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The spatial arrangement of stove hotplates and associated controls and linkages has been of concern to ergonomists. In this study, two different approaches were used to determine preferred arrangements. In the first, one group of participants were given locations of controls and asked to place hotplates; a second group was given hotplate locations and asked to place controls. In each case, linkages were to be indicated. In the second approach, drawings of stove layouts with controls and linkages were given. Scales of preference of control/hotplate layouts were established. Arrangements having high spatial congruence between hotplate and controls were nominated and most preferred by participants in the first approach. In the second approach, it was found possible to discriminate between arrangements that had high spatial congruence and high compatibility between hotplate and control and, hence, to determine 'best' designs in terms of participant preferences.

Statement of Relevance: Most research on stove layout has been with hotplates in a square arrangement. Two different approaches to design show the importance of spatial congruence between hotplate and control for obtaining preferred designs having high compatibility, which are superior from an ergonomics viewpoint.

Keywords: compatibility; control/hotplate arrangements; expectancies; stove layout

1. Introduction

The four-burner stove problem is an outstanding issue in ergonomic design. The typical problem that has been studied is shown in Figure 1, where the controls are in the vertical plane as illustrated or on the same plane as the hotplates. Most of the reported research has concentrated on the layout shown in Figure 1, attempting to determine an optimum layout for the hotplates and controls with a linkage that produces a strong stereotype for control. Very little research has been reported on the more ergonomic approach, in which control/hotplate layouts are evaluated that have a more direct spatial congruence than the hotplates and controls of Figure 1 (Chapanis and Lindenbaum 1959, Shinar and Acton 1978, Payne 1995, Wu 1997, Tlauka 2004, Yu and Chan 2004)

The problem of uncertainty of the relationship (linkages) between controls and hotplates of a four-burner stove was, at least partially, solved as far back as the early work of Chapanis and Lindenbaum (1959), where it was shown that, by slightly displacing the burner locations, the arrangement gave a strong spatial relationship between hotplates and controls and there were strong stereotypes in the mappings of controls to hotplates. There are, of course, other arrangements that will also give these strong mappings – it is up to manufacturers to use them in their products! It is strange that research has continued on the poor arrangements of Figure 1, rather than concentrating on development of better designs.

There is a long history of studies of the four-burner stove control/display arrangement, such as those of Chapanis and Lindenbaum (1959), Shinar and Acton (1978), Payne (1995), Wu (1997) and Tlauka (2004). The more recent studies have looked specifically at the differences that occur in measures of compatibility when using paper and pencil tests and tests using hardware. There have been differences found in the arrangements of hotplates and controls that people consider the best (amongst the poor designs) and those with which they actually perform best. 'Best' here means that they made fewer errors or had a shorter reaction time in using the device. The research has been summarised in Hoffmann (2009).

Wu (1997) has reported a comparison of the results of various forms of test, in particular the effect of labelling the hotplates and controls in various ways. He compared his own data, that of Shinar and Acton (1978) and Hsu and Peng (1993), showing that the linkages expected between controls and hotplates are dependent on the way in which the controls or hotplates are labelled (Table 1).

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Excellent research that has not been acknowledged in the ergonomic literature is that of Fisher and Levin (1989), this lack of referencing possibly being due to the relatively obscure place of publication. They studied the standard four-burner layout, but without restriction on the particular linkages between hotplate and control. Participants could indicate any linkage they thought preferable between the control and hotplate. This is different to most other experiments, where not all possibilities were available to the participants. The interesting outcome of this procedure was that about one-third of participants had linkages that crossed the midline of the stove. There were also some 'unique' linkages that were inconsistent, in that one control was linked to more than one hotplate. With this experimental method, the preferred arrangement was the same as that of Wu (1997) using hardware, but different to that obtained by others, being BACD, corresponding to the controls 1, 2, 3 and 4, in the notation of Figure 1 (Note that Figure 1 has notation different to that of Fisher and Levin). In total, 36.7% of participants preferred this arrangement compared with 16.7% for the 'best' arrangement (ABDC). Ray and Ray (1979) found that 35.7% preferred the ABDC arrangement compared with 25% for the BACD arrangement.

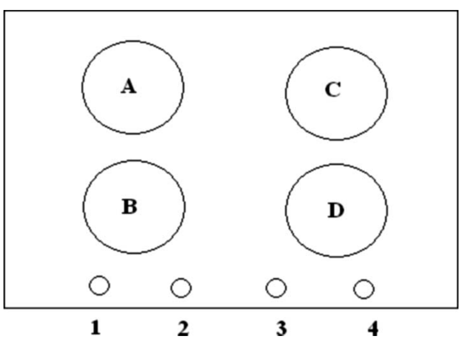


Figure 1. Arrangement of hotplates and controls used in studies by Chapanis and Lindenbaum (1959), Wu (1997), Payne (1995), Shinar and Acton (1978) and Tlauka (2004).

With four hotplates and four controls, there are 24 possible linkages between hotplates and controls. Only four of these do not have crossover of a vertical midline between the sets of hotplates. In neither of these preferred linkages of Ray and Ray (1979) or Fisher and Levin (1989) is there any crossover of the control linkages over the midline of the stove. In both cases, the linkages are mirror images about the stove midline. Ray and Ray (1979) found the outer controls to be linked to the rear hotplates; Fisher and Levin (1989) found these to be linked to the inner two controls. Thus, many experiments show that a strong stereotype is obtained with mirror symmetry about the stove midline. A similar technique was used by Wu (1997), who, in a hardware test found the best linkage to be BACD. This was the case for evaluation based on both reaction time and error rate. Here the linkages are in agreement with those of Fisher and Levin (1989). A third major pattern of linkages is that found by Hsu and Peng (1993) and the paper and pencil tests of Wu (1997). Here, there is an identical pattern to the left and right of the stove centreline with the first and third controls operating the rear burners.

Relevant to this work is the comparison of paper and pencil tests of Wu (1997) and Shinar and Acton (1978), with reaction time and error rate data on hardware of Chapanis and Lindenbaum (1959) and of Ray and Ray (1979) and the computer simulation of Hsu and Peng (1993). A summary of data for the various tests is given in Table 1. It is seen that there are effects of population tested, the coding used on the layout and also differences between tests using paper/pencil, computer simulation and hardware. The differences between the paper/pencil tests and

Table 1. Summary of various tests of the stereotypes for four-burner stoves, comparing pencil and paper tests with hardware tests for USA, Chinese and South African populations.

Authors	Population	Test Type	Coding	Measure	Best arrangement
Chapanis and Lindenbaum (1959)	USA	Hardware	–	Reaction time	ABDC
Shinar and Acton (1978)	USA	Paper/pencil	Alpha	Stereotype	ABDC
Ray and Ray (1979)	USA	Hardware	–	Errors	ABDC
Hsu and Peng (1993)	Chinese	Paper/pencil	Alpha	Stereotype	ABCD
Hsu and Peng (1993)	Chinese	Paper/pencil	Symbols	Stereotype	ABCD
Hsu and Peng (1993)	Chinese	Computer simulation	–	Reaction time, errors	ABCD
Wu (1997)	Chinese	Paper/pencil	Alpha	Stereotype	ABCD
Wu (1997)	Chinese	Paper/pencil	Symbols	Stereotype	ABCD
Wu (1997)	Chinese	Hardware	–	Reaction time, errors	BACD
Fisher and Levin (1989)	South African	Hardware	–	Stereotype	BACD

Note: The 'best' arrangements refer to the stove hotplate layout corresponding to the controls 1, 2, 3 and 4 shown in Figure 1. The 'Alpha' coding corresponds to the labelling of the hotplates in Figure 1; 'Symbols' means non-alphabetic labels.

hardware tests, for the same population, indicate that pencil/paper tests do not necessarily give a true measure of subject's performance.

1.1. Using laterally displaced hotplates and sensor lines

The problem with the 'standard' four-burner stove (Figure 1) lies in the spatial relationship between the controls and the hotplates. If there was spatial congruence (or geometrical similarity) of hotplates and controls (i.e. in the same spatial pattern), the problems occurring in the above are unlikely to exist and paper and pencil tests are likely to give results similar to those with hardware. An example of this is in arrangement (item 13B) of hotplates and controls in Tlauka (2004). In that case, the hotplates were displaced sideways in such a way that the controls were directly below the corresponding hotplates and on a line across the front of the stove. With this arrangement, 88% and 92% of participants (studies 1 and 2 of Tlauka) gave the 'correct' response relating the controls to the hotplates with the paper/pencil test. The 'correct' response in this case was that from the reaction time data of Chapanis and Lindenbaum (1959). Thus, spatial congruence is an extremely important factor in determining stereotype strength.

Osborne and Ellingstad (1987) used reaction time and errors to compare layouts of four stoves, one having displaced hotplates, one a standard arrangement and two others using either partial or complete sensor lines, showing the linkages between controls and hotplates. In all arrangements the linkages between hotplates and controls was identical. The results showed the displaced hotplates to be superior in both reaction time and errors, followed by the case with full sensor lines, partial sensor lines and, finally, the case of a standard layout.

Chapanis and Yoblick (2001) placed 'sensor lines' painted on the stove top to indicate the linkage between control and hotplate. The results were mixed; sensor lines improved performance (reaction time and errors) with the 'compatible' panels and decreased performance with the 'incompatible' panels. It should be added that the array of hotplates used was the standard square design, which does not have high compatibility with any control arrangement.

Stephens *et al*. (2006) compared usability judgements of three forms of hotplate/control arrangements with young and older adults. The forms used were displaced hotplates as in Chapanis and Lindenbaum (1959), sensor lines showing linkages between hotplates and controls and also a standard square arrangement of hotplates. Their data were averaged over three other tasks and, hence, results for stoves cannot be extracted. There was, however, a better performance of older (ages 65–75 years) participants compared to younger (ages 18–22 years) in selecting the 'best' designs.

1.2. Improved spatial relationships

Part of the solution to better compatibility is that of displaced hotplates, as mentioned above. A second approach is to design the location of the controls to mimic the layout of the hotplates. This method has been mentioned by Bridger (2003, p. 389) and is used on some commercially available stoves. As far as the authors are aware, no research has been reported on this case, but it is expected that stereotype strength would be high, reaction times low and error rate low.

The aim of the present work was to again investigate compatibility between controls and hotplates of four-burner stoves, but using two experimental techniques not previously used in the literature:

(1) On a model stove present participants with control layouts and obtain their preferred hotplate layouts and linkages. This is to be followed by participants being given hotplate layouts and them being asked to give their preferred control layouts and linkages.
(2) Participants to be shown a set of hotplate and control layouts with corresponding linkages and obtain their preferences for particular arrangements.

2. Experiment 1

2.1. Method

Rather than people being given various arrangements of linkages to evaluate (in terms of preferences, reaction times and expectancy of linkages), participants were asked what arrangement they would like to have between controls and hotplates. This is an inverse approach in that it is completely user-centred and thus is more in line with human factors methods. As far as the present authors know, this approach has never been attempted for stovetop design – at least there is no published research of this type. The method used was:

(1) Part 1 – Participants were shown four controls in different locations on the stove top. Five different control layouts were presented to participants. This was done on a half-size model of a stove top. Participants were asked to suggest the best arrangement of hotplates and their associated linkages so that the relationships between controls and hotplates

are clear to them. The control arrangements are shown in Figure 2.

(2) Part 2 – Participants were shown a set of hotplate layouts. In this part of experiment 1, five different hotplate layouts were presented to participants. Their task was to locate the controls on the top surface of the stove and show the linkages for the four hotplates. The hotplate arrangements are shown in Figure 3.

2.1.1. Hardware

A half-size model of a stove top was constructed of dimensions 350 mm × 250 mm. The top surface was painted white. Scaled to the size of the stove top were hotplates (95 mm diameter) and controls (30 mm diameter), which were painted black. The hotplates and controls were easily placed at the required locations on the stove top.

2.1.2. Design of experiment

Two different groups of participants took part in the experiment. One group performed the tests where only control locations were given; the other where only hotplate locations were given. A different random order of presentation of the sets of hotplates or controls was used for each participant. Participants were not given any indication of what might be a best design.

2.1.3. Participants

In each part of experiment 1, there were 50 subjects distributed uniformly over five age groups (15–

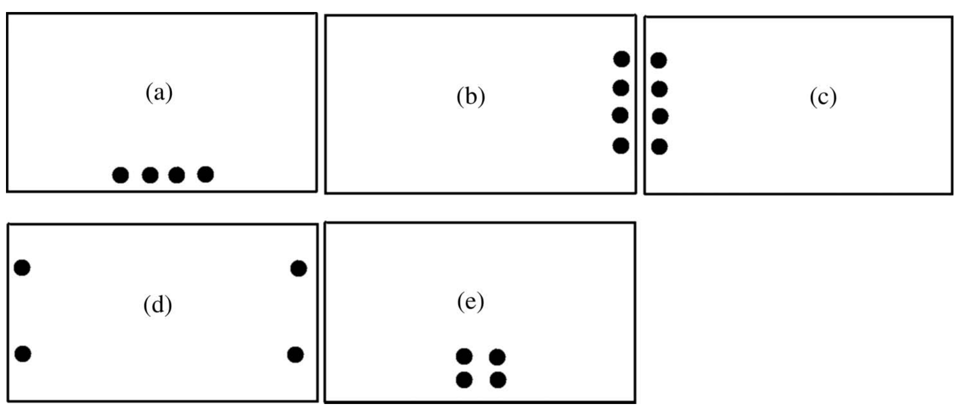


Figure 2. The five control arrangements used in part 1 of experiment 1. These were presented to participants on a half-size model of a stove top.

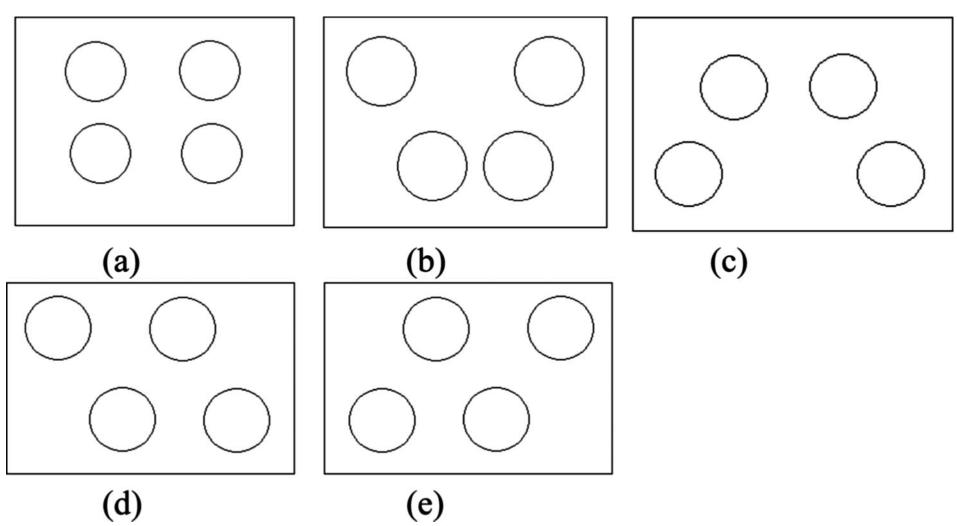


Figure 3. The five hotplate arrangements used in part 2 of experiment 1. These were presented to participants on a half-size model of a stove top.

25;26–35; 36–45; 46–55; 56–65 years). Of the 10 subjects within each age group, five were male and five female. All participants were right-handed, as determined by the Edinburgh Handedness Test. All were residents of the Hong Kong Special Administrative Region. Few of the participants would have been familiar with the form of stove top used in these experiments as most used stoves with one or two hotplates and a small proportion with three hotplates. None was familiar with use of a four hotplate stove. Occupation of the younger age group was generally 'student', whereas the other groups all had a wide range of occupation – clerks, accountants, nurses, shop assistant, housewife, engineer and so on. The median number of stove uses each week was in the one to five group. Because of the simplicity of the stoves they commonly used (one or two hotplates), most participants expressed a high level of certainty about the linkages of control to hotplate for their stove. Participants took part under the ethical guidelines of the City University of Hong Kong.

2.1.4. *Instructions to participants (given in Cantonese)*

(1) Control locations only shown. 'I am going to show you a model of a stove top that will have four burners (or electric hotplates). Only the control knob locations are shown on the model. I want you to think about where you would want to place the hotplates so that it would be most convenient for a person to remember which controls are connected to which hotplates. When you have thought about this, place the hotplates where you think they should be and indicate to me which control is connected to which hotplate. In doing this arrangement, consider safety of the user so that he/she is not bending over hot cooking in order to operate controls'.

(2) Hot-plates only shown. 'I am going to show you a model of a stove top that has four burners (or electric hotplates). I want you to think about where you would want to place the controls for the hotplates so that it would be most convenient for a person to remember which controls are connected to which hotplates. When you have thought about this, place the controls where you think they should be and indicate to me which control is connected to which hotplate. In doing this arrangement, consider safety of the user so that he/she is not bending over hot cooking in order to operate controls'.

2.1.5. *Procedure*

Response sheets were drawn up for use by the experimenter to record locations of hotplates (controls) and the associated linkages. As there were likely to be a number of fairly standard arrangements suggested by participants, particularly if they are familiar with the stove they use at their home, there may be some bias introduced into the data. Codes in this case may be verbal signs or a picture showing the layout. In recording data, the codes of Figure 1 were used (note that neither the hotplates nor controls were labelled).

2.2. *Results*

2.2.1. *Part 1: control locations only shown*

In line with the notation shown in Figure 1, the hotplates are labelled as A, B, C and D and controls labelled 1, 2, 3 and 4. Controls increase from 1 to 4 in the direction of left to right; top to bottom and, when in the same grid arrangement as hotplates, they are labelled sequentially down on the left followed by down on the right. The results are given in these terms for the arrangements of hotplates and the linkages indicated by participants. Participants used a number of the hotplate arrangements shown in Figure 3 and these will be used to indicate the arrangement percentages and the resultant linkages. Of the 17 different responses listed in Table 2, 13 could be expressed in terms of the control/hotplate arrangements shown in Figures 2 and 3. For example, the combination Ac indicates the control arrangement 'A' in Figure 2 combined with the hotplate layout 'c' in Figure 3.

Results for control locations shown are given in Table 2 for cases where there were more than two of the 50 participants giving the control/hotplate/linkage arrangement. Other responses were either two or one for a given arrangement and are not included here.

(1) With the four controls linearly arranged at the front of the stove (arrangement A of Figure 2), six different arrangements were given by participants. Only four of these had more than two respondents for a given arrangement and these are shown in Table 2. In order to satisfy the criteria given to participants (safety of use, convenience and ease of remembering), 90% of the responses had displaced hotplates (not in a square arrangement), so that there was good spatial correspondence between the

Table 2. Results of experiment 1 with control only locations presented

Control arrangement (Figure 2)	Nominated hotplate arrangement (Figure 3)	Percentage response	Nominated linkage	Comment on special arrangements of hotplates
A	c	42	BACD	
A	b	40	ABDC	
A	d	8	ABCD	
A	a	6	ABDC	
B	a	34	ACBD	
B	–	24	ACBD	RHS hotplate displaced down
B	a	18	ACDB	
B	–	12	CADB	LHS hotplate Displaced down
C	–	26	ACBD	RHS displaced down
C	a	20	ACBD	
C	a	14	CABD	
C	a	14	CADB	
C	–	12	CADB	RHS Displaced up
C	–	6	ACDB	LHS wider spaced vertically
D	a	100	ABCD	
E	a	68	ABCD	
E	c	32	ABCD	

RHS = right-hand side; LHS = left-hand side.
Note: Responses are for hotplate locations and associated linkages. Results for hotplate arrangements for which there were two or fewer responses are not included.

hotplate and control, along with clear linkages between these. Only in one case (6% of responses) was there an arrangement that is commonly found in commercially available stoves.

(2) Controls linearly arranged on the right-hand side (arrangement B of Figure 2). Altogether, 10 arrangements were suggested by participants. Of these, only four had more than two of the same response (Table 2). Two arrangements had the hotplates in quadrature and had 34% and 18% of the total responses. The remaining two arrangements used displaced hotplates with 24% and 12% of the total responses. The two arrangements in quadrature used the two commonly found linkages between controls and hotplates; those with displaced hotplates used linkages that had good spatial correspondence between control and hotplate.

(3) Two controls located each side of stove (arrangement D of Figure 2). Here 100% of participants placed hotplates next to the relevant control.

(4) Controls located in a square arrangement at centre-front of stovetop (arrangement E of Figure 2). Only two different arrangements of hotplate were nominated (Table 2). In both cases, there was strong spatial congruence between control and hotplate and the linkages were to the spatially similar locations.

(5) Controls on the left-hand side of the stovetop (arrangement C of Figure 2). Nine different arrangements were nominated, six of which had more than two responses. Three of these six used a square arrangement of hotplates, the others displaced hotplates in various ways (Table 2). Compared with other control arrangements, the percentages of nominated hotplate arrangements were generally lower than for other arrangements (26, 20, 14, 14, 12 and 6%).

2.2.2. *Part 1: discussion*

Participants in this part of the experiment, although naïve, were able to use the concept of spatial congruence to design a stovetop so that the relationship between controls and hotplates was clear. The best arrangements of controls and hotplates, when the controls are on the front of the stove, are those with displaced hotplates (90%). This pattern is not so clear when the controls are on the left or right of the stove, apart from when they are placed two on the left and two on the right with a vertical arrangement (100%). With a square arrangement of controls placed at the front-centre location, 100% of the responses were given to a hotplate arrangement that was geometrically similar to the control layout. Spatial congruence is apparently the factor most important in determining a 'good' arrangement of control/hotplate/linkage.

The best four control/hotplate/linkage arrangements nominated in this part of the experiment are shown in Figure 4. All of these have high spatial congruence. When the four controls are at the front of the stove, the non-square arrangements of the hotplates account for 84% of the subject responses. For the square arrangement of controls, 100% of responses are with the hotplates in a square or offset pattern. This design may, however, have some practical difficulties due to the necessity of using the left hand for control of the left-hand knobs.

There were 250 responses for the controls-given case. Of these, there were only two responses that had linkages that crossed the line of symmetry (or mirror symmetry) of the hotplate arrangement. Thus, for a case where the controls were horizontally arranged at the front of the stove, the two left-hand controls actuated the left-hand pair of hotplates and vice versa. Similarly, with a vertical arrangement of controls, the two top controls actuated the two top hotplates and vice versa. Thus, this appears to be an important principle for design.

2.2.3. *Part 2: hotplate locations only shown*

The data for this case are more complex than those for the case of control-location shown. Participants nominated many more possible arrangements of control location for the given hotplate arrangements. As these were a different subject group to that used previously, there was no bias introduced between parts of the experiment. The results are given in Table 3 for responses having more than two from the 50 participants. The results were only rarely described as combinations of controls/hotplates shown in Figures 2 and 3. Of the 15 nominated cases listed in Table 3, only four had a combination of these two layouts such as 'aE'. Many non-standard arrangements were suggested by participants.

The two different methods of component presentation elicited many different responses from participants. For example, when control locations were presented at the two sides of the stove (Figure 2d), 100% of the participants located the hotplates directly next to the control. When only the hotplates were presented (Figure 3a), two participants (4%) nominated this location for the controls. The hotplate/control/linkage configurations nominated most commonly are shown in Figure 5. Again, participants located controls where there was high spatial congruence with the hotplates.

Of the 250 responses when hotplates only were presented, only a single response had control linkages that crossed the line of symmetry of the hotplates; thus, again showing the importance of this principle in design. This is different to the results of Fisher and Levin (1989), who found that about 30% of responses crossed the stove centreline when the hotplates were in quadrature. The elimination of this problem may be due to the higher levels of spatial congruence of the control/hotplate arrangements nominated by participants in this experiment.

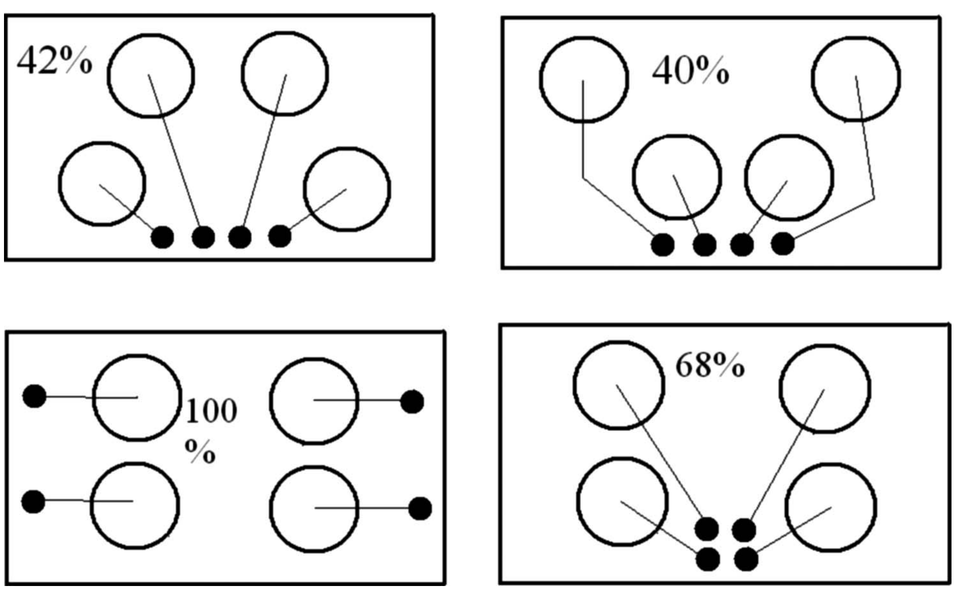


Figure 4. The four most nominated designs for a stove top when only the control locations are presented to the subject. Note that all designs have high spatial congruence between the control locations, hotplate locations and associated linkages.

Table 3. Results of experiment 1 with hotplate locations only presented to participants

Hotplate arrangement (Figure 3)	Nominated control arrangement (Figure 2)	Percentage response	Nominated linkage	Comment on special arrangements of controls
a		26	ABDC	Two on each side of panel
a	E	22	ABCD	
a	A	14	ABDC	
a		12	ABDC	Two under each pair hotplates
a		12	ABCD	Two arranged vertically each side of panel
b		82	ABDC	Directly under hotplates
b		14	ABCD	Two arranged vertically each side of panel
c	A	74	BACD	
c	E	22	BACD	
d		66	ABCD	Controls directly under hotplates
d		12	ABCD	Two sets vertically – left and centre
d		6	ABCD	Two sets horizontal. Left and centre.
e		74	BADC	Controls directly under hotplates
e		8	ABCD	Two sets vertically – right and centre
e		6	ABCD	At hotplate and below

Note: Responses are for locations of controls and linkages. Results for control locations for which there were two or less responses are not included.

2.3. *Discussion of experiment 1*

The major factors arising from the results of experiment 1 are:

(1) The linkages between controls and hotplates should not cross lines of symmetry or mirror-symmetry.
(2) Designers should use arrangements that have strong spatial congruence between control and hotplate. If this is done, there will be a high expectancy of the relationship between control and hotplate.

All designs nominated by participants and that had a high rate of response in experiment 1 are shown in Figures 4 and 5. Not many of these designs are seen in common use, in fact the common designs of control/hotplate arrangements did not generally enter into the designs with high spatial congruence. This is seen in the data of Table 1 from previous researches.

3. Experiment 2

3.1. *Introduction*

Previous research has found 'best' arrangements of control linkages for hotplates in a square arrangement. For example in Table 1, best linkages ABCD, ABDC, etc. are seen. The data show the extent to which the arrangements are different in terms of the strength of the stereotype of operation or the reaction time for responding to a particular presented hotplate/control arrangement. They do not, however, indicate the subjective preferences in terms of a location on a scale, that is, the distances between the various arrangements.

A second experiment was designed to determine if such a scale could be developed and whether the scale satisfied the basic assumptions of the Thurstone scaling method, Case V (Edwards 1983). This method makes several assumptions that can be tested. The most important is that the hotplate/control arrangements can be modelled on a single linear scale – in other words, the physical layout or geometrical variables of the arrangements are the only factor affecting a participant's judgements. A second important assumption is that the standard deviations of all the distributions of preferences are similar. Both of these assumptions are testable from the data. With the designed hotplate/control arrangements, it may be possible to determine the characteristics of the spatial arrangement of hotplate and controls that yield a high subjective preference.

3.2. *Method*

3.2.1. *Design*

In this second method, participants were presented with a set of seven hotplate/control arrangements, designed to have various apparent levels of compatibility based on spatial organisation. In each case, the linkages between hotplate and control were

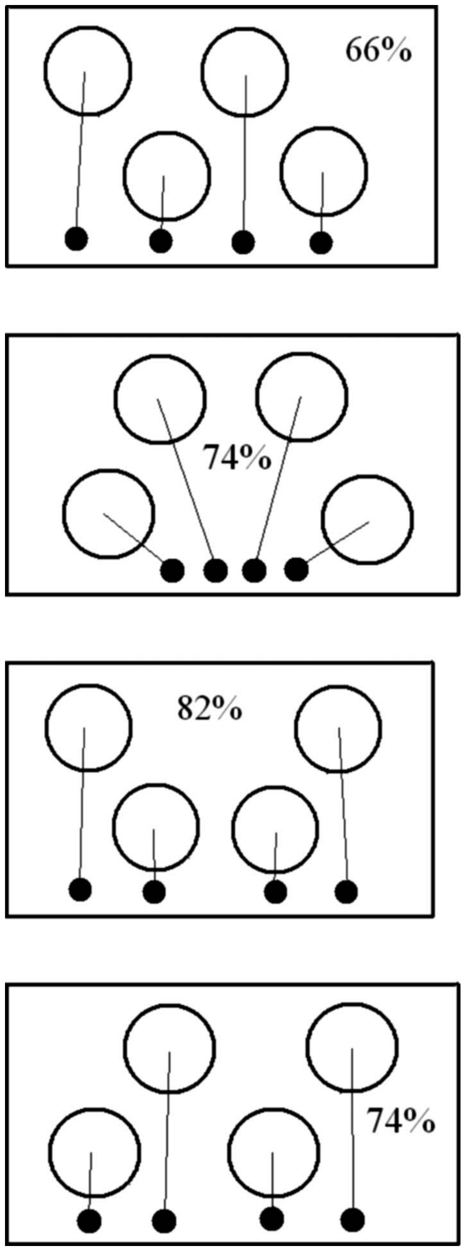


Figure 5. The four most nominated designs for control locations when only hotplate locations are presented.

specified. A method of paired comparisons was used and data analysed according to Case V of the Thurstone scaling method. As there were seven separate designs for the hotplate/control/linkage arrangements, there were 21 paired comparisons given to participants. The hotplate/control arrangements were presented as drawings, two to each A4 sheet for each of the 21 comparisons. The top/bottom locations of the two comparison arrangements were interchanged for half of the participants in order to avoid any bias due to order of arrangements. The 21 sheets were presented in a different random order for each participant. The participant's task was to express a preference for one of the arrangements on each sheet. The preference was to be based on the preferred arrangement of hotplate and controls. This preference was recorded by the experimenter.

3.2.2. Stove designs

There are numerous possible designs for the arrangement of hotplates and controls. Seven designs were selected for this study, based on having different characteristics in terms of the displacement of hotplates, location of controls and grouping of controls. Two of these were known to have low compatibility between hotplates and controls. There were five designs that were expected to have a high degree of spatial compatibility. The designs selected are shown in Figure 6.

Designs 1 and 6 were expected to have low compatibility, while other designs were expected to have high compatibility. Arrangement 1 was found by Hsu and Peng (1993) to be the best for the case where the four hotplates are located in a square and the controls are at the front of the stove. Arrangement 6 is one commonly found in commercial stoves, but has not been evaluated experimentally in the published literature. Pilot tests on a small group of participants, using arrangements 2, 3, 4, 5 and 7, but without the linkages shown, found that 100% of participants gave the mappings of controls and hotplates shown in Figure 2. These then could be considered as designs that are ergonomically good from a mapping viewpoint, but the relative merits need to be investigated. Although proportion of 'correct' mappings used by participants in these initial trials did not discriminate between designs, it was thought that the use of scaling for preferred arrangements might yield such discrimination.

3.2.3. Participants

A total of 40 participants were recruited from the university students and the local population. There were 18 males and 22 females. Median age was 25 years, with a range from 18 to 60. They took part under the ethical guidelines of City University of Hong Kong.

3.2.4. Instructions to participants

'In this experiment, I am going to show you a series of drawings of stove tops, showing the positions of the hotplates, the control knobs and lines that indicate

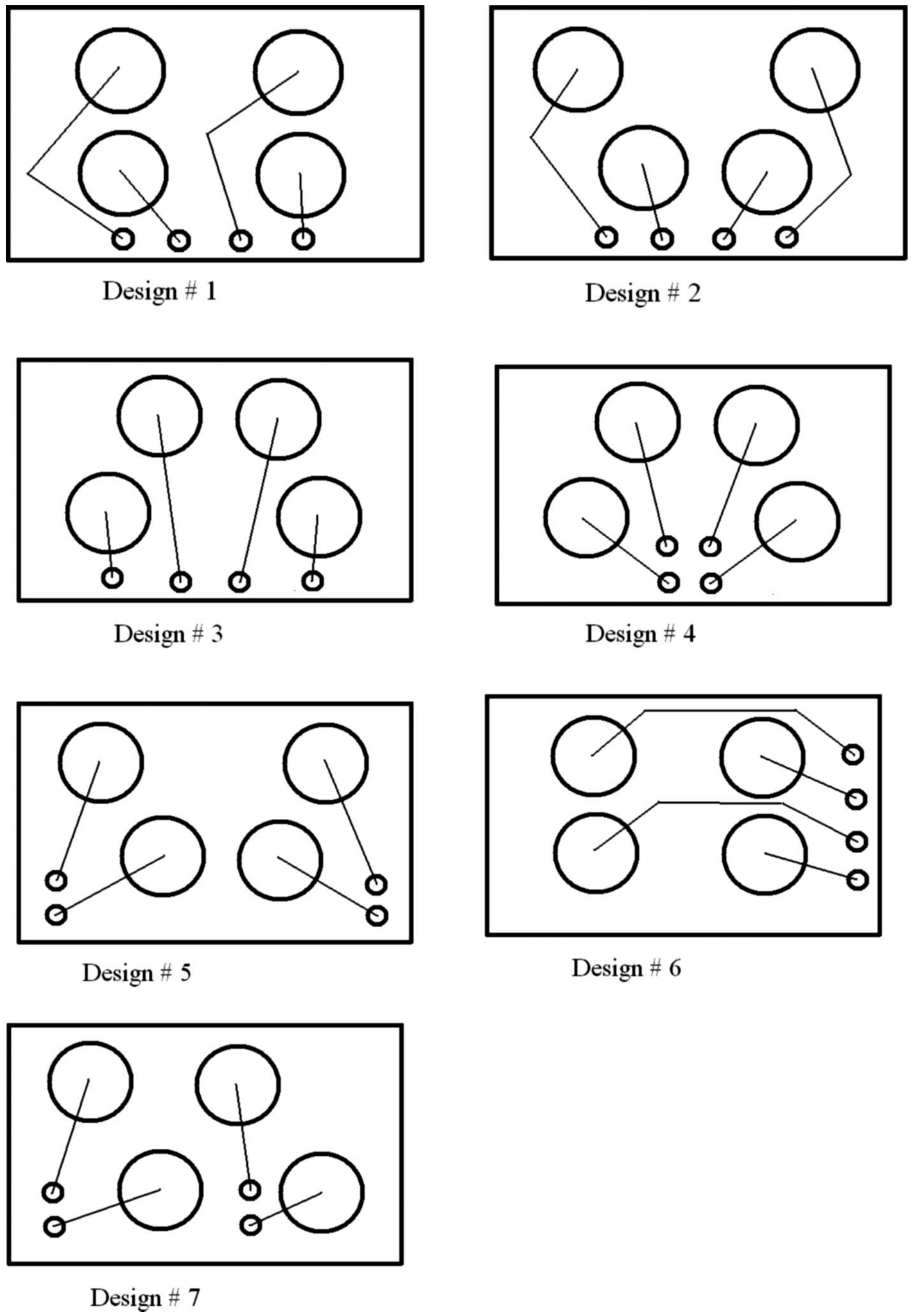


Figure 6. The designs of hotplate, controls and linkages used for preference ratings in experiment 2.

which control operates which hotplate. You will be shown two arrangements at a time and your task is to decide which arrangement is the better of the two in terms of convenience of use, and in particular for remembering which control operates each hotplate. You may have difficulty in some cases and consider the two arrangements to be equally good or bad. When this occurs, you must make a decision – you are forced to make a choice in each comparison.

Do you have any questions before we start?'

3.2.5. *Procedure*

The experimenter used standard response sheets to record preferences for the 21 comparisons made by each subject. Participants were shown each of the sheets of drawings, each in a different random order.

3.3. *Data analysis and results*

Data were analysed according to the Case V model of Thurstone (Edwards 1983). Responses for preferred ratings of participants are shown in Table 4. The table entries show the number of preferences (out of 40 comparisons) for the column arrangement compared to the row arrangement. The order of arrangements in Table 4 is from least to most preferred, as determined in the experiment.

Edwards (1983) gives a detailed demonstration of the technique for Case V scale construction. The resulting scales are interval, with an arbitrary zero. Placing the least preferred at a value of zero on the interval scale gives the data of Table 5. The relative rankings of preference are shown graphically in Figure 7.

The analysis showed an average discrepancy of 0.0504 between the theoretical proportions predicted by the model and the actual values. A chi-square test to determine whether the observed and theoretical proportions corresponding to Table 4 are in accord with each other yielded a value of $\chi^2 = 19.98$, which with 15 degrees of freedom is not significant. Thus, the assumption of all stove arrangements lying along a single univariate scale appears to be valid. The further assumption of the standard deviation being constant for all discriminal processes is close to correct for all except arrangement 1, where the standard deviation is small compared to others. According to Edwards (1983), this may not cause a problem as that stove arrangement is near the centre of the range.

Table 4. Number of preferred hotplate/control arrangements for the columns compared to the rows, with the arrangements shown in Figure 6.

Stove arrangement	7	6	1	5	4	2
7	20					
6	17	20				
1	5	4	20			
5	5	10	13	20		
4	5	9	17	17	20	
2	2	5	7	9	15	20
3	2	4	9	12	8	16

Note: Self-comparisons were not made and it was assumed that, with a forced response, the numbers for each would be half the total of 40. Rows are in order of preferred arrangements, with '7' being least preferred and '3' most preferred.

Table 5. Means and standard deviations of preferences along an interval scale for the seven stove hotplate/control arrangements shown in Figure 6.

Stove arrangement	Mean scale value	SD
7	0	1.031
6	0.282	1.206
1	1.004	.505
5	1.106	.950
4	1.153	1.004
2	1.640	.981
3	1.750	1.323

Note: Rows are in order of preferred arrangements, with '7' being least preferred and '3'most preferred.

Student t-tests were used to test for significance of differences between each of the stove arrangements. These tests showed that the arrangements are in three groups, within which stoves are not significantly different. The three groups (7, 6), (1, 5, 4) and (2, 3) are all significantly different at $p < 0.05$ or less (Figure 7).

3.3.1. *Characteristics of groups of stove arrangements*

Other than broad statements, it is difficult from the limited data available (seven stove arrangements) to make any strong conclusions about the factors within the layouts of the stove that produce strong expectancies and preferences for the stove control/hotplate/linkage arrangement. In Table 6, various characteristics of proximity of the stove layout are listed: (i) the presence of spatial congruence between control and hotplate; (ii) the arrangement of the controls, whether in a horizontal or vertical array; (iii) whether there are controls interposed between the hotplates; (iv) the controls are in a single group, whether horizontally, vertically or in a square arrangement; (v) the relative length of the linkages between the controls and the hotplates (measured as a ratio of the length of a particular arrangement relative to stove top '3', which has the shortest linkage length).

A correlation between the scale value for preferred layout and each of these factors, using a '1' for yes and '0' for no, showed a single significant factor – this was for the controls being in a horizontal direction ($r = 0.77$, $p = 0.042$). There are insufficient data to

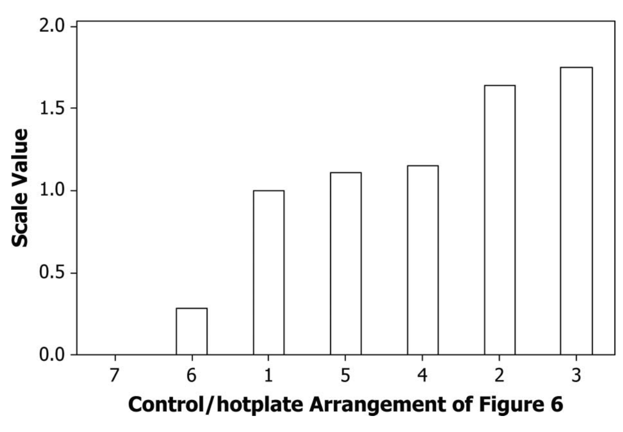


Figure 7. Scale values of preferences obtained in experiment 2 for the seven control/hotplate/linkage designs of Figure 6. Preference for arrangements increases from left to right.

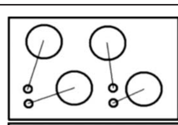
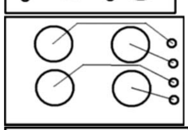
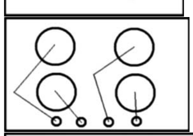
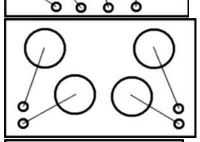
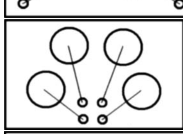
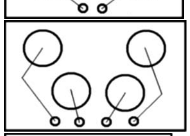
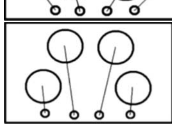
perform a regression as degrees of freedom are too small to be meaningful. However, it is possible to make some observations from Table 6, based on the groups of arrangements that are not significantly different in preferences values.

Consider arrangements 2 and 3. These have the highest ratings and have the same characteristics for all of the columns in Table 6. The next lower in rated value is arrangement 4. The only major difference here is that the controls are interposed between the hotplates, rather than being in a single horizontal group. Yet, in experiment 1, each of these arrangements was nominated strongly as a preferred arrangement and, in preliminary experiments, all three arrangements produced 100% consistency in the responses for linkages between controls and hotplates. Thus, it would appear that it is the location of the controls relative to the hotplates (being centred) that has reduced the scale value for arrangement 4 relative to arrangements 2 and 3.

There are two other arrangements (1 and 5) that are not significantly different to 4. Arrangement 4 has good spatial congruence, as has 5 and has a similar rating. Of some surprise is arrangement 1, which is one of the commonly available commercial layouts. Here, the spatial congruence is poor and it can only be assumed that it is rated equivalent to arrangements 4 and 5, because of its familiarity to the participant group. None of the characteristics listed in Table 6 would appear to account for the performance of arrangement 1 relative to arrangements 4 and 5.

The lowest rated group was that for stoves 7 and 6. Arrangement 6 is similar to arrangement 1, in that the linkages are identical, except the controls are in the vertical rather than the horizontal direction. It is again one of the fairly commonly available commercial arrangements. Arrangement 7 was the lowest rated and this is surprising as it does have a good level of spatial congruence. It does, however, have intervening

Table 6. The seven hotplate/control arrangements tested in experiment 2 and possible factors affecting participant's preference response.

Stove arrangement	Layout and linkages	Spatial similarity (displaced hotplates)	Control direction horizontal	Controls interposed	Controls in group	Length of linkage lines
7		Yes	No	Yes	No	1.02
6		No	No	No	Yes	1.58
1		No	Yes	No	Yes	1.10
5		Yes	No	No	No	1.08
4		Yes	Yes/No	Yes	Yes	1.02
2		Yes	Yes	No	Yes	1
3		Yes	Yes	No	Yes	1

Note: The 'length of linkage lines' is a ratio of the value for an arrangement to the shortest in the set of arrangements and is the sum of the direct lines measured from control to centre of the hotplate. Rows are in order of preferred arrangements, with '7' being least preferred and '3' most preferred.

controls, which was seen in the comparison of 4 with 2 and 3 to cause a reduction in value of preference.

Maybe the simplest explanation for the preference values can be explained by a preference for a 1-D relationship between controls and hotplates. Ray and Ray (1979) found that, when both the controls and hotplates were arranged linearly, there was 100% agreement on the linkages between control and hotplate. Arrangements 2 and 3 are essentially linear arrangements that can be verbally or mentally thought of as having a one-to-one relationship. Hence, with this interpretation, preferences for arrangements 2 and 3 are similar. Arrangements 4 and 5 also have high spatial congruence, but the relationship between controls and hotplates is 2-D and requires further coding compared with arrangements 2 and 3. As expected, due to low spatial congruence, arrangement 1 has a low level of preference. Arrangement 7 does not fit comfortably into this interpretation. The poor preference for arrangement 7 may be due to its unfamiliarity, as no current design appears to use this layout of hotplates and controls.

3.4. *Discussion of experiment 2*

This experiment has shown that, with the assumed physical factors describing the control/hotplate arrangements, the major factor affecting preference for a stove design is the spatial congruence of hotplate and controls. Of greatest importance in establishing this spatial congruence are the lateral displacement of hotplates and the location of the control, such that there is no uncertainty about the linkages that exist between the two.

The experiment only considered horizontal displacement of the hotplates, but it is likely that vertical displacement would produce as strong a result with the use of a vertical array of controls. The horizontal arrangement is, however, superior for practical use as the vertical arrangement would require greater reaching distances than the horizontal displacement.

The experiment has shown that placing the controls in one group and in the same direction, and not intervening between the hotplates, is also a factor affecting the level of preference. Of some surprise is the performance of arrangement 4, where the hotplates and the controls all appear to have high spatial congruence. This has shown the effect of controls not all being in the same direction, even though they have complete spatial congruence with the hotplate layout.

4. Overall discussion

Hoffmann and Whitfield (2011) note that there are very strong effects of the realism of testing for stereotypes of operation and this may have affected some of the data in Table 1, where results are for paper/pencil tests and hardware tests. The example given by Hoffmann and Whitfield was for water tap operation and may not be typical of all systems. The reason for this is that tap operation is opposite to strong population expectancies for increase of a quantity; anticlockwise for a tap valve, but clockwise for most other devices. Hoffmann (2009) in a review of the differences between paper/pencil tests and hardware tests notes that, when there is high spatial congruence between control and display, paper/pencil tests may give a good estimate of stereotype strength. Thus, this may be true in the present case.

4.1. *Characteristics of a 'good' design*

These experiments, which have approached the problem of control/hotplate layout differently to earlier research, have revealed a number of features that produce a strong expectancy between the arrangement of the hotplates, controls and linkages between these. The methods of experiment 1 have produced a set of layouts (Figures 4 and 5) having a high rate of nomination by participants for where the controls and hotplates should be located. The results of experiment 2 have discriminated between arrangements that have high expectancy for operation (at ceiling values) and indicate two designs that are excellent from the viewpoint of producing a high expectancy for operation and which are preferred by participants. This experiment was able to discriminate between arrangements 2 and 3 (statistically the same) and arrangement 4, which, on the basis of expectancy always produced a 100% response. Arrangement 3 is a more practical design than arrangement 2 as the space between hotplates at the rear of the stove is more difficult to use than the space available at the front of arrangement 3.

4.2. *Comparison with previous results*

4.2.1. *Designs with hotplates in quadrature*

A comparison may be made with the data of Table 1. There are three linkage arrangements in the table that may be compared with the data from experiment 1.

(1) ABDC. This is an arrangement where there is mirror symmetry about the stove midline. Experiment 1 showed that only 6% of participants nominated this design and 14% in experiment 2. There were, however, further participants in experiment 2 who had this arrangement of linkages but, rather than the controls being together in a centrally located

group, they were in two groups of two near to the sides of the stove top (26% and 12% for different control spacings).

(2) ABCD. Here there is symmetry about the stove midline. In experiment 1, 2% of participants nominated this design. In experiment 2, there was none of this design suggested.

(3) BACD. Another design with mirror symmetry about the stove centreline. There was none of this design suggested in experiment 1 and 2% in experiment 2.

The outstanding feature of the results is that the commonly found linkages in commercially available stoves were nominated by participants in very low percentages of the total responses.

4.2.2. *Designs with displaced hotplate arrangements*

There are a few previous reports that allow some comparison. Chapanis and Lindenbaum (1959) using the 'Ac' arrangement of Figures 2 and 3, found that there were zero errors made in nominating the linkages between the controls and hotplates. This design was one of the highly nominated designs in both methods of experiment 1 (Figures 4 and 5) and also the design with the highest preference rating in experiment 2 (Table 5 and Figure 7). Similarly, Tlauka (2004) found that, for the arrangement shown in the top-left corner of Figure 5, the percentage of 'correct' responses was 88%, with the standard quadrature arrangement being selected on 12% of responses. A similar result was obtained by Osborne and Ellingstad (1987) for this arrangement of controls and hotplates.

4.3. *Implications for future stove design*

The data have shown that it is only with designs that have high levels of spatial congruence between controls and hotplates that people will have a high level of expectancy about the relationship between control and hotplate. Such designs are few in commercially available stoves. There is of course a disadvantage to such designs; the layout requires more stovetop area than that required for the quadrature design. In some countries, where living areas are relatively small, this may be a disadvantage to using such designs.

There are other possible designs having high spatial congruence between hotplates and controls that have not been tested in these experiments. Such arrangements may have the trapezoidal layouts of hotplates as in of Figure 3b,c and with a corresponding geometrically similar layout of controls. These designs, as well as having high spatial congruence, may offer safety advantages due to ease of reaching one hotplate without passing over another.

5. Conclusions

Two new approaches to the design of stove control/hotplate and linkage arrangements showed that:

(1) Participants showed knowledge of spatial compatibility that allowed them to nominate stove top designs that were more compatible than the commonly produced designs.

(2) Using a preference rating method, it was possible to distinguish between various designs, which produced close to 100% 'correct' responses for the linkages between controls and hotplates.

(3) Nominated designs contained only small proportions of the commercially available designs, which generally have poor stereotypes for control/hotplate operation.

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