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A method for simultaneously counterbalancing condition order and assignment of stimulus materials to conditions

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Abstract Counterbalanced designs are frequently used in the behavioral sciences. Studies often counterbalance either the order in which conditions are presented in the experiment or the assignment of stimulus materials to conditions. Occasionally, researchers need to simultaneously counterbalance both condition order and stimulus assignment to conditions. Lewis (1989; Behavior Research Methods, Instruments, & Computers 25:414-415, 1993) presented a method for constructing Latin squares that fulfill these requirements. The resulting Latin squares counterbalance immediate sequential effects, but not remote sequential effects. Here, we present a new method for generating Latin squares that simultaneously counterbalance both immediate and remote sequential effects and assignment of stimuli to conditions. An Appendix is provided to facilitate implementation of these Latin square designs.

Keywords Counterbalancing · Latin square · Order effects · Sequential effects · Experimental design

Researchers from such diverse fields as cognitive psychology, neuroscience, political science, clinical science, movement science, and human factors research frequently counterbalance condition order to prevent the effects of general practice, fatigue, or other unwanted order effects from causing differences between conditions. Counterbalancing is generally achieved by creating Latin squares. Table 1 shows a Latin square that counterbalances condition order. In the Latin square, each condition (represented by a letter) occurs once in each row (i.e., for each participant) and once in each column (i.e., on each ordinal position). Note, however, that each condition is always preceded by the same other condition (e.g., condition B is always preceded by condition A). Thus, the Latin square in Table 1 counterbalances ordinal position, but not immediate sequential effects.

In this article, we discuss methods that counterbalance sequential effects in addition to ordinal position. Sequential effects occur when performance in a condition is affected by the condition(s) preceding it. For example, a particularly difficult condition may induce a negative affective state that lingers for some time and negatively influences performance in the condition presented after it. If the same conditions follow each other for each participant (e.g., condition B always follows condition A), comparisons of performance in the different conditions may be tainted. Imagine, for example, that one uses the Latin square shown in Table 1 and that condition A exerts a negative influence on performance in the condition immediately following it. Because condition B always follows condition A, performance in condition B will be underestimated relative to the other conditions (i.e., C, D, E, and F). Performance in a condition can be affected by a condition immediately preceding it (i.e., an *immediate* sequential effect) or by a condition preceding it by two or more positions in the sequence of conditions (i.e., a *remote* sequential effect). Studies have shown that immediate and remote sequential effects do, in fact, occur and affect diverse dependent variables such as category judgments (Petzold & Haubensak, 2001), memory judgments (Malmberg & Annis, 2012), absolute identification (Stewart, Brown, & Chater, 2005), skill acquisition (Matlen, & Klahr, 2013), questionnaire-based measurements of shame (Faulkner & Cogan, 1990), and the taste of food and wine (Durier, Monod, & Bruetschy, 1997; Schlich, 1993). Such widespread findings of sequential effects indicate that it is safer to control for sequential effects than to simply assume (or hope) that sequential effects won't affect the results. Thus, rather than

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Table 1 Example of a Latin square design with six conditions

Participant	Condition Order
1, 7, …	A B C D E F
2, 8, …	B C D E F A
3, 9, …	C D E F A B
4, 10, …	D E F A B C
5, 11, …	E F A B C D
6, 12, …	F A B C D E

Note. Capital letters represent conditions. In a typical counterbalanced design, each participant receives one condition order, and an equal number of participants are tested with each condition order

using a type of Latin square such as the one shown in Table 1, which counterbalances ordinal position, but not sequential effects, we recommend using Latin squares that counterbalance sequential effects in addition to ordinal position.

Several methods have been developed for counterbalancing immediate sequential effects in addition to ordinal position (Bradley, 1958; Wagenaar, 1969; Williams, 1949). The Latin square in Table 2 is constructed according to a method proposed by Bradley. In this method, the top row of the square is constructed as A, N, B, $N-1$, C, $N-2$, and so on, where N is the total number of conditions. Subsequent rows are created by putting the next letter in the alphabetical sequence below each letter of the preceding row. An important property of the Latin square in Table 2 is that across participants, no condition is preceded (and followed) more than once by another condition, a property that has been referred to as ''digram-balanced'' (Wagenaar, 1969). Note that the Latin square shown in Table 2 counterbalances immediate sequential effects, but not remote sequential effects. Latin squares that counterbalance remote sequential effects exist for some situations and are discussed later. Latin squares are often discussed in the context of counterbalancing order effects but are also used to counterbalance the assignment of stimulus materials to conditions. Counterbalancing stimulus assignment to conditions eliminates confounds in item difficulty between the different conditions of the experiment (e.g., Pollatsek & Well, 1995) and plays an important role in the design of many behavioral experiments.

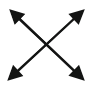
Table 2 Example of digram-balanced Latin square designs with six conditions

Condition Order
A F B E C D
B A C F D E
C B D A E F
D C E B F A
E D F C A B
F E A D B C

In some experiments, both the condition order and assignment of stimulus materials to conditions need to be counterbalanced. For example, de Jonge, Tabbers, Pecher, and Zeelenberg (2012) studied the effect of presentation rate on paired-associate learning. Word pairs (e.g., *hammer–elevator*) were presented for a total study time of 16 s in five blocks with different presentation rates (i.e., 16 × 1 s, 8 × 2 s, 4 × 4 s, 2 × 8 s, and 1 × 16 s). Presentation rate was blocked so that within each block the presentation rate was constant. After study, one word of each pair (e.g., *hammer*–?) was presented in a cued recall test, and participants had to report the corresponding target word (e.g., *elevator*). To sensibly compare performance under different presentation rate conditions, the order of conditions (blocks) needs to be counterbalanced. Moreover, for obvious reasons, a single participant cannot study the same word pair in each of the five conditions. The stimuli must therefore be divided into separate stimulus sets that are assigned to the different presentation rate conditions. Because word pairs differ in how easy they are to learn (e.g., Nelson & Dunlosky, 1994), the assignment of stimulus materials to conditions also needs to be counterbalanced (i.e., in addition to condition order). A combination of all possible condition orders and all possible stimulus assignments to conditions results in $n! \times n!$ permutations (giving 14,400 permutations for an experiment with five conditions). As a result, in all but the simplest designs, using all possible permutations is practically impossible.

A more useful approach to this problem is to use a Latin square design that counterbalances both condition order and assignment of stimuli to conditions. A solution to this problem is provided by Lewis (1989, 1993). Since the method is somewhat easier for experiments with an odd number of conditions, we describe that situation first. In the first step, a pair of Latin squares representing the conditions is created using Bradley's (1958) method (where the second square is the vertically mirrored version of the first square). In the second step, a pair of Latin squares representing the stimulus sets is created. This second pair of Latin squares is a copy of the first pair, except that numbers are used in the second pair of Latin squares. The numbers in the second set of Latin squares correspond to the letters of the first set of Latin squares such that the letter A becomes the number 1, the letter B becomes number 2, and so forth (compare the adjacent letter and number matrices, shown below). In the third step, these Latin squares are combined in a diagonal fashion (i.e., the first square of letters is combined with the second square of numbers and vice versa), to create two Latin squares that counterbalance condition order and the assignment of stimulus materials to conditions. The resulting Latin squares are shown in Table 3.

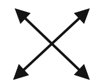
A	E	B	D	C		1	5	2	4	3
B	A	C	E	D		2	1	3	5	4
C	B	D	A	E		3	2	4	1	5
D	C	E	B	A		4	3	5	2	1
E	D	A	C	B		5	4	1	3	2



C	D	B	E	A		3	4	2	5	1
D	E	C	A	B		4	5	3	1	2
E	A	D	B	C		5	1	4	2	3
A	B	E	C	D		1	2	5	3	4
B	C	A	D	E		2	3	1	4	5

The procedure is different for Latin squares with an even number of conditions. In the first step, a pair of Latin squares representing the conditions is created. The first Latin square is again created using Bradley's (1958) method. The second Latin square representing conditions is created by swapping each pair of adjacent columns (e.g., columns 1 and 2, columns 3 and 4, etc.) of the first Latin square. In the second step, a pair of Latin squares representing stimulus sets is created. The first Latin square for stimulus sets is a copy of the first Latin square for conditions where the letters have been replaced by corresponding numbers (i.e., A → 1, B → 2, etc.). The second Latin square for stimulus sets is created by copying the second Latin square for conditions in a similar fashion, but an additional transformation is needed. The rows of this Latin square are rotated by one position (i.e., row 1 of this Latin square becomes row 8, row 2 becomes row 1, row 3 becomes row 2, etc.). The resulting matrices are shown below. In the third step, these Latin squares are combined in a diagonal fashion (just as before). See Table 4 for the resulting pair of Latin squares.

A	H	B	G	C	F	D	E		1	8	2	7	3	6	4	5
B	A	C	H	D	G	E	F		2	1	3	8	4	7	5	6
C	B	D	A	E	H	F	G		3	2	4	1	5	8	6	7
D	C	E	B	F	A	G	H		4	3	5	2	6	1	7	8
E	D	F	C	G	B	H	A		5	4	6	3	7	2	8	1
F	E	G	D	H	C	A	B		6	5	7	4	8	3	1	2
G	F	H	E	A	D	B	C		7	6	8	5	1	4	2	3
H	G	A	F	B	E	C	D		8	7	1	6	2	5	3	4



H	A	G	B	F	C	E	D		1	2	8	3	7	4	6	5
A	B	H	C	G	D	F	E		2	3	1	4	8	5	7	6
B	C	A	D	H	E	G	F		3	4	2	5	1	6	8	7
C	D	B	E	A	F	H	G		4	5	3	6	2	7	1	8
D	E	C	F	B	G	A	H		5	6	4	7	3	8	2	1
E	F	D	G	C	H	B	A		6	7	5	8	4	1	3	2
F	G	E	H	D	A	C	B		7	8	6	1	5	2	4	3
G	H	F	A	E	B	D	C		8	1	7	2	6	3	5	4

The method proposed by Lewis (1989) counterbalances condition order and the assignment of stimulus materials to conditions for digram-balanced Latin squares constructed with Bradley's method. Bradley (1958) pointed out, however, that this procedure counterbalances immediate sequential effects, but not remote sequential effects. For example, in the Latin square shown in Table 2, condition E is twice preceded by condition F in the second cell preceding it (see rows 1 and 2 of the Latin square). To solve this problem, Alimena (1962)

Table 3 A pair of Latin squares that counterbalances condition order and the assignment of stimulus materials to conditions

A3	E4	B2	D5	C1
B4	A5	C3	E1	D2
C5	B1	D4	A2	E3
D1	C2	E5	B3	A4
E2	D3	A1	C4	B5
C1	D5	B2	E4	A3
D2	E1	C3	A5	B4
E3	A2	D4	B1	C5
A4	B3	E5	C2	D1
B5	C4	A1	D3	E2

Note. Capital letters represent conditions; numbers represent stimulus sets

Table 4 A pair of Latin squares that counterbalances condition order and the assignment of stimulus materials to conditions

A1	H2	B8	G3	C7	F4	D6	E5
B2	A3	C1	H4	D8	G5	E7	F6
C3	B4	D2	A5	E1	H6	F8	G7
D4	C5	E3	B6	F2	A7	G1	H8
E5	D6	F4	C7	G3	B8	H2	A1
F6	E7	G5	D8	H4	C1	A3	B2
G7	F8	H6	E1	A5	D2	B4	C3
H8	G1	A7	F2	B6	E3	C5	D4
H1	A8	G2	B7	F3	C6	E4	D5
A2	B1	H3	C8	G4	D7	F5	E6
B3	C2	A4	D1	H5	E8	G6	F7
C4	D3	B5	E2	A6	F1	H7	G8
D5	E4	C6	F3	B7	G2	A8	H1
E6	F5	D7	G4	C8	H3	B1	A2
F7	G6	E8	H5	D1	A4	C2	B3
G8	H7	F1	A6	E2	B5	D3	C4

developed a method for constructing Latin squares that counterbalances immediate and remote sequential effects.

The method for constructing these Latin squares is somewhat complicated and perhaps best illustrated for a 10 × 10 Latin square. The first step in constructing this type of Latin square is to fill the first column by inserting the letters representing the conditions in ascending order. Subsequently, fill the last column by inserting the letters in descending order. Third, fill the cells on the diagonals with the letters that they connect (A to A and J to J in the example below). This results in the following partially filled matrix.

```
A                 J
B A             J I
C   A         J   H
D     A     J     G
E       A J       F
F       J A       E
G     J     A     D
H   J         A   C
I J             A B
J                 A
```

In the next step, the columns are filled by inserting letters in ascending order starting at the A in each column that is not yet completely filled. In the first partially filled column, insert the letter B by skipping one row (in the matrix below, see the column with number 1 above it). Then insert the letter C in this column, again skipping one row, and so on for all letters. The second partially filled column is filled by inserting the letter B skipping two rows below the letter A. The letter C is then inserted by again skipping two rows. Working your way through the matrix from left to right, each time you shift to the next right column, the number of rows skipped increases by 1 (the numbers above the columns indicate the number of rows that need to be skipped before inserting the next letter).

```
0 1 2 3 4 5 6 7 8 9
___________________
A                 J
B A             J I
C   A         J   H
D B   A     J     G
E       A J       F
F C B   J A       E
G     J     A     D
H D J B       A   C
I J C           A B
J E     B         A
```

Whenever the bottom of the column is reached, continue from the top of the column, but skip one row less than you normally would for that column. For example, for the column with the number 1 above it, the letter F is inserted on the first row. The easiest way to implement this rule is to include the row with numbers above the matrix in the count of the number of rows that are skipped. After continuing from the top of the column, insert the other letters by skipping the appropriate number of rows for that column (e.g., in the column with the number 2 above it, the letter E is inserted by skipping two rows). Depending on the column, you will need to cycle through this procedure several times before the column is completely filled. The matrix below shows an intermediate result in which we started once from the top of the matrix for each column.

```
0 1 2 3 4 5 6 7 8 9
___________________
A F D C   B       J
B A             J I
C G A         B J H
D B E A C   J     G
E H   D A J   B   F
F C B   J A       E
G I F J     A   B D
H D J B       A   C
I J C E         A B
J E G   B         A
```

Table 5 presents the completely filled matrix (i.e., the 10 × 10 Latin square). As was noted by Alimena (1962), this method works only when $n + 1$ is a prime number (where n is the number of conditions). Thus, this method can be used to construct Latin squares for experiments with 2, 4, 6, 10, 12, 16, 18, 22, 28, . . . conditions.

As was mentioned, the method proposed by Lewis (1989) counterbalances condition order and the assignment of stimulus materials to conditions, but this method controls only for immediate sequential effects. To the best of our knowledge, no such method has been published for designs that control for both immediate and remote sequential effects. We therefore set out to find a method that counterbalances condition order and assignment of stimulus materials to conditions for Latin squares that control for both immediate and remote sequential effects. The following method provides a solution. Like the method proposed by Lewis (1989), this method requires constructing a

Table 5 Example of a Latin square with ten conditions that controls for both immediate and remote sequential effects

A F D C I B H G E J
B A H F G D E C J I
C G A I E F B J D H
D B E A C H J F I G
E H I D A J G B C F
F C B G J A D I H E
G I F J H C A E B D
H D J B F E I A G C
I J C E D G F H A B
J E G H B I C D F A

pair of Latin squares. The first step involves creating a pair of Latin squares representing conditions. The first Latin square representing conditions is constructed using the method of Alimena (1962). The second Latin square representing conditions is constructed by mirroring the first square. Note that the first square can be mirrored along either the vertical axis or the horizontal axis, since this gives the same result. Below is an example for an experiment with six conditions.

```
A D E B C F
B A C D F E
C E A F B D
D B F A E C
E F D C A B
F C B E D A

F C B E D A
E F D C A B
D B F A E C
C E A F B D
B A C D F E
A D E B C F
```

The construction of the Latin squares representing stimulus sets is somewhat complicated and involves several operations. First, copy the first Latin square for conditions and replace the letters with their corresponding numbers (i.e., A→1, B→2, etc.). This results in the following Latin square:

```
1 4 5 2 3 6
2 1 3 4 6 5
3 5 1 6 2 4
-----------
4 2 6 1 5 3
5 6 4 3 1 2
6 3 2 5 4 1
```

Next, two Latin squares representing stimulus sets need to be created. The first Latin square is created by separately mirroring the top and bottom halves of the original Latin square along an imaginary horizontal line running through the center of the matrix. For a 6 × 6 Latin square, this causes rows 1 and 3 to be swapped, as well as rows 4 and 6, resulting in the following Latin square:

```
3 5 1 6 2 4
2 1 3 4 6 5
1 4 5 2 3 6
6 3 2 5 4 1
5 6 4 3 1 2
4 2 6 1 5 3
```

The second Latin square is created by swapping the adjacent rows of numbers from the original number Latin square but leaving the top and bottom rows untouched. Thus, for a 6 × 6 Latin square, rows 3 and 2 are swapped, and rows 4 and 5 are swapped, resulting in the following Latin square:

```
1 4 5 2 3 6
3 5 1 6 2 4
2 1 3 4 6 5
5 6 4 3 1 2
4 2 6 1 5 3
6 3 2 5 4 1
```

Next, the Latin squares representing conditions and the Latin squares representing stimulus sets need to be combined to construct a pair of Latin squares. It turns out that the two Latin squares representing conditions and the two Latin squares representing stimulus sets can be paired either way, as long as each Latin square is used only once. Both possible pairings result in a pair of Latin squares counterbalancing condition order and assignment of stimulus materials to conditions, while controlling for both immediate and remote sequential effects. One of the two possible pairings is shown in Table 6.

We have no formal proof that this method works for Latin squares of all sizes but have successfully tried it for Latin squares up to size 16 × 16, a number that seems large enough for all but the most ambitious experiments.

Concluding remarks and recommendations

In this article, we have discussed methods that counterbalance sequential effects in addition to ordinal position. As has been shown, the methods of Bradley (1958) and Alimena (1962) can be extended to simultaneously counterbalance sequential effects and the assignment of stimulus materials to conditions. We recommend that researchers use counterbalancing methods that maximize control over sequential effects. More specifically, for studies that require simultaneous counterbalancing of

Table 6 A pair of Latin squares that counterbalance condition order and the assignment of stimulus materials to conditions and control for both immediate and remote sequential effects

A1	D4	E5	B2	C3	F6
B3	A5	C1	D6	F2	E4
C2	E1	A3	F4	B6	D5
D5	B6	F4	A3	E1	C2
E4	F2	D6	C1	A5	B3
F6	C3	B2	E5	D4	A1
F3	C5	B1	E6	D2	A4
E2	F1	D3	C4	A6	B5
D1	B4	F5	A2	E3	C6
C6	E3	A2	F5	B4	D1
B5	A6	C4	D3	F1	E2
A4	D2	E6	B1	C5	F3

Note. Capital letters represent conditions; numbers represent stimulus sets condition order and stimulus assignment to conditions, we recommend the following.

1. Whenever possible, use the method developed in the present article to create Latin squares that simultaneously counterbalance condition order and stimulus assignment to conditions. These Latin squares control for both immediate and remote sequential effects. Note that this method can be used only when the number of conditions + 1 is a prime number (i.e., for experiments with 2, 4, 6, 10, 12, . . . conditions).
2. If the method developed in the present article cannot be used, use the method proposed by Lewis (1989).

Note that either method of simultaneously counterbalancing the order of conditions and assignment of stimuli to conditions requires a pair of Latin squares (regardless of the number of conditions). The methods for generating these Latin squares are somewhat complicated, but the Appendix should make implementation easy. The Appendix presents pairs of Latin squares for experiments with 2, 4, 6, 10, and 12 conditions that were created with the method proposed here. Lewis (1989) presents Latin squares that can be used for experiments with 3, 5, 7, or 8 conditions.

Appendix

Pairs of Latin squares that simultaneously counterbalance the order of conditions and the assignment of stimulus materials to conditions

2 conditions

A1	B2
B2	A1

B1	A2
A2	B1

4 conditions

A1	C3	B2	D4
B3	A4	D1	C2
C2	D1	A4	B3
D4	B2	C3	A1

D2	B1	C4	A3
C1	D3	A2	B4
B4	A2	D3	C1
A3	C4	B1	D2

6 conditions

A1	D4	E5	B2	C3	F6
B3	A5	C1	D6	F2	E4
C2	E1	A3	F4	B6	D5
D5	B6	F4	A3	E1	C2
E4	F2	D6	C1	A5	B3
F6	C3	B2	E5	D4	A1

F3	C5	B1	E6	D2	A4
E2	F1	D3	C4	A6	B5
D1	B4	F5	A2	E3	C6
C6	E3	A2	F5	B4	D1
B5	A6	C4	D3	F1	E2
A4	D2	E6	B1	C5	F3

10 conditions

A1	F6	D4	C3	I9	B2	H8	G7	E5	J10
B3	A7	H1	F9	G5	D6	E2	C10	J4	I8
C2	G1	A8	I6	E7	F4	B5	J3	D10	H9
D5	B8	E9	A4	C1	H10	J7	F2	I3	G6
E4	H2	I5	D1	A3	J8	G10	B6	C9	F7
F7	C9	B6	G10	J8	A3	D1	I5	H2	E4
G6	I3	F2	J7	H10	C1	A4	E9	B8	D5
H9	D10	J3	B5	F4	E7	I6	A8	G1	C2
I8	J4	C10	E2	D6	G5	F9	H1	A7	B3
J10	E5	G7	H8	B2	I9	C3	D4	F6	A1

J5	E8	G9	H4	B1	I10	C7	D2	F3	A6
I4	J2	C5	E1	D3	G8	F10	H6	A9	B7
H3	D7	J1	B9	F5	E6	I2	A10	G4	C8
G2	I1	F8	J6	H7	C4	A5	E3	B10	D9
F1	C6	B4	G3	J9	A2	D8	I7	H5	E10
E10	H5	I7	D8	A2	J9	G3	B4	C6	F1
D9	B10	E3	A5	C4	H7	J6	F8	I1	G2
C8	G4	A10	I2	E6	F5	B9	J1	D7	H3
B7	A9	H6	F10	G8	D3	E1	C5	J2	I4
A6	F3	D2	C7	I10	B1	H4	G9	E8	J5

12 conditions

A1	G7	I9	J10	H8	K11	B2	E5	C3	D4	F6	L12
B3	A8	E1	G4	C11	I7	D6	J2	F9	H12	L5	K10
C2	H1	A5	D7	K3	G9	F4	B10	I6	L8	E12	J11
D5	B9	J6	A11	F1	E3	H10	G12	L2	C7	K4	I8
E4	I2	F10	K1	A6	C5	J8	L7	B12	G3	D11	H9
F7	C10	B11	H5	I4	A12	L1	D9	E8	K2	J3	G6
G6	J3	K2	E8	D9	L1	A12	I4	H5	B11	C10	F7
H9	D11	G3	B12	L7	J8	C5	A6	K1	F10	I2	E4
I8	K4	C7	L2	G12	H10	E3	F1	A11	J6	B9	D5
J11	E12	L8	I6	B10	F4	G9	K3	D7	A5	H1	C2
K10	L5	H12	F9	J2	D6	I7	C11	G4	E1	A8	B3
L12	F6	D4	C3	E5	B2	K11	H8	J10	I9	G7	A1

L6	F3	D2	C8	E9	B1	K12	H4	J5	I11	G10	A7
K5	L9	H6	F11	J1	D3	I10	C12	G2	E7	A4	B8
J4	E2	L10	I1	B6	F5	G8	K7	D12	A3	H11	C9
I3	K8	C1	L4	G11	H7	E6	F2	A9	J12	B5	D10
H2	D1	G5	B7	L3	J9	C4	A10	K6	F8	I12	E11
G1	J7	K9	E10	D8	L11	A2	I5	H3	B4	C6	F12
F12	C6	B4	H3	I5	A2	L11	D8	E10	K9	J7	G1
E11	I12	F8	K6	A10	C4	J9	L3	B7	G5	D1	H2
D10	B5	J12	A9	F2	E6	H7	G11	L4	C1	K8	I3
C9	H11	A3	D12	K7	G8	F5	B6	I1	L10	E2	J4
B8	A4	E7	G2	C12	I10	D3	J1	F11	H6	L9	K5
A7	G10	I11	J5	H4	K12	B1	E9	C8	D2	F3	L6

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