appropriate display settings. For pointer adjustment in a circular display, a rotary knob is usually used given the clear and direct association of circular movements of the rotary knob and pointer. The manipulation of rotary knobs in different control planes for a digital counter may present uncertainties of control movement direction amongst operators as there is no direct physical linkage associated with the rotary motion of controls and change of numerical values on the counter. The ‘clockwise for increase’ principle, originally developed in researches with different types of mechanical displays (linear, circular, semicircular, etc.), was commonly adopted in many interfaces of industrial products on which no physical movement of pointer or component exists. For example, we usually turn a rotary knob clockwise to increase the brightness, temperature, flow, sound volume, and voltage values. However, it is also noted that in many situations, reversed movement direction for increase of the values was required. With a pneumatic pressure regulator, a screw is usually turned anticlockwise for increasing pressure. For adjusting the hands of watches and clocks from say, 1 to 2 o’clock (which is perceived as an increase in value setting), usually an anticlockwise turn of the rotary knob positioned at the sagittal plane needs to be exercised. Although no detailed research had been conducted, a general review of products in the market reveals that mixed use of the clockwise-for-increase (CI) and anticlockwise-for-increase (AI) for temperature control in ovens and pressure control in pressure pumps are not uncommon. It is also interesting to note that the mixed use of CI and AI can be found in one single product that users are asked to rotate the knob clockwise to increase the master pressure and water pressure, but decrease the water coolant flow.

A rotary control-digital counter configuration is different from the rotary control-linear display that consideration of Warrick's Principle does not apply. The digital counter is also dissimilar to the circular display in which principles like clockwise-for-clockwise, anticlockwise-for-anticlockwise, clockwise-for-right, etc. can be used for accounting and predicting movement stereotypes. Although there is a growing importance of the digital display, it is surprising to find that no detailed study on this category of control-display configuration had ever been reported. The present study hence aimed at examining the similarities and differences in response preferences and response times for the rotary control-digital counter configuration and the common rotary control-circular display configuration. Detailed comparisons of results in strength and reversibility of stereotype of these two configurations were made, and the explanations for the differences found were given. For determining the contributions of component principles for movement stereotypes, if any, found in this study, the approach of model building and analysis proposed by Hoffmann [7] was adopted. It was hypothesized that due to the acquired habit in daily exposure, the clockwise-for-increase (CI) and anticlockwise-for-decrease (AD) stereotypes more commonly found in domestic and industrial products are stronger than the less common anticlockwise-for-increase (AI) and clockwise-for-decrease (CD) stereotypes. Given the benefit of the visualization of physical movement direction and the relative position of the moving pointer relative to the reference location, it was also hypothesized that the strengths of clockwise-for-clockwise (CC) and anticlockwise-for-anticlockwise (AA) in circular displays are stronger than the clockwise-for-increase (CI) and anticlockwise-for-decrease (AD) stereotypes in digital displays.

II. METHODS

A. Experimental Design

For better presentation of stimulus materials and immediate capturing of the dynamic performance of subjects, a personal computer with a Visual Basic application program was used for testing. The display was always shown directly in front of subjects in the frontal plane and a rotary control might appear in one of the four planes (Fig.1 and Fig. 2). Subjects were requested to select their choices of manipulating an anticlockwise or clockwise control movement to either increase or decrease the digital counter reading to the target value of '0010' immediately after the counter value was shown. The time between the showing of the counter and subject's moving the control was recorded as the response time. There were four control planes and two instructions of change of number, each with four different display readings (2, 4, 6, 8 for the increase instruction, and 12, 14, 16, 18 for the decrease instruction), giving altogether 32 different testing conditions, which were randomly tested and pre-arranged for all subjects who paced and initiated presentations themselves.

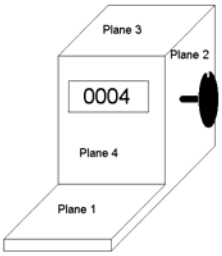
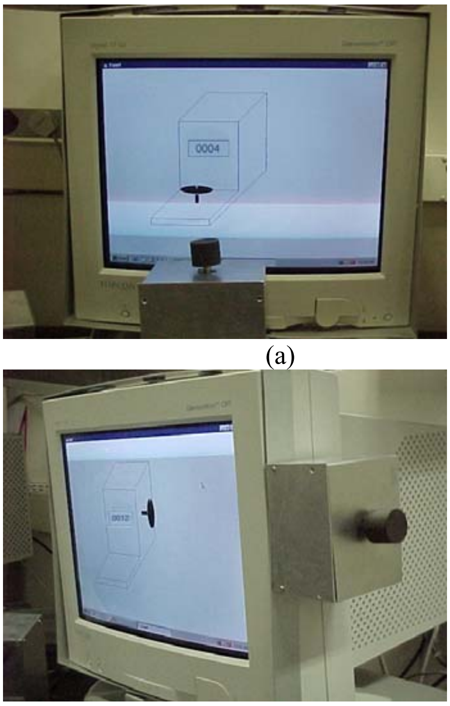


Fig. 1 A schematic diagram showing the rotary control, digital display and four control planes tested in the study.



(a)

(b)

Fig. 2 Control box mounted on different planes of the configuration in the test; for examples, plane 1 in (a) and plane 2 in (b).

B. Subjects

Thirty-eight male undergraduates of the City University of Hong Kong aged 25 and 44 (median = 36) took part in this test. They were all Hong Kong Chinese.

III. RESULTS

The frequency and percentage of responses for different testing conditions are shown in Table 1. Student's t test sowed that there was no significant difference between the total proportions of clockwise responses (50.2%) recorded and the chance probability of 50% for all testing conditions. Chi-square tests (Table 2) performed on the number of clockwise responses in the requested directions of change (increase or decrease) showed that while the plane effect (*P*) was non-significant, the instruction of the change of number effect (*I*) was significant ($p < 0.005$). The interaction of *P* x *I* was also non-significant, indicating that the instruction effect remained the same across different planes.

Table 1 Number and percentage of clockwise and anticlockwise response made for different instructions and planes in the experiment

		Instruction of Change of Number			
Plane	Response	Increase		Decrease	
		N	%	N	%
1	Clockwise	*131	86.2	*23	15.1
	Anticlockwise	*21	13.8	*129	84.9
2	Clockwise	*132	86.8	*20	13.2
	Anticlockwise	*20	13.2	*132	86.8
3	Clockwise	*130	85.5	*20	13.2
	Anticlockwise	*22	14.5	*132	86.8
4	Clockwise	*131	86.2	*23	15.1
	Anticlockwise	*21	13.8	*129	84.9
Total	Clockwise	524	86.2	86	14.1
	Anticlockwise	84	13.8	522	85.9

* significant at the 0.001 level.

Table 2 χ^2 analysis across the number of responses in the requested change

Component	d.f.	χ^2	Significance
P	3	0.07	
I	1	315.68	< 0.001
PI	3	0.43	
Total	7	316.18	< 0.001

P = Plane (1, 2, 3, 4); *I* = Instruction of change of number (increase, decrease).

A. Response Preference

The majority proportion of responses choosing clockwise or anticlockwise varied within a small range between 84.9% and 86.8% in this test. Chi-square tests across the frequencies of anticlockwise and clockwise responses for each condition were conducted for determining the significance levels of stereotypes, which were shown beside the corresponding frequency values in Table 1. As expected, strong clockwise-for-increase (CI) (range: 85.5% - 86.8%, all p's < 0.001) and strong anticlockwise-for-decrease (AD) (range: 84.9% - 86.8%, all p's < 0.001) stereotypes were found in all planes. The results suggested that the virtual movement direction in increasing and decreasing number magnitude coincides with the clockwise and anticlockwise movements of the rotary control, respectively. The findings confirmed the first hypothesis that the more commonly found clockwise-for-increase (CI) and anticlockwise-for-decrease (AD) stereotypes are stronger than the anticlockwise-for-increase (AI) and clockwise-for-decrease (CD) stereotypes.

B. *Response time*

The average response times captured by the software program ranged from 560 to 686 ms with a mean of 615 ms and a standard deviation of 32 ms. Student's *t*-test showed that the average response times for the increase and decrease instructions were statistically the same ($p > 0.05$). The regression analysis for the preferred response percentage (p) for instructions of change of number showed that the higher the preferred response percentage, the shorter the mean response time (Fig. 5.3) and the expression relating response time and preferred response performance is:

Response time (ms) =1306 – 8.04 p ($r = 0.722$, $n = 32$, $p < 0.001$)

As predicted from the equation, the mean response time ranges from 502 ms (p = 100%) to 904ms (p = 50%). The regression equation clearly showed that a substantial reduction of response time could be achieved if there is a high level of compatibility built between the rotary control and digital counter [8].

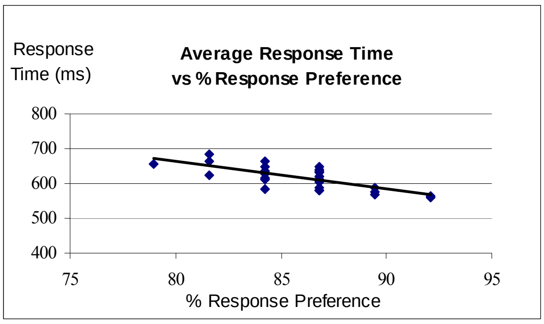


Fig. 3 Average response time vs. % response preference.

C. *Discussion*

1. *Stereotype Strength and Reversibility*

The term 'reversible stereotype' is used here to describe the situation in which a subject who turns a rotary control clockwise to increase the display value will also turn the control anticlockwise to decrease the display value to the target value. The index of reversibility, IR was so evaluated based on the sum of two products. One product was derived from the proportion of clockwise-for-increase (CI) and anticlockwise-for-decrease (AD) responses, and the other came from the proportion of the opposite pair of anticlockwise-for-increase (AI) and clockwise-for-decrease (CD) responses. Mathematically, the form is expressed as follows:

$$IR = p(CI) \times p(AD) + p(CD) \times p(AI)$$

Significant CI and AD stereotypes were found in all planes, and the strongest ones found in Plane 2 for CI (86.8%) and Plane 2 and 3 (86.8%) for AD. The mean IRs were at high levels of 0.752, 0.771, 0.762 and 0.752 in planes 1, 2, 3, and 4, respectively and the overall average IR for the rotary control-digital counter configuration was 0.759.

Table 3 shows a comparison of the mean stereotype strengths (SSs) and indexes of reversibility (IRs) obtained with the rotary control-digital display in this study and that with the rotary control-circular display reported in [9]. The mean SS for the circular study was the arithmetic mean of the CC and AA stereotypes; while the mean SS for the digital counter was the arithmetic mean of CI and AD stereotypes. Except in plane 2, the mean SSs and IRs of the CI and AD stereotypes are weaker than those of CC and AA, indicating the higher compatibility of circular displays over digital counters in working with a rotary control. The results might suggest that the compatible mapping of clockwise motion patterns of the pointer and rotary controls led to better results than the situation of associating the comparatively vague concept of increase or decrease with rotary control motion, though the CI and AD stereotypes are commonly seen in our daily life.

The weaker strength for the rotary control in the sagittal plane (plane 2) of the circular display configuration can be explained by the fact that as the rotary control was 90° offset from subjects' line of sight and the frontal plane of the display, the associated mechanical pointer movement (left or right) in the circular display was also 90° offset from the control, which then inevitably led to degradation of the subject performance. For the digital display, as there was no mechanical pointer movement involved, the problem of offset between control and pointer movements did not exist, and hence non significant plane effect was found.

In the circular display study, it was recommended that the pointer should always be positioned at 12 o'clock for check reading or resetting purpose for ensuring a compatible person-machine design. The specific results obtained at pointer position 1 hence warranted further examination for demonstrating a more representative comparison of the pragmatic design condition between the two configurations.

Table 3 also shows a comparison of mean stereotype strengths (SSs) and indexes of reversibility (IRs) obtained from the two tests when only the results of pointer position 1 only were taken into consideration. It shows that the mean SSs and IRs for the rotary control-circular display pair are much stronger than that of the rotary control-digital display pair in all planes when the pointer was positioned at 12 o'clock, further confirming the superiority of the circular display over the digital counter in working with the rotary control.

Table 3 A comparison of the mean stereotype strengths (SSs) and indexes of reversibility (IRs) on different planes for rotary control-circular display [9] and rotary control-digital display configurations

	DISPLAY	PLANE			
		1	2	3	4
Mean SS	Circular (a)	0.924	0.836	0.918	0.934
	Circular (b)	0.921	0.908	0.934	0.974
	Digital	0.856	0.868	0.862	0.856
Mean IR	Circular (a)	0.860	0.725	0.849	0.877
	Circular (b)	0.855	0.832	0.877	0.949
	Digital	0.752	0.771	0.762	0.752

Circular (a) - values for all pointer positions
Circular (b) - values for pointer position 1 only.

Table 4 A comparison of the contribution of component principles for rotary control-digital counters and rotary control-circular displays [9]

	COMPONENT PRINCIPLE	STRENGTH	COMPONENT PRINCIPLE	STRENGTH
Circular Display	CC	0.411	AA	0.395
Digital Display	CI	0.362	AD	0.359

2. Contribution of Component Principles

Unlike the situation in the rotary control-circular display configuration [9], which involves the components of clockwise-for-clockwise (CC) and clockwise-to-right (CR) for the clockwise response, and the components of anticlockwise-for-anticlockwise (AA) and anticlockwise-to-left (AL) for the anticlockwise response, the only components demonstrated in the digital counter setting are clockwise-for-increase (CI) for the clockwise response and the anticlockwise-for-decrease (AD) for the anticlockwise response. In the analysis of the contribution of component principles, it was assumed that the linear sum of the strengths of the various principles gave the proportions of clockwise (or anticlockwise) responses, and the magnitudes of the strengths of the principles sum up to 0.5. In this study, the measured proportion of clockwise responses p_c can then be expressed as $p_c = \text{CI} + 0.5$.

Based on the response proportions shown in Table 1, the average value for CI was 0.362 which is found weaker than CC (0.411) in [9] (Table 4). Similarly, for the anticlockwise response, the average value for AD was 0.359, which is again found weaker than AA (0.395). These results confirmed the second hypothesis stated earlier that the CI and AD stereotypes are weaker than the CC and AA stereotypes.

D. Summary and Conclusion

In summary, the results showed that the CI and AD stereotypes were generally strong in the rotary control-digital display test. The mixed use of clockwise-for-increase and anticlockwise-for-increase in a product or across different products as illustrated in the Introduction section should be discouraged. However, considering the mean stereotype strengths and indexes of reversibility, the compatibility of rotary control-digital display is comparatively lower than that of rotary control-circular display configuration. The findings suggested that the circular display is a better partner than the digital counter in working with rotary control for simple tasks of generally increasing and decreasing display values. However, it is interesting to note that if the rotary control needs to be installed in the sagittal plane, a digital display is a better alternative than a circular one positioned on the frontal plane. The negative correlation coefficients obtained from the average response time and the average proportion of majority response showed that subjects in general needed to do less mental work in compatible settings where dominant preferences of movement directions were evidenced [8]. The results provided important design implications for the seemingly simple rotary control-digital counter configuration which had been neglected by many researchers.

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