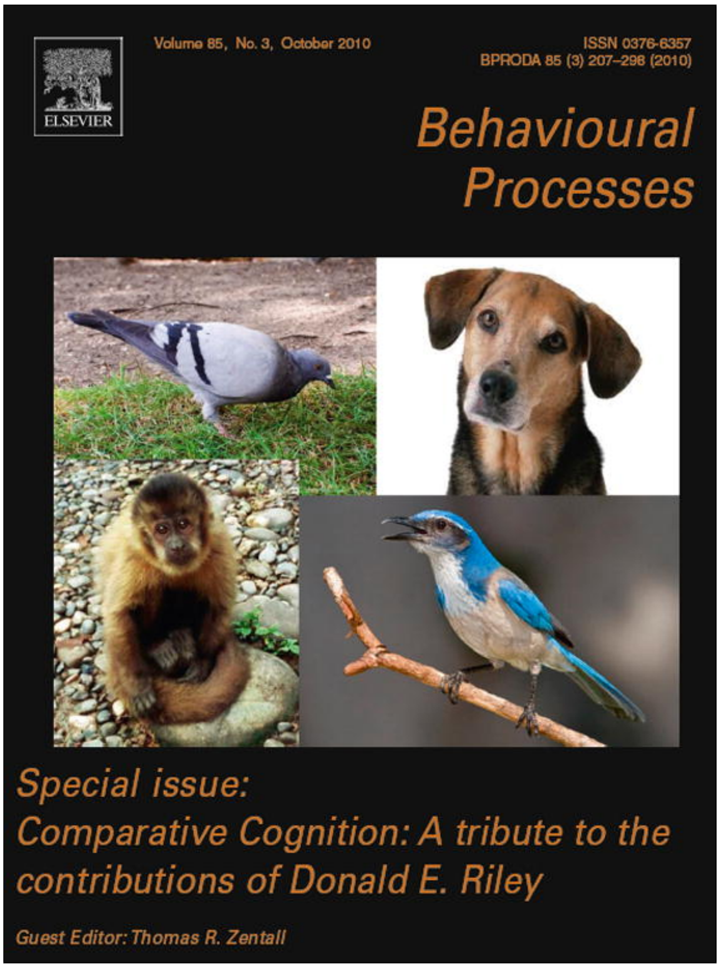
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Precedence of spatial pattern learning revealed by immediate reversal performance

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ABSTRACT

Human participants learned to choose eight correct locations in a 4×4 matrix on a computer display. The locations were arranged either in a structured spatial pattern or an unstructured but consistent spatial arrangement. When the assignment of correct and incorrect locations was reversed after initial learning, participants in the spatial pattern condition demonstrated reversal performance immediately (i.e., following the first choice after reversal of the contingencies). Follow-up experiments confirmed that immediate reversal performance depends on a structured spatial pattern among the locations and that a learned motor pattern cannot explain the immediate reversal performance. This pattern of results shows that learning the spatial relations among locations has precedence over learning about the individual locations, even when the individual locations are completely valid predictive cues.

Spatial patterns are often important components of the structure of visual stimuli (e.g., Lockhead and Pomerantz, 1991). However, spatial patterns can also be embedded in the functional properties of stimuli even when no perceptual cues correspond to the pattern. It seems evident that such hidden spatial patterns can be identified and control behavior even though they are defined only by the functional properties of locations. For example, carpenters learn the spatial pattern of the structure hidden behind walls (e.g., vertical members separated by 16 in. in traditional residential buildings in the United States).

Such spatial pattern learning has been investigated by Brown and colleagues (for reviews, see Brown, 2006a,b). Rats searched among a 5×5 matrix of discrete spatial locations, defined by food wells at the top of poles. On each experimental trial, some of the locations contained food. The baited locations were not defined by any perceptual cues, and they were unpredictable at the beginning of each trial. However, the baited locations were arranged in a consistent spatial pattern. Once one or more of them had been located, the spatial pattern provided information about the remaining locations. The choices of rats were controlled by several such patterns, including squares (Brown and Terrinoni, 1996) and checkerboards (Brown et al., 2001). Thus, rats learned the abstracted spatial pattern and used representations of the pattern to more efficiently locate places that form an exemplar of the pattern (Brown, 2006b).

Sturz et al. (2009) recently tested humans in similar experimental paradigms. One paradigm involved a search task very similar to that used with rats and a second was an analogous dynamic first-person perspective three-dimensional virtual environment grid of spatial locations. In both paradigms, human subjects were strongly controlled by a square pattern of goal locations, and this control was facilitated by perceptual cues corresponding to the goals. Sturz et al. (2010), using the same experimental paradigms, found evidence for control by a diamond pattern of spatial locations (four baited locations forming a diamond with a non-baited location in the center). In both sets of experiments, participants learned about the spatial pattern even in the presence of redundant, relevant visual cues that specified the locations that were correct on each trial. On the basis of associative accounts of spatial cue learning (e.g., Pearce et al., 2006), those cues would be expected to reduce learning about the spatial pattern. In fact, the presence of the visual cues facilitated control by the spatial patterns.

The present experiments were motivated by the question of how learning about the individual locations that form a spatial pattern is related to learning about the pattern itself. In the spatial pattern learning experiments we have conducted with humans and non-humans, the spatial locations of individual goal locations have varied unpredictably from trial to trial. Thus, learning the locations of specific goal locations was not possible. But what if the goals were consistently located during learning, such that both individual locations and a spatial pattern of locations were relevant to the search task? To what extent would a hidden spatial pattern be learned even when the individual goals are consistently located

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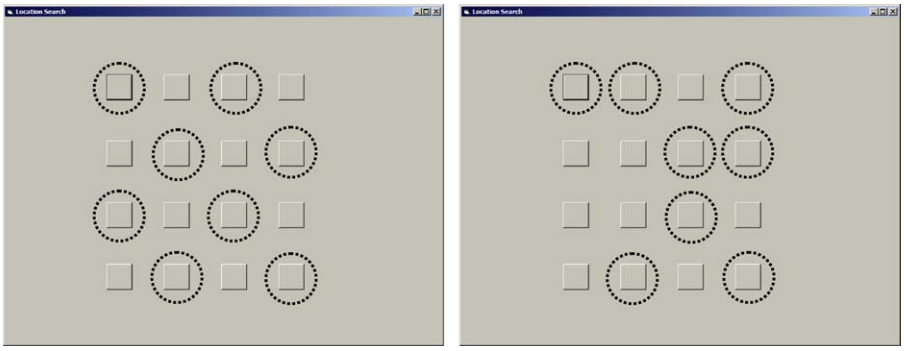

Fig. 1. The stimulus display, with example configurations of correct button locations indicated for the Pattern Condition (left panel) and Random Condition (right panel) in Experiment 1. The dashed circles are superimposed on the stimulus display to indicate example correct button locations; they were NOT included in the stimuli shown to participants.

with respect to spatial cues, and are therefore sufficient to support performance?

There has been much recent debate in the spatial learning literature about the extent to which perceptual cues specifying a location compete for learning with more global spatial cues, such as geometric cues. Cheng (1986) initially suggested that the geometric properties of an environment do not compete with perceptual cues specifying locations and that the coding and processing of such cues involves a geometric "module" that is, at least to some extent, isolated from other learning processes. This idea has had a great deal of influence on the study of human and non-human spatial learning (see Cheng and Newcombe, 2005 for a review). Recent theoretical and empirical developments have complicated this idea (Cheng, 2008; Doeller and Burgess, 2008; Miller and Shettleworth, 2007; Sturz and Diemer, 2010). The spatial patterns used in the present experiments apparently do not compete with perceptual cues specifying locations in studies using either rats (Brown et al., 2002) or humans (Sturz et al., 2009, 2010). This might be interpreted as suggesting that spatial pattern learning is isolated from learning about the perceptual cues corresponding to individual spatial locations, although alternative explanations (similar to those applied in the case of geometric cues) are possible (Sturz et al., 2009, 2010).

In the present experiments, human participants chose locations from a 4×4 grid of locations on a computer display. During the learning phase, a consistent set of eight locations was correct. Participants could learn the correct locations over trials, thereby increasing the efficiency of their search. In the experimental condition, the correct locations were arranged in a structured spatial pattern (checkerboard; see Fig. 1). We used the term "pattern" to refer to such a structured spatial configuration. In the control conditions used in most of the present experiments (Experiments 1, 3, 4, and 5), correct locations were chosen randomly for each participant. Thus, in the control conditions, there was no spatial structure inherent in the spatial configuration of correct locations (i.e., unstructured spatial configuration), although there were consistent spatial relationships among the correct locations in both cases. Participants in the experimental condition could learn the locations of individual correct choice alternatives, the pattern according to which they were arranged, or both. Presumably, learning the spatial relations among the correct locations would be much more difficult in the control condition.

As far as we are aware, all existing theoretical views of spatial learning predict that the individual correct locations would be learned, although some would predict that the extent of that learning would be diminished by the presence of the spatial pattern as a redundant, relevant cue. However, it is not clear whether the pattern of spatial locations would be expected to acquire control of choices, given that the individual locations provide valid information about their status.

We used a reversal learning paradigm to examine the relationships between learning the individual spatial locations and learning the spatial pattern formed by the locations. After participants learned to choose the correct locations, the identity of correct and incorrect locations was reversed such that all of the formerly correct locations became incorrect and all of the formerly incorrect locations became correct. In the experimental condition, the checkerboard pattern that had defined correct locations also defined the spatial relationship among the correct locations after the reversal. After participants learned the new contingencies, they were reversed again. This process of reversal after learning was repeated.

The experimental paradigm was designed to be analogous to that used by Vaughan (1988) with pigeon subjects and arbitrary sets of complex visual stimuli. Vaughan found that, after several reversals, pigeons began responding correctly to individual stimuli to which they had not been exposed since the last reversal. Thus, he concluded, the pigeons must have formed categories of stimuli based on their functional properties ("equivalence sets") allowing correct responding to particular members of the category after being exposed to the changed contingencies for other members of the category. Similarly, we expected that evidence of categories of individual locations would come in the form of correct responses to newly reversed locations after several reversals. Furthermore, we expected a spatial pattern of locations to facilitate such reversal learning. That result would provide evidence that locations are coded in terms of the pattern.

1. Experiment 1

In Experiment 1, reversal performance was compared in a group for which correct and incorrect locations were arranged in a checkerboard pattern and a control group for which the sets of locations were chosen (and therefore spatially arranged) randomly. For both groups, the identity of all correct and incorrect locations changed with each reversal. For the pattern group, however, the spatial relations among the correct locations, among the incorrect locations, and between the sets of correct and incorrect locations are all preserved following reversals. Thus, representation of the correct and/or incorrect locations in terms of the checkerboard pattern should be revealed by more rapid reversal learning relative to the control group.

1.1. Method

1.1.1. Participants

Forty-four Villanova University students (24 female) participated as part of a research requirement in an introductory psychology course.

1.1.2. Materials

Stimuli were displayed on standard 19-in. liquid crystal display (LCD) computer monitors (1152 × 864 pixels). Choice responses involved using a standard computer mouse to move a cursor over a stimulus element and clicking the left mouse button. The stimuli and trial procedures were implemented by a program created using Microsoft Visual Basic (Version 6.0).

Participants were tested either alone or in groups of up to six, in a room containing approximately 20 computers. When groups of participants were tested together, they were separated in the room to minimize distracting each other.

1.1.3. Procedure

Each participant was randomly assigned to one of two experimental conditions (Pattern Condition or Random Condition) with the constraint that approximately equal numbers of female and male participants were assigned to each condition.

After reading and signing a standard experimental consent form, a participant was seated in front of a computer monitor with a keyboard and mouse on a table. The participant was asked to read the following written instructions:

> You will see a 4 × 4 grid of buttons on each of many trials. About half of the buttons are correct on each trial. Your job is to locate all of the correct buttons and click on them. There is no way to know which buttons are correct at first. But when you choose a correct location, the background will turn GREEN. When you choose an incorrect location, the background will turn RED. So you may be able to learn the locations of correct buttons. The more rapidly you learn the correct locations, the sooner you will be able to complete the experiment.
> Thanks for your participation in this experiment!

At this point, the computer monitor displayed a standard Microsoft Windows "window" (grey background with a blue band at top labeled "Location Search" as shown in Fig. 1). There was a 3 cm (wide) by 1 cm (tall) grey button centered near the top of the display (1.5 cm above where the top row of buttons would later appear) labeled "Begin Session". After being asked if they had any questions about the procedure, participants were instructed to click on that button whenever they were ready to begin the experiment.

Clicking the "Begin Session" button resulted in immediate display of the standard stimulus display. The stimulus display was a 4 × 4 matrix of grey squares ("buttons"), each 1.1 cm on each side and separated from adjacent squares by 1.8 cm (edge to edge) displayed on a grey background as shown in Fig. 1. When a participant chose a button by clicking on it, two things occurred: first, feedback that a choice had been made was provided by an "X" appearing in the center of the chosen button and a dotted square appearing within the boundary of the button; second, if the button was designated as correct for that participant, then the background changed to green. If the button was incorrect, the background changed to red. This visual feedback about the button chosen and whether it was correct remained in place until the next choice was made.

For each participant in the Pattern Condition, one of two sets of buttons was correct during the Initial Learning Phase of the experiment. Each set formed a checkerboard spatial pattern and consisted of either the eight buttons indicated as an example in the left panel of Fig. 1 or the complementary set of eight buttons (the dotted circles used in Fig. 1 to identify the members of the set are for illustration purposes only. The dotted circles were NOT included in any stimulus shown to participants). The set of buttons forming the checkerboard pattern during the Initial Learning Phase was determined randomly for each participant in the Pattern Condition. For each participant in the Random Condition, a randomly selected set of eight buttons was designated correct (example illustrated in right panel of Fig. 1).

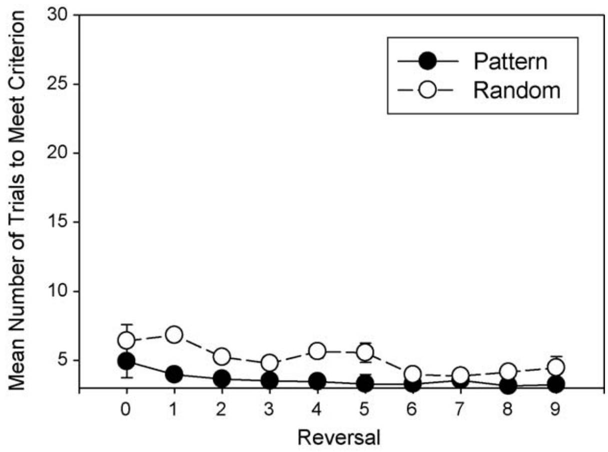

Fig. 2. The mean number of trials required to meet the performance criterion during Initial Learning (Reversal 0) and phases following each of the nine reversals in the Pattern and Random conditions of Experiment 1. Three trials are minimum required to meet the performance criterion. Error bars indicate one Standard Error of the Mean (S.E.M.).

Participants made choices with the computer mouse. A mouse click occurring while the arrow cursor point was within the boundaries of a button designated choice of that button. During each trial, the participant made choices until all eight correct buttons had been chosen. The matrix of buttons then disappeared and a display reading "Congratulations! You Found Them All" appeared just above the area where the matrix of buttons had been. This display remained during the 3 s inter-trial interval (ITI). The next trial was then initiated by reappearance of the matrix of buttons. The program recorded the sequence of choices and the time of each choice.

The Initial Learning Phase (Reversal 0) consisted of repeated trials until a learning criterion of three consecutive trials with zero or one error occurred. An error was defined as choice of an incorrect button (repeated choices of a correct button were not considered to be errors). The identity of the correct and incorrect buttons was then reversed for the following trials (Reversal 1 Phase). Trials continued until the same learning criterion was again met at which point the identity of the correct and incorrect buttons was reversed (back to the original set; Reversal 2 Phase). This process repeated until a total of nine reversals had been completed. Sessions typically lasted 15–25 min.

1.2. Results

Fig. 2 shows the number of trials required to meet the learning criterion during Initial Learning and each of the nine reversal phases of the experiment. A three-way mixed analysis of variance (ANOVA) on number of trials to reach criterion with Experimental Condition (pattern, random), Gender (male, female), and Reversal (0–9) as factors revealed that more trials were required to meet criterion in the Random Condition than in the Pattern Condition, $F(1, 40) = 10.8$, $p < .05$ and that performance differed over the course of Reversals, $F(9, 360) = 3.2$, $p < .05$. There was no evidence of an interaction between the effects of these variables, $F(9, 360) < 1$. There was no effect of Gender, $F(1, 40) < 1$. There was an interaction between the effects of Gender and Reversal, $F(9, 360) = 2.6$, $p < .05$, apparently due to the faster learning during the Initial Learning Phase by males (trials to criterion $M = 3.9$) than by females ($M = 7.1$). There were no other interactions involving Gender (all Fs < 1).

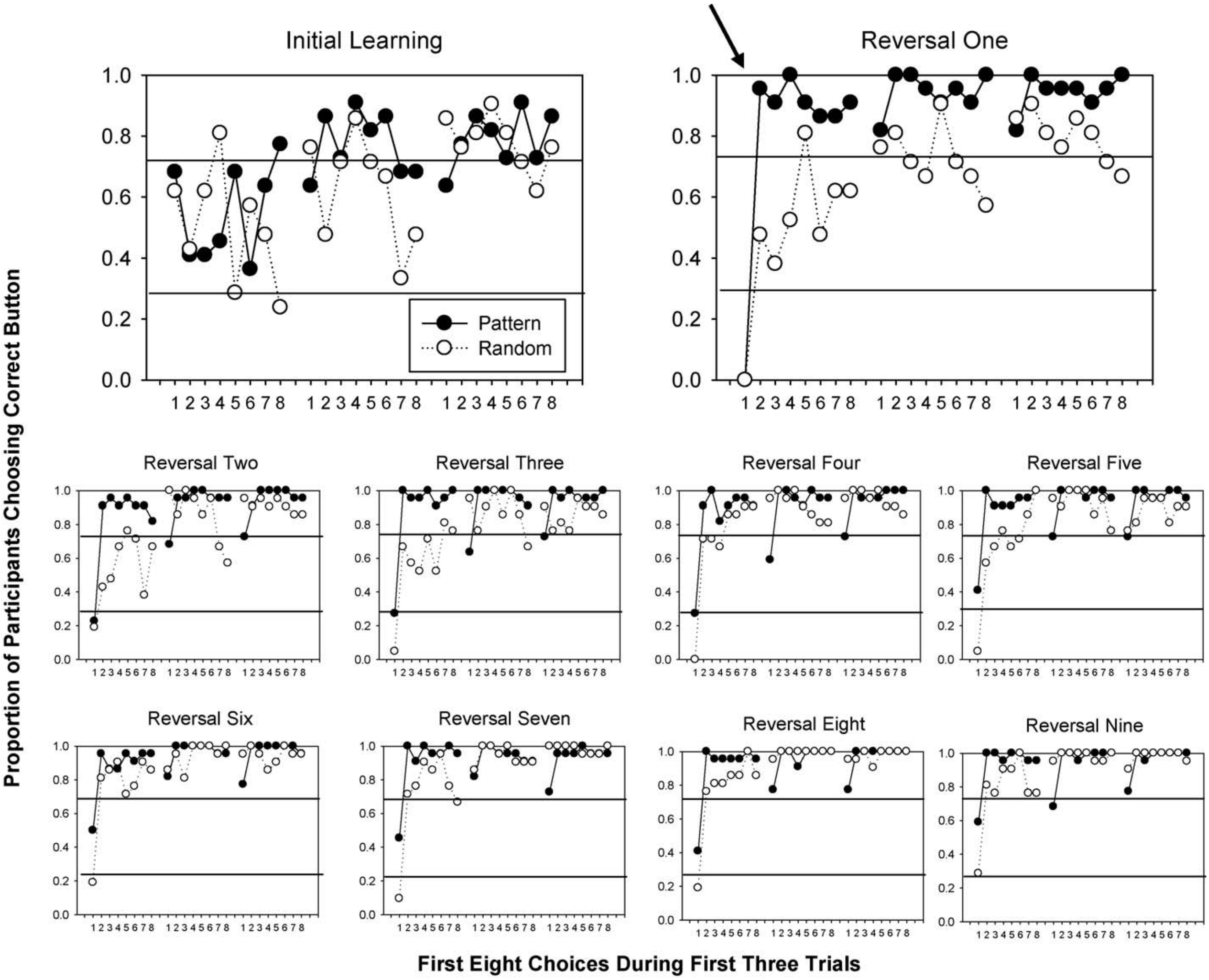

Fig. 3. The proportion of participants choosing a correct button during the first eight choices of the first three trials of Initial Learning (Reversal 0) and phases following each of the nine reversals in the Pattern and Random conditions of Experiment 1. The reference lines indicate values that are significantly below or above chance (50%; binominal test). The arrow highlights the data point for the critical second trial following the first reversal.

To examine the course of reversal performance with a higher degree of resolution, we analyzed the first eight choices made during the first three trials of initial learning and each of the nine reversals (Fig. 3). The analysis was restricted to the first eight choices because eight is the minimum number of choices that must be made during a trial, allowing for comparisons that include the behavior of all participants. Likewise, the analysis was restricted to the first three trials of each reversal because three is the minimum number of trials required to meet the learning criterion. The reference lines in Fig. 3 indicate the values above and below chance (0.5) that are statistically reliable (binomial test).

The key result is that reversal learning occurred immediately in the Pattern group. Following the first reversal, every participant (i.e., 100%) chose an incorrect button on her or his very first choice. However, on the next choice all but one participant (i.e., 96%) choose a correct button. In the Random group, on the other hand, above-chance levels of choice accuracy did not occur immediately after a reversal until the sixth reversal. This key result is isolated in Fig. 4, which shows the proportion of participants who chose a correct button on each of the first eight choices during the first reversal phase (top panel) as well as the proportion of participants who chose a correct button on the critical second choice following a reversal across the nine reversals (bottom panel).

1.3. Discussion

Although it was predicted that arrangement of locations in a spatial pattern would facilitate reversal learning, the immediate reversal performance obtained in the Pattern condition was unexpected and surprising. Following the first reversal, all participants made an incorrect choice, confirming that they had learned the initially correct locations and that there was no artifactual cue indicating those locations were no longer correct. All but one participant (i.e., 96%) choose a newly correct location on the very next choice. Thus, reversal of performance occurred *immediately* (on the second choice following the reversal; the outcome of the very first choice following the reversal provided the only cue that a reversal had occurred). Following the first and subsequent reversals, participants chose correct locations and avoided choice of incorrect locations before they had experienced any feedback about the change in status for those individual locations.

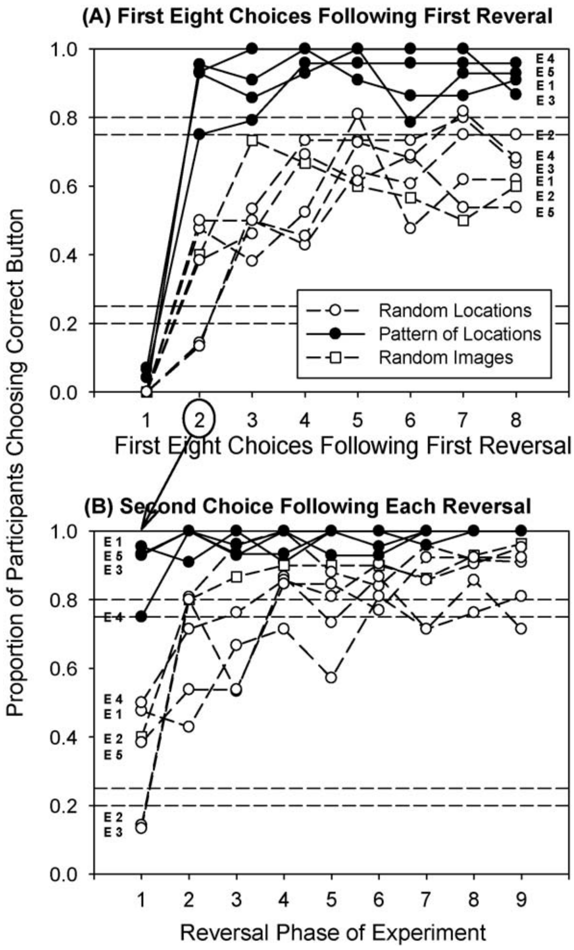

Fig. 4. Isolation of the critical performance shown in Fig. 3 from Experiment 1 (labeled "E1") and corresponding data from the other four experiments to be presented below ("E2", "E3", "E4" and "E5" indicate data from Experiments 2, 3, 4, and 5, respectively). Panel A: Choice accuracy following the first reversal. Panel B: Choice accuracy during the second choice following each reversal. Reference lines indicate the range of values that are significantly below or above chance across the condition of all four experiments. In the case of Experiment 5, only data from the free choices conditions are shown.

Vaughan (1988) interpreted the (slow) development of reversal performance as evidence that the two sets of stimuli became "functional equivalence sets" such that changes in the properties of one (or more) member(s) of a set applied to other members of the same set. In the case of arbitrarily assigned sets, such as Vaughan used, the equivalence set learning required a number of reversals. In the control condition of the present experiment, reversal learning emerged over the course of several reversals; thus performance in this condition can be understood in terms of an acquired relationship among the members of the two sets of locations, along the lines suggested by Vaughan for visual stimuli. However, the processes involved in the immediate reversal performance found in the pattern condition must be interpreted differently. Reversal performance in the pattern condition did not require repeated exposure to the change in outcome common to members of a stimulus set, as does acquired equivalence performance. Rather, something inherent in the stimulus set is required to explain the reversal of performance following exposure to the outcome that followed a single stimulus in the set. We propose it is the structure in the spatial arrangement of the correct locations (i.e., the pattern) that allows immediate reversal performance.

We propose that the immediate reversal performance indicates that participants in that condition represented the correct locations *primarily* in terms of the checkerboard pattern defining the spatial relations among them. To the extent that the locations of individual goals were learned, that learning would have reduced choice of correct locations immediately following a reversal.

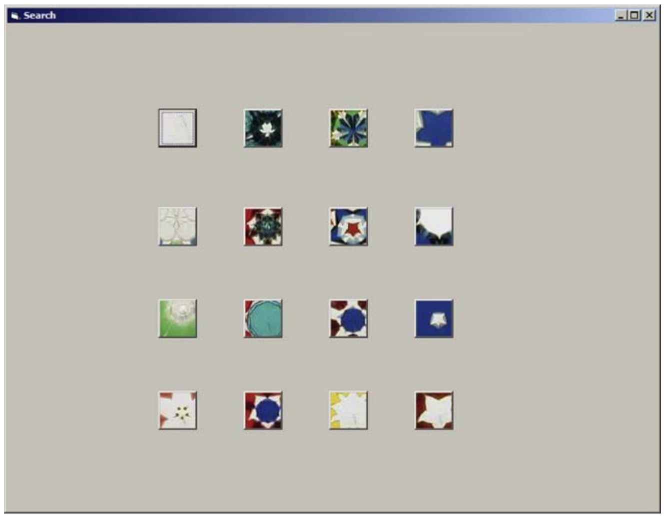

Fig. 5. An example of the stimulus display used in Experiments 2, 3, 4, and the free-choice conditions of Experiment 5. The 16 images were randomly assigned to button locations on each trial.

2. Experiment 2

Reversal performance in the control condition of Experiment 1 was not immediate. However, after a seemingly small number of reversals (five or six), choices were reliably correct on the second choice following a reversal. This raises the possibility that systematic spatial patterns not only like the checkerboard pattern used in Experiment 1, but also perhaps any consistent spatial configuration of goals, can produce rapid reversal performance. The spatial configuration, in addition to the individual goal locations, can serve as a cue that allows more rapid acquisition of correct responding when the contingencies defining the correct locations are reversed.

Experiment 2 was designed to investigate this possibility by comparing reversal performance when the two sets of alternatives are defined by their spatial location (as was the case in both conditions of Experiment 1) and when they are defined by distinct visual features. The same matrix of 16 choice alternatives used in Experiment 1 was used in Experiment 2 but the alternatives were distinguished by both their location and visual features (Fig. 5). In both conditions, the visual features defining the alternatives varied randomly from trial to trial in terms of their location. For some participants, the two sets of alternatives were defined by visual features (and location was irrelevant). For others, the two sets of alternatives were defined by location (and visual features were irrelevant). The question was whether the acquisition of reversal performance would be similar in these two conditions. To the extent that spatial relations among locations are represented in the latter condition, it would be expected that reversal performance would be acquired more rapidly in that condition.

2.1. Method

2.1.1. Participants and materials

Fifty-nine Villanova students (43 female) participated as part of a research requirement in an introductory psychology course. The experiment was conducted in the same room and using the same computers as Experiment 1.

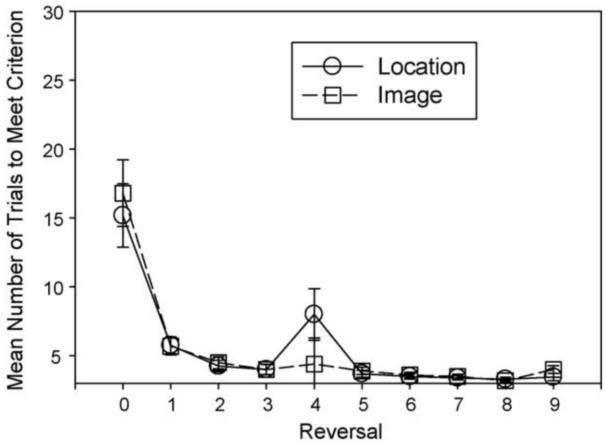

Fig. 6. The mean number of trials required to meet the performance criterion during Initial Learning (Reversal 0) and phases following each of the nine reversals in the Location and Visual Image conditions of Experiment 2. Three trials is the minimum required to meet the performance criterion. Error bars indicate one S.E.M.

2.1.2. Procedure

Each participant was randomly assigned to one of two experimental conditions (Location Condition or Image Condition), with the constraint that approximately equal numbers of female and male participants were assigned to each condition (females: 23 in the Location Condition, 20 in the Image Condition; males: 7 in the Location Condition, 9 in the Image Condition).

The stimulus display was the same as that used in Experiment 1 except that each button had one of the 16 images shown in Fig. 5. These images were snippets of kaleidoscope images, produced by cropping areas of the images used by Wright et al. (1985). The label at the top of the window in which the stimulus display was shown was changed (relative to that used in Experiment 1) to read "Search".

Regardless of experimental condition, each of the 16 images was randomly assigned to one of the 16 button locations on every trial. For each participant in the Location Condition, a set of 8 buttons (locations) was randomly selected as correct for the Initial Learning Phase (Reversal 0). Those locations were correct regardless of the images that appeared in them. For each participant in the Image Condition, a set of 8 images was randomly selected as correct for the Initial Learning Phase (Reversal 0). Those images were correct regardless of the button location in which they appeared. The same learning criterion and reversal procedure was used as in Experiment 1 except that, if a participant did not complete the protocol within 25 min, the session was aborted.

2.2. Results

Ten participants did not complete the protocol within the time limit: 3 females in the Location Condition (sessions aborted during Reversal 7, 8, and 9), 2 males in the Image Condition (Reversal 0 and 1), and 5 females in the Image Condition (Reversal 2, 5, 7, 9, and 9).

The same analyses used for Experiment 1 were applied to the data of the participants who completed the experimental protocol. Fig. 6 shows the number of trials required to meet the learning criterion during Initial Learning and each of the nine reversal phases of the experiment. A three-way mixed ANOVA on number of trials to reach criterion with Experimental Condition (location, image), Gender (male, female), and Reversal (0–9) as factors revealed that as in Experiment 1, performance differed over the course of Reversals, $F(9, 405) = 31.6$, $p < .05$. There was no evidence of a difference between the Experimental Conditions, $F(1, 45) < 1$ nor of an interaction between the effects of Condition and Reversal, $F(9, 405) < 1$. There was no effect of Gender or any interaction involving Gender (all Fs < 1.2).

Fig. 7 shows the proportion of participants (among those who completed the experimental protocol) who chose a correct button (defined by location or image, depending on experimental condition) over the first eight choices of the first three trials of each reversal. Fig. 4 isolates these proportions for the first reversal and the second choice across reversals. Learning and reversal performance was similar in the location and image conditions, with several reversals required before choice performance reversed immediately following a reversal.

2.3. Discussion

The acquisition of reversal performance was similar for participants who had to discriminate correct and incorrect choices based on their visual features and those who had to discriminate based on their location. Thus, these data provide no evidence that the consistent spatial relations among the locations, in comparison to the arbitrary relationships among the two sets of visual stimuli, provide an advantage for discriminating between members of the two sets. Of course, we have no control over (or measure of) the difficulty of the particular spatial discriminations involved in this task relative to the difficulty of the particular visual discriminations involving the stimuli used. It is possible that the spatial relations among the locations in the Location Condition did facilitate discrimination and reversal performance in that condition but that the advantage was balanced by the visual discrimination involved in the Image Condition being easier than the spatial discrimination involved in the Location Condition in other ways. However, these data suggest that, when they are not arranged in structured patterns, discrimination of spatial locations does not produce reversal performance substantially different from that produced by discrimination of visual stimuli.

The performance obtained with visual stimuli in this experiment can be described as a case of equivalence class formation (Sidman, 1994). The two sets of visual stimuli were arbitrarily determined. After several reversals, appropriate responding to a particular stimulus occurred before the reversed contingency with respect to that particular stimulus had been experienced. In the framework of equivalence class formation, this occurs because the stimuli within each set come to be treated as equivalent. The similar performance with sets of locations to that obtained with visual stimuli suggests that the results obtained in the present experiments with randomly chosen sets of spatial locations can also be understood as a case of equivalence class formation. Although equivalence class formation has been suggested as a possible explanation of spatial reversal learning in radial arm maze procedure (Brown and Giumetti, 2006), we are not aware of any earlier demonstrations of equivalence class formation in humans involving sets of spatial locations.

3. Experiment 3

Experiment 3 is a replication of Experiment 1, but with the visual stimuli used in Experiment 2 present. Although the stimuli were present and varied randomly in their location over trials (just as in Experiment 2), they were irrelevant to the task. However, they constitute a property of choice alternatives other than location which, from participants' perspective, *could* be relevant during original learning or following reversals. Specifically, the presence of the visual cues defining correct locations in Experiment 2 may have been detrimental to learning the spatial configuration of locations for participants in the pattern condition. Participants may have needed not only to learn the spatial configuration of loca-

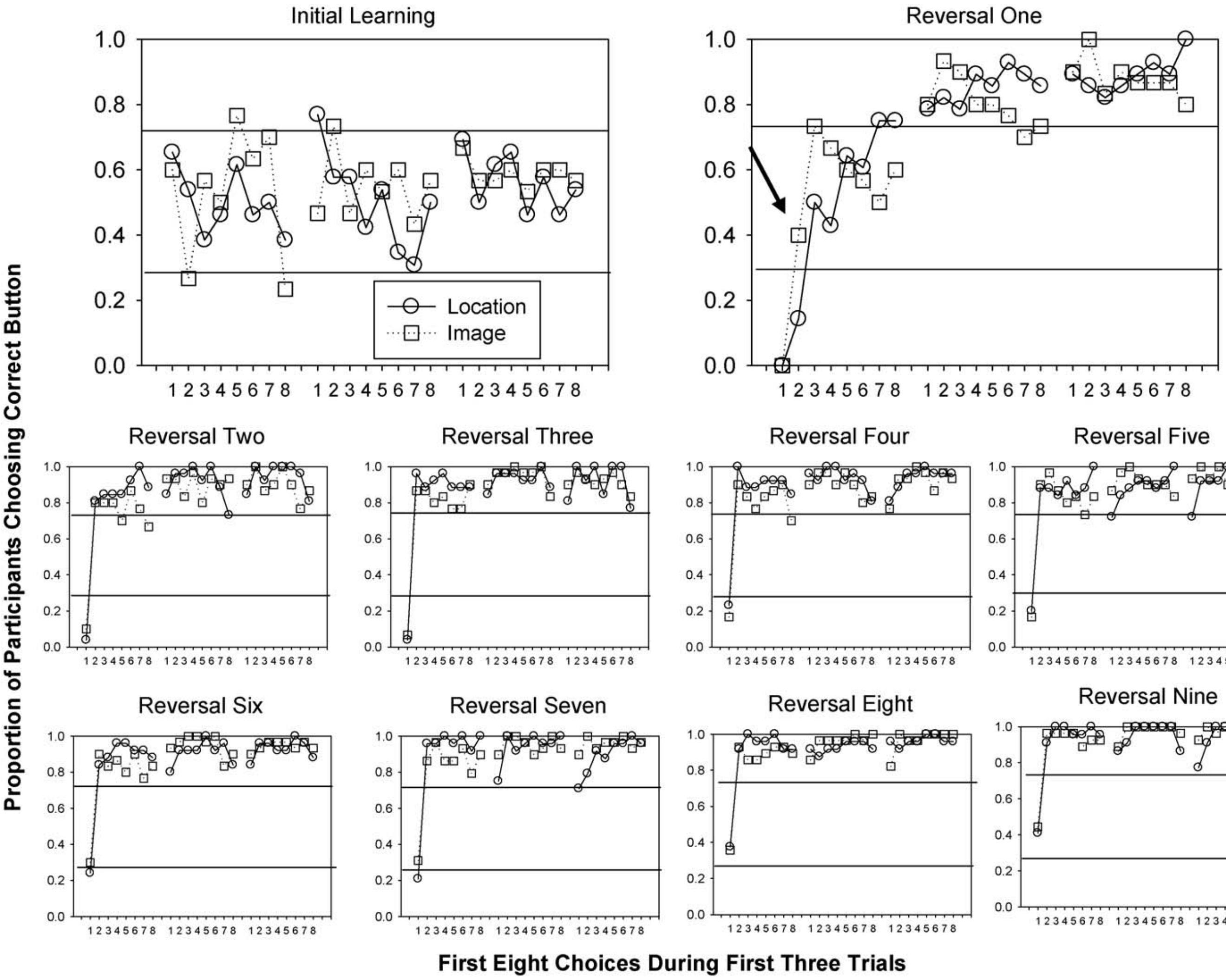

Fig. 7. The proportion of participants choosing a correct button during the first eight choices of the first three trials of Initial Learning (Reversal 0) and phases following each of the nine reversals in the Location and Visual Image conditions of Experiment 2. The reference lines indicate values that are significantly below or above chance (50%; binominal test). The arrow highlights the data point for the critical second trial following the first reversal.

tions but also to ignore the visual cues. As a result, the question of primary interest in Experiment 3 was whether the immediate reversal performance found in the checkerboard pattern condition of Experiment 1 would be found when choice alternatives varied not only in location but also in terms of their visual features. To the extent that visual cues are detrimental to learning the spatial configuration of locations, immediate reversal performance found in Experiment 1 should be diminished by the presence of these visual cues.

3.1. Method

3.1.1. Participants and materials

Thirty Villanova students (11 female) participated as part of a research requirement in an introductory psychology course. The experiment was conducted in the same room and using the same computers as Experiments 1 and 2.

3.1.2. Procedure

Each participant was randomly assigned to one of two experimental conditions (Pattern Condition or Random Condition), with the constraint that approximately equal numbers of female and male participants were assigned to each condition (females: 6 in the Pattern Condition, 5 in the Random Condition; males: 9 in the Pattern Condition, 10 in the Random Condition).

The procedure was the same as that of Experiment 1, except that the images used in Experiment 2 were present, the label above the Window in which the experiment was presented was labeled “Search” (as in Experiment 2), and the same session time limit used in Experiment 2 was in force. Each of the 16 images was assigned to a random button location in the matrix on each trial. Thus, images appeared in a manner that was irrelevant to the experimental task in both conditions.

3.2. Results

All but one participant completed the experimental protocol within the session time limit (a male in the Random condition, who completed Reversal 5 before time expired and the session was aborted). The data presented below do not include this participant.

Fig. 8 shows the number of trials required to meet the learning criterion during Initial Learning and each of the nine reversal phases of the experiment. A three-way mixed ANOVA on number of trials to reach criterion with Experimental Condition (pattern, random), Gender (male, female), and Reversal (0–9) as factors revealed, as in Experiments 1 and 2, performance differed over the course of

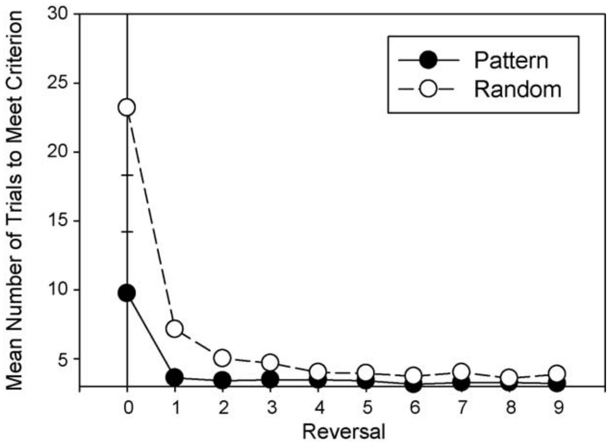

Fig. 8. The mean number of trials required to meet the performance criterion during Initial Learning (Reversal 0) and phases following each of the nine reversals in the Pattern and Random conditions of Experiment 3. Three trials are minimum required to meet the performance criterion. Error bars indicate one S.E.M.

reversals, $F(9, 225) = 4.3$, $p < .05$. There was not a significant effect of Condition, $F(1, 25) = 2.78$, $p = .1$, nor an interaction between the effects of Condition and Reversal, $F(9, 255) < 1$. There was no evidence of an effect of Gender or any interaction involving Gender (all $Fs < 1$).

Fig. 9 shows the proportion of participants who chose a correct button location over the first eight choices of the first three trials of each reversal. Fig. 4 isolates these proportions for the first reversal and the second choice across reversals. As in Experiment 1, there was immediate reversal learning in the Pattern Condition. During the first trial following the first reversal, all but one participant chose an incorrect button on the first choice (i.e., 94%), but then all but one participant chose a correct button on the second choice (i.e., 94%). Performance continued to be nearly perfect, with the exception of the first choice on trials during early reversals. Immediate reversal learning did not occur in the Random Condition, although there were very high levels of reversal performance starting with the second reversal.

3.3. Discussion

As in Experiment 1, virtually all participants chose an incorrect button on the first choice after the first reversal, showing

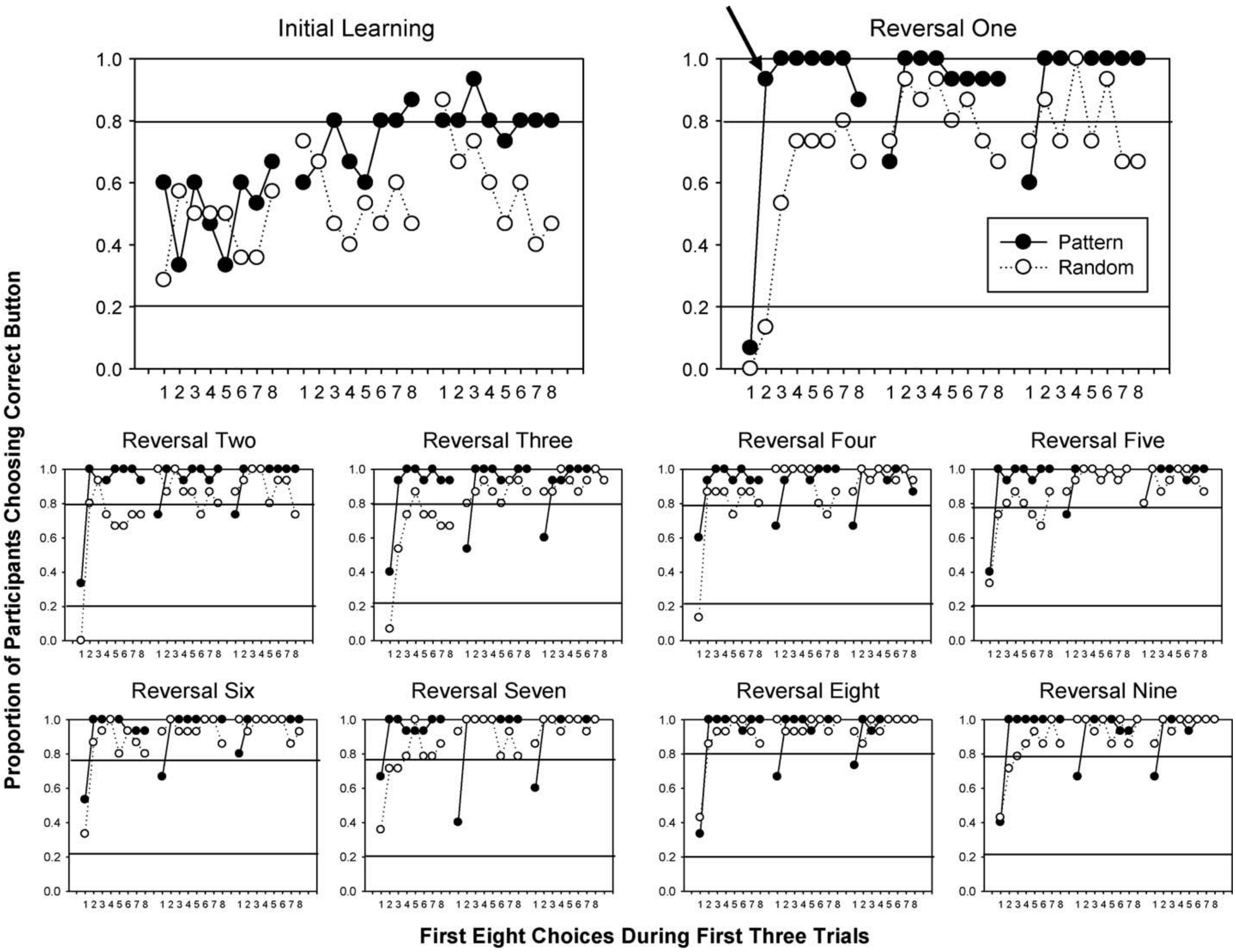

Fig. 9. The proportion of participants choosing a correct button during the first eight choices of the first three trials of Initial Learning (Reversal 0) and phases following each of the nine reversals in the Pattern and Random conditions of Experiment 3. The reference lines indicate values that are significantly below or above chance (50%; binominal test). The arrow highlights the data point for the critical second trial following the first reversal.

that there were no artifactual cues revealing that something had changed. Also as in Experiment 1, choices were virtually always correct thereafter, except on the very first choice following subsequent reversals. Thus, the presence of distinct visual stimuli as alternatives to spatial location did not diminish immediate reversal performance.

4. Experiment 4

The structured spatial pattern used in all of the previous experiments was a checkerboard. It is important to determine whether the immediate reversal performance discovered to occur in those experiments is a function of some particular property of the checkerboard pattern or of structured patterns of spatial locations more generally. Experiment 4 was designed to determine whether immediate reversal performance occurs with a second relatively simple structured spatial pattern. Specifically, the pattern was alternating lines of correct and incorrect locations (either alternating rows of buttons or alternating columns of buttons).

The checkerboard pattern and alternating lines patterns differ in a number of ways. For example, in the case of rows (or columns) of buttons, correct locations are adjacent to each other in one dimension (the horizontal dimension for rows of correct locations and the vertical dimension for columns of correct locations) but are separated from each other by one location in the alternate dimension. In the case of the checkerboard pattern, on the other hand, the correct locations are separated from each by one location in both dimensions. Both checkerboard and line patterns have structure that a random configuration of locations does not, and both have been shown to control spatial choice in rats (Brown et al., 2000; Brown and Terrinoni, 1996). Thus, if the presence of this spatial structure is an important factor in producing the immediate reversal performance obtained in the previous experiments, we expect the line patterns to also produce immediate reversal performance similar to those obtained with the checkerboard pattern.

4.1. Method

4.1.1. Participants and materials

Forty-nine Villanova students (24 female) participated as part of a research requirement in an introductory psychology course. The experiment was conducted in the same room and using the same computers as the previous experiments.

4.1.2. Procedure

The experimental design called for each of 48 participants to be randomly assigned to one of two experimental conditions (Pattern Condition or Random Condition) with the constraint that equal numbers of female and male participants were assigned to each condition. An "extra" (49th) participant was a male assigned to the Random Condition. The male and female participants in the pattern condition were equally distributed into four subgroups. Six participants of each gender had alternating rows of correct and incorrect buttons and six of each gender had alternating columns of correct and incorrect buttons. With each of these subgroups, for three participants the buttons in the first and third row (or column) were correct during the Initial Learning Phase. For the other three participants in each subgroup, the buttons in second and fourth row (or column) were correct during the Initial Learning Phase. For those in the Pattern Condition, the pattern remained either rows or columns throughout the experiment. Reversals consisted of changes in whether the correct buttons were in the first and third row (or column) or in the second and fourth row (or column).

Aside from the difference in the pattern used in the Pattern Condition, the procedure was identical to that used in Experiment 3.

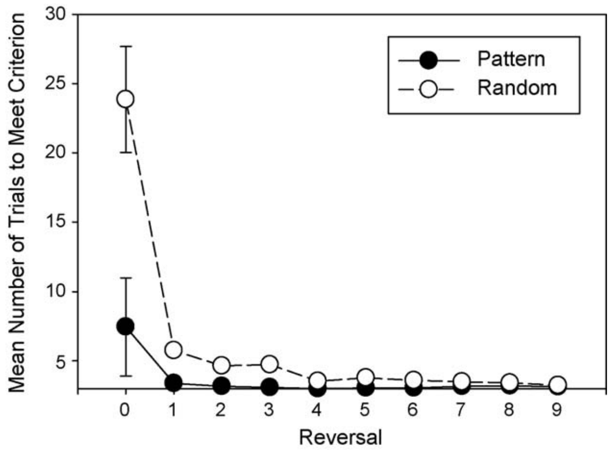

Fig. 10. The mean number of trials required to meet the performance criterion during Initial Learning (Reversal 0) and phases following each of the nine reversals in the Pattern and Random conditions of Experiment 4. Three trials are minimum required to meet the performance criterion. Error bars indicate one S.E.M.

4.2. Results

Four participants failed to complete the experimental protocol within the session time limit. These participants all failed to meet the learning criterion during the Initial Learning Phase. All four were in the Random Condition (two females and two males). The data presented below do not include these participants.

Fig. 10 shows the number of trials required to meet the learning criterion during the Initial Learning Phase and each of the nine reversal phases of the experiment. A three-way mixed ANOVA on number of trials to reach criterion with Experimental Condition (pattern, random), Gender (male, female), and Reversal (0–9) as factors revealed that, as with the earlier experiments, performance differed over the course of Reversals, $F(9, 369) = 21.5$, $p < .05$. There was a significant effect of Experimental Condition, $F(1, 41) = 3.87$, $p < .05$ and an interaction between the effects of Condition and Reversal, $F(9, 369) = 8.93$, $p < .05$. There was also an interaction among the effects of Condition, Reversal, and Gender, $F(9, 369) = 3.45$, $p < .05$, but no evidence of a main effect of Gender or a Gender $\times$ Reversal interaction. The triple interaction involving gender is apparently due to males requiring fewer trials ($M = 15.5$) than females ($M = 32.1$) during initial learning in the random condition, $F(1, 19) = 11.9$, $p < .05$, whereas the mean number of trials required to complete the initial learning phase in the pattern condition did not differ for males ($M = 5.8$) and females ($M = 9.1$), $F(1, 22) < 1$.

Fig. 11 shows the proportion of participants who chose a correct button over the first eight choices of the first three trials of each reversal. Fig. 4 isolates these proportions for the first reversal and the second choice across reversals. As in Experiments 1 and 3, there was immediate reversal learning in the Pattern Condition. During the trial immediately following the first reversal, all but one participant in the Pattern Condition chose an incorrect button on the first choice (i.e., 96%), but then 75% of the participants chose a correct button on the second choice, $p < .01$, binomial test. Performance was subsequently close to perfect, with the exception of the first choice on trials during early reversals. Above-chance performance did not occur immediately after the first reversal in the Random Condition, although it was reached during the first reversal and very high levels of reversal performance occurred starting with the second reversal.

4.3. Discussion

Immediate transfer of spatial choices following a first reversal of location values was obtained when the locations formed a pat-

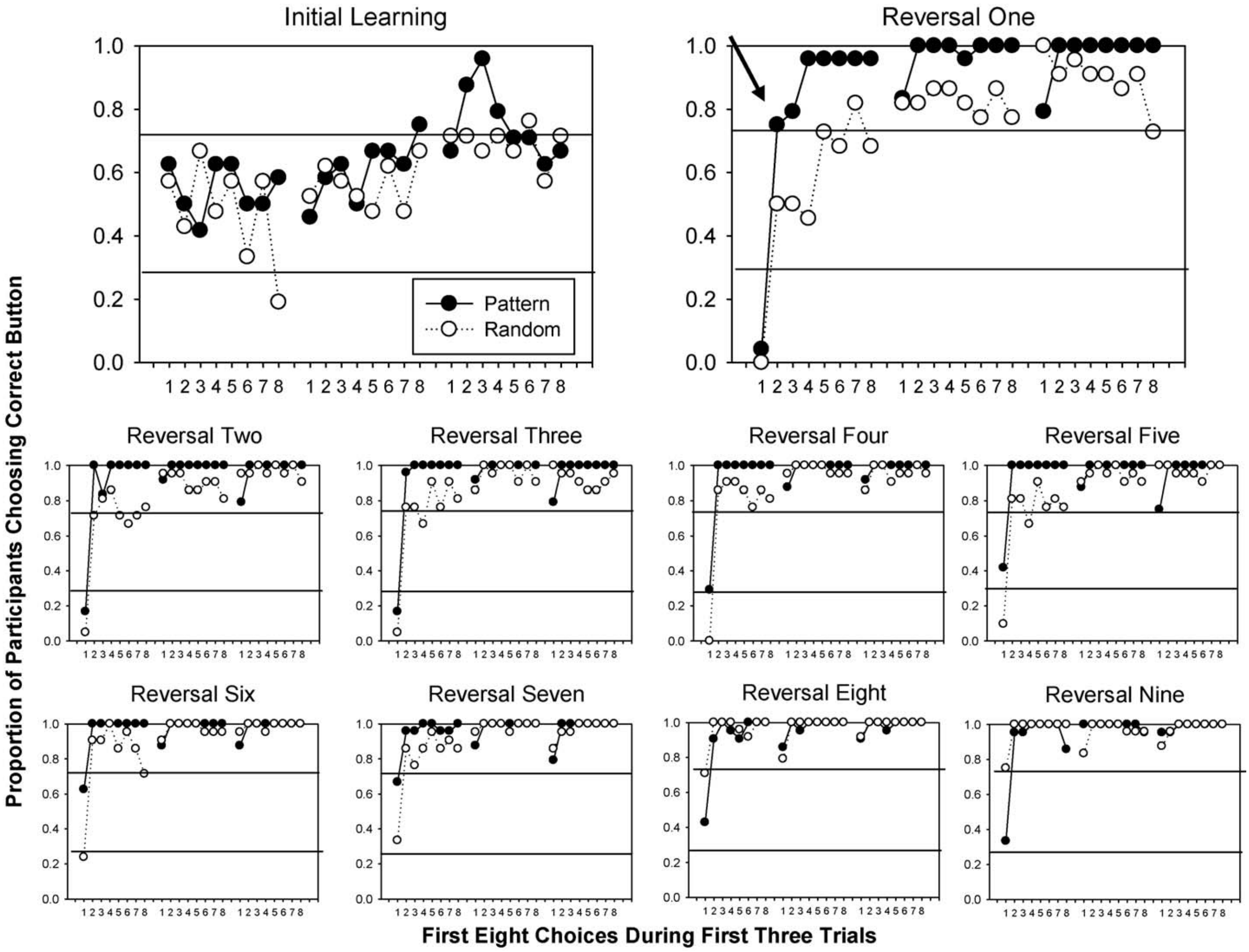

Fig. 11. The proportion of participants choosing a correct button during the first eight choices of the first three trials of Initial Learning (Reversal 0) and phases following each of the nine reversals in the Location and Pattern conditions of Experiment 4. The reference lines indicate values that are significantly below or above chance (50%; binominal test). The arrow highlights the data point for the critical second trial following the first reversal.

tern of alternating rows or columns. It should be noted that the percentage of participants choosing a (newly) correct location on the second choice following the reversal was not as high as in the experiments using a checkerboard pattern. However, immediate reversal performance is not restricted to a checkerboard pattern, but appears to be obtained with simple structured spatial patterns of locations more generally.

5. Experiment 5

One possible explanation for rapid accommodation of the reversed contingencies in the pattern conditions of these experiments involves the transfer of motor performance. Participants might learn a motor pattern that corresponds to a route through the set of correct buttons. In the case of the checkerboard or line patterns, elements of that motor pattern would facilitate transfer following reversal; for example, "choose a button in the same row or column as the just-chosen button but separated by one button" in the case of the checkerboard or "choose a button adjacent to the just-chosen button" in the case of the line pattern (see Brown et al., 2001 for an analysis of this possibility for rat spatial learning). A motor pattern learned in the random conditions would not support transfer following a reversal. Learned motor patterns cannot fully explain the immediate transfer that is the primary result of the previous experiments, because the critical correct second choice following a reversal is not consistent with the hypothetical motor pattern. However, learned motor patterns could provide a partial explanation for the high levels of performance following reversals.

Experiment 5 was designed to examine reversal performance when the possibility of motor pattern learning was eliminated. To this end, a modified version of the procedure was used in which participants had a series of two-alternative forced choices (2AFC) between buttons. The two buttons available as choices were sampled pseudo-randomly such that no consistent pattern of movement from correct button to correct button was possible. Performance in four conditions was compared. Two conditions were identical to those used in Experiment 3 (free choices with either a checkerboard pattern of correct locations or a random configuration of correct locations). The two novel conditions required 2AFCs with either a checkerboard pattern of correct locations or a random configuration of correct locations. Immediate reversal performance with a 2AFC condition could not be explained in terms of a learned motor pattern.

Fig. 12. An example of the stimulus display used in the 2AFC conditions of Experiment 5. The 16 images were randomly assigned to button locations on each trial. Two buttons indicated by frames are available for choice.

5.1. Method

5.1.1. Participants and materials

Fifty-nine Villanova students (33 female) participated as part of a research requirement in an introductory psychology course. The experiment was conducted in the same room and using the same computers as those reported above.

5.1.2. Procedure

Each participant was randomly assigned to one of four experimental conditions 2AFC-Pattern (9 females/7 males), 2AFC-Random (9 females/7 males), Free-Pattern (7 females/6 males), or Free-Random (8 females/6 males), with the constraint that approximately equal numbers of female and male participants were assigned to each condition.

The procedures for the Free-Pattern and Free-Random conditions were identical to those used in Experiment 3.

The procedures for the 2AFC-Pattern and 2AFC-Random conditions were modified versions of the earlier procedures. At the beginning of each trial, two buttons were indicated as possible choices by a frame surrounding each of them, as shown in Fig. 12. Choice of a button other than those two had no effect. One of the indicated buttons was correct and the other was incorrect. Two different buttons were indicated following the choice feedback (or at the beginning of the next trial). For the first eight choices of each trial, the indicated correct button was selected randomly without replacement from among the eight correct buttons, and the indicated incorrect button was selected randomly without replacement from among the eight incorrect buttons. This process of selecting without replacement from the sets of correct and incorrect buttons was repeated as necessary for additional sets of eight choices.

Participants in the 2AFC conditions were informed of the meaning of the frames by the following sentence, which substituted for the 3rd sentence in the participant instructions provided above: "You will see two buttons at a time indicated by squares—your job is always to choose the correct button from these two by clicking on it."

5.2. Results

The results of one participant (a male in the 2AFC-Pattern condition) were not included because of a corrupted data file.

The results from the free choice conditions replicated the results of Experiment 3 and the key results are included in Fig. 4. As in the earlier experiments, there was immediate reversal performance in the Pattern Condition but not in the Random Condition.

Performance in the 2AFC conditions was quite different from that observed in the earlier experiments as well as that observed in the free choice conditions of the present experiment. Only two participants (of 15) in the 2AFC-Pattern Condition and one participant (of 16) in the 2AFC-Random Condition completed the experimental protocol of nine reversals. Three participants in the 2AFC-Random Condition did not meet the learning criterion during initial learning (and therefore did not experience a reversal). Including those three participants, the mean number of reversals completed was 3.6 for the 2AFC-Random Condition and 4.2 for the 2AFC-Pattern Condition. Thus, the discrimination task was much more difficult under the modified (2AFC) procedure.

Among the participants who did meet the learning criterion during the Initial Learning Phase, however, the basic result of immediate reversal performance when a pattern was present but not when it was absent was replicated. Specifically, in the 2AFC-Pattern group, 12 of 15 (i.e., 80%) participants chose a correct button on the second choice following the first reversal, which is significantly more than expected on the basis of chance, $p < .05$, binomial test. In the 2AFC-Random group, only 5 of the 12 (i.e., 42%) participants who completed Initial Learning did so.

5.3. Discussion

Although the 2AFC task was substantially more difficult than the free choice task, immediate reversal performance occurred when the correct locations were arranged in a checkerboard pattern. This cannot be explained by a learned motor pattern because a systematic pattern of responding to correct locations was not possible with the 2AFC procedure.

6. General discussion

When correct locations were randomly determined, performance following the first and subsequent reversals was similar to that found in many previous animal (e.g., Jitsumori et al., 2002; Tomonaga, 1999) and human (e.g., Lionello-DeNolf et al., 2008; Smeets et al., 1995) reversal learning experiments using visual stimuli. That is, over the course of several reversals, participants came to respond appropriately to stimuli after several trials, such that the reversed contingencies affected responding to stimuli that had not been presented since the previous reversal. This finding has typically been interpreted in terms of acquired equivalence classes (Sidman, 1994; Sidman et al., 1989). That is, stimuli with common functions or that are followed by common outcomes come to be treated equivalently. The traditional explanations of acquired equivalence classes appeal to associative processes (e.g., Hall et al., 2003; Urcuioli, 1996) although there are recent arguments that at least some cases of equivalence class formation are better explained by other kinds of mechanisms (e.g., Liljeholm and Balleine, 2010; Smyth et al., 2008).

The results of Experiment 2 show that reversal performance with the randomly chosen sets spatial locations used in the present experiments is quite similar to reversal performance based on visual stimuli (kaleidoscope images). That is, reversal performance developed over the course of several reversals when the locations were randomly assigned to sets. To our knowledge, the use of sets of spatial locations in a human reversal learning paradigm is novel and it is noteworthy that the performance obtained conforms to that obtained with the commonly used arbitrary sets of visual stimuli and interpreted in terms of equivalence class formation.

However, when sets of locations were defined by a simple structured spatial pattern, people immediately began choosing locations in the alternative set following the first trial after a reversal, including the first reversal. Immediate reversal performance was found for both checkerboard (Experiments 1, 3, and 5) and line (row or column; Experiment 4) patterns. Immediate reversal performance with a checkerboard pattern was obtained even when the discrimination task was rendered relatively difficult and precluded the use of systematic motor patterning of choice responses (Experiment 5).

We believe that immediate reversal performance cannot be interpreted in terms of equivalence class formation. Acquisition of an equivalence class in a reversal learning paradigm depends on experiencing the change in outcome that is common to members of the class. In the present context, the reversed contingencies for each of the stimuli would have to be experienced at least once (during Reversal 1) in order for the commonality of the contingencies that correspond to them to be effective. Immediate reversal performance, on the other hand, must be explained in terms of processes or mechanisms that occur during initial learning. The results of these experiments support the idea that the inherent spatial structure in the pattern defining correct locations allows immediate reversal performance.

Discrimination of the correct locations during initial learning could have been based on the locations of individual buttons. The spatial pattern formed by the correct buttons in the Pattern Condition is certainly a relevant cue during initial learning, but the spatial pattern does not uniquely define the correct buttons, as do their individual locations. Thus, on the basis of cue validity considerations one would predict learning about the individual locations to be stronger than learning about the spatial relations among them. In fact, the individual locations of correct buttons turned out to have very little control over choice. Following a single incorrect choice (of a previously correct button location) after the first reversal, participants began choosing buttons in direct opposition to the status they had during initial learning. Instead, the vast majority of choices made following reversals conformed to the spatial pattern, while being in opposition to the status that individual locations had before the reversal. Thus, the spatial pattern among the locations rather than individual locations was the dominant property controlling spatial choice during initial learning. This result strongly suggests that the spatial pattern of correct locations has precedence over the locations themselves for control of spatial choice, at least under the conditions of these experiments.

A representation of the pattern that defines the spatial relations among the correct locations, abstracted from the spatial relations among particular locations (Brown, 2006a), seems necessary to explain the immediate transfer from the exemplar of the pattern in place during initial learning to the (opposite, in terms of individual locations) exemplar of the pattern in place after reversal. Furthermore, this abstracted representation acquires excellent control of choices despite the fact that, during initial learning, the individual spatial locations of the choice alternatives are perfectly valid cues. It is not clear why the spatial pattern of correct locations should dominate the locations themselves in terms of acquiring control of spatial choices. The effect is reminiscent of the global precedence effect seen in the perception of complex visual stimuli (Kimchi, 1992; Navon, 1977), according to which the global structure of a stimulus is processed more effectively and efficiently than the parts of which it is composed. Of course, the global processing that has precedence in the present case is not perceived, but rather abstracted from behavioral interactions with the stimuli over the course of trials.

It is possible that some of the same processes involved in perceptual phenomena related to structured patterns contribute to the precedence of spatial pattern learning in the present experiments. Thompson et al. (2008) have shown that properties of objects not noticed when the objects were physically present can be determined from "visualized" representations of the objects in their absence. In addition, Borst and Kosslyn (2008) provided evidence using an image scanning paradigm that representations of absent visual stimuli (images) are processed using some of the same processes used in early vision. These findings suggest the possibility that, in our experiments, the correct (or incorrect) button locations are visualized based on a history of interactions with the display and then the spatial pattern formed by them is perceived in that representation and processes as a visual stimulus. If so, the precedence of the spatial pattern over the individual locations can be explained in terms of the same global precedence effects seen in visual perception.

Whatever the mechanism turns out to be, the immediate reversal performance seen in these experiments shows clearly that, at least under some conditions, spatial learning does not occur in terms of spatial locations even when locations are perfectly valid cues. Instead, it appears that a consistent spatial relation among locations is sometimes psychologically primary.

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