Information Representation and Mechanism in the Integration of Sequential Arrays: Evidences from Eye Movements

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Were sequential visual arrays represented as separate representations or as a combine representation in the visual short-term memory (VSTM) and whether the information of individual object in the first array could be represented in the VSTM? We investigated these two questions by manipulating topological property of objects in the first array and tracking the participants' eye movement when subjects were required to perform empty cell localization task. The results showed that during integration of sequential arrays, the participants paid more attention to the empty cell locations in the first array, which supporting convert-and-compare hypothesis. The results also showed that the variation of the topological property of objects in the first array would impact on eye movement behavior, though this effect could only be observed in complex pattern condition. This suggested that topological property of objects in the first array would be represented in the VSTM to some extent.

INTRODUCTION

Although we view the whole world through a temporally discontinuous series of eye fixations and the whole visual world we inhabit contains more information than can be sampled and processed in a single glance, the world we perceive appears to be a coherent whole. In order to build up a coherent representation of the world, observers must shift their attention and gaze from one place to another place and gradually integrate what has been seen with what is being seen. In recent years, the investigators examined information integration between the contents of active short-term memory (i.e., a visual image) and the newly arriving perceptual information (Brockmole & Irwin, 2005; Brockmole & Wang, 2003; Brockmole, Irwin, & Wang, 2003; Brockmole, Wang, & Irwin, 2002; Hollingworth, Hyun, & Zhang, 2005; Jiang, 2004; Jiang & Kumar, 2004; Jiang, Kumar, & Vickery, 2005; Ren, Xuan, & Fu, 2007).

Brockmole et al. (2002) firstly examined whether visual images can be integrated with visual percepts to form a single representation that contains information from each source. They used empty cell localization task in which observers viewed two complementary dots arrays presented sequentially within a square grid and the dots arrays, if superimposed, filled all but one cell in the grid, and observers tried to identify the location of the empty cell (Di Lollo, 1980; Dixon & Di Lollo, 1994; Groner, Bischof, & Di Lollo, 1988; Hogben & Di Lollo, 1974; Loftus & Irwin, 1998). Brockmole et al. (2002) found that the performance improved steadily as the ISI increased from 100 ms to 1300 ms, at which point accuracy asymptoted and did not decay through delays of 5000 ms. They explained this findings with the image-percept integration hypothesis and argued that the improvement in accuracy over time was due to formation of a visual image, and that the image could be integrated with later perceived visual information of the second array.

Brockmole, Irwin, and Wang (2003) held that image-percept integration hypothesis was further supported by the subsequent experiment that, during the ISI, selective spatial attention is deployed to the grid locations previously occupied by a dot in the first array.

Brockmole and Irwin (2005) recorded participants' eye movement behavior during the integration between the first array and the second array and the subsequent analysis demonstrated that the percentage of fixations on the first array position did not reliable differ from the chance level.

Jiang, Kumar, and Vickery (2005) manipulated the ratio of same-difference comparison task and empty cell localization task and asked participants to finish both tasks in the same experimental block. Based on this experimental manipulation, they proposed convert-and-compare hypothesis to explain the higher performance at longer ISI. They assumed that, according to visual marking theory (Watson & Humphreys, 1997, 2000), the first array might be used to visually mark grid positions as locations that cannot constitute the correct answer. As a result, these positions might be inhibited, and attention was directed to the positions that Array 1 left empty, enhancing the detection of the space left unfilled by the second array.

Hollingworth, Hyun, and Zhang (2005) employed the asymmetric stimuli to test the two hypothesis proposed above, in which the first array dot pattern was simpler or more complex than the negative space pattern. Under image-percept hypothesis, long ISI performance should be higher when the first array dot pattern was relatively simple than that when the first array negative space pattern was relatively simple. Under convert-and-compare hypothesis, long ISI performance should be higher when the first array negative space pattern was relatively simple than that when the first array dot pattern was relatively simple. Subsequent findings supported convert and compare hypothesis. Ren, Xuan, and Fu (2007) monitored participants’ eye movement behavior during the integration between the first array and the second array. The subsequent analysis found that the percentage of fixating on the dot position in first array was lower than the percentage of fixating on the empty position in the first array, and this result supported convert-and-compare hypothesis.

Brockmole and Wang (2003) explored the possibility of image-percept integration across changes in the spatial characteristics of the to-be-integrated stimuli over time. The results showed that image-percept integration is possible when the spatial properties of the to-be-integrated stimuli do not match. They raised a question that what kind of information about the stimulus is maintained in the image. For example, whether the image of the first array may encode the individual dots in the first array or not, treating each of these as a separate element, or it may encode the overall shape or gestalt created by the dots.

Hollingworth, Hyun, and Zhang (2005) manipulated the dot pattern complexity of the first array to examine the information representation of the first array in the VSTM. They found that pattern complexity did not have a significant effect on the performance at 0 ms ISI but had a large effect on the performance at longer ISIs and supported the hypothesis that apparently high-capacity visual memory at long ISIs results, at least in part, from figural grouping in VSTM. This finding suggested that the figural information of the first array was represented in VSTM during the integration between the visual image of the first array and the percept of the second array.

Ren, Xuan, and Fu (2007) manipulated the dot pattern complexity of the first array and monitored participants' eye movements during the integration between the first array and the second array. Subsequent analysis found figural grouping effect was not only exhibited on integration accuracy, array 1 error rate and array 2 error rate, but also on eye movement behavior, such as pupil diameter and fixation position.

Thus it could be seen that, to date, there were two open questions to be solved. The first question was that how visual image of the first array maintained in VSTM was represented, that is, whether the visual image of the first array encoded the individual dots in the first array, or it encode only the pattern created by the dots in the first array? The second question was that how the visual image of the first array integrated with the percept of the second array, in other words, which hypothesis, namely, image-percept integration hypothesis or convert-and-compare hypothesis, could explain the integration process better?

Chen (1982, 2005) held that global nature of perceptual organization can be described in terms of topological invariants and the primitives of visual form perception are geometric invariants at different levels of structural stability.

In order to explore the information representation of the first array in VSTM, we manipulated the topological property (topology invariant vs. topology variant) of the objects and pattern (simple pattern vs. complex pattern) created by the objects in the first array. If topology property of objects in the first array would influence integration performance and eye movement behavior when pattern information kept invariant, then topology property of objects was represented in the visual image of the first array. If, on the other hand, pattern created by objects in the first array would influence integration performance and eye movement behavior when topology property kept invariant, then pattern created by the objects was represented in the visual image of the first array.

In order to reconcile image-percept integration hypothesis and convert-and-compare hypothesis, we monitored participants' eye movement behavior during the integration between the first array and the second array. If the image-percept integration hypothesis is right, the percentage of fixating on the object position in the first array would be higher than the percentage of fixating on the empty position in the first array with the delay of ISI. If the convert-and-compare hypothesis is right, the percentage of fixating on the empty position in the first array would be higher than percentage of fixating on the object position in the first array with the delay of ISI.

METHOD

Participants

Twelve undergraduates (5 male and 7 female, All were between ages of 19 and 23, and their average ages were 21.08) from the China Agricultural University participated in the experiment. All participants had normal or corrected-to-normal vision and were naive with respect to the experimental hypotheses. After the experiment, they were paid 35 RMB for participating.

Stimuli

Stimuli consisted of two unique dot arrays were sequentially presented within an enclosed 4 x 4 square grid. The first array contained eight black dots (triangles or cirques) and the second array contained seven black dots. Together, the arrays filled all but one square in the grid. The grid was composed of interconnected light-blue lines, superimposed over a light-gray background so that the color of the grid space and the area surrounding the grid was the same. The first dot array were drawn from two sets: a simple pattern set and a complex pattern set, and these pattern sets were generated based on complexity ratings compiled by Ichikawa (Ichikawa, 1985). Each stimulus collected by Ichikawa was a 4 x 4 grid with eight of the cells filled by dots (triangles or cirques). A total of 140 different patterns were rated by participants, and the stimuli were ordered from least complex (item 1) to most complex (item 140). The set of 32 simple and 32 complex pattern stimuli for the experiment were items 1-32 and 109-140 from Ichikawa's experiment material respectively. Apart from the dot array, the triangle array and the cirque array were also introduced. On each trial, elements of the first array would change from dots to triangles or cirques, but the positions of the elements would not change. Sample stimuli from the simple pattern set and complex pattern set in the first object array were showed in Figure 1. The second dot array stimuli were constructed by randomly filling seven of the eight cells not filled in Array 1. As a result, the position of the empty cell was also randomly determined. The background subtended 36° x 27° of visual angle and the entire grid subtended 20° of visual angle (both horizontally and vertically). Each cell in the grid subtended 5° of visual angle and the diameter of each dot was 4° of visual angle.

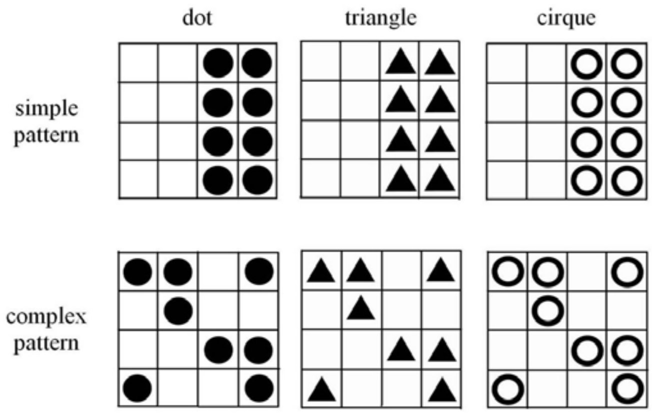


Figure 1. Sample stimulus of the first array from the simple pattern (upper) and from the complex pattern set (lower) in the experiment.

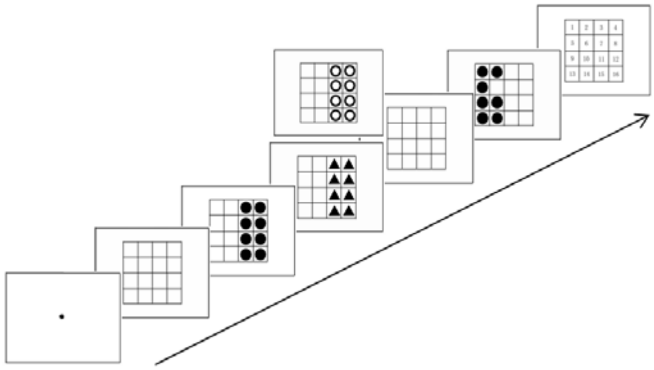
Apparatus

The stimuli were presented at a resolution of 1024 by 768 pixels on a 19-inch video monitor at a refresh rate of 85 Hz. The presentation of stimuli and collection of responses was controlled by Experiment Builder software running on a Pentium IV PC. Viewing distance was maintained at about 60 cm. Eye position was sampled at a rate of 500Hz (every 2 ms) with an EyeLink II eye tracker (SR Research Ltd. in Canada) which had a resolution of 0.01 in pupil only mode. The eyetracker and display monitor were interfaced with a computer that controlled the experiment. This system used video-based infrared oculography to measure eye and head position.

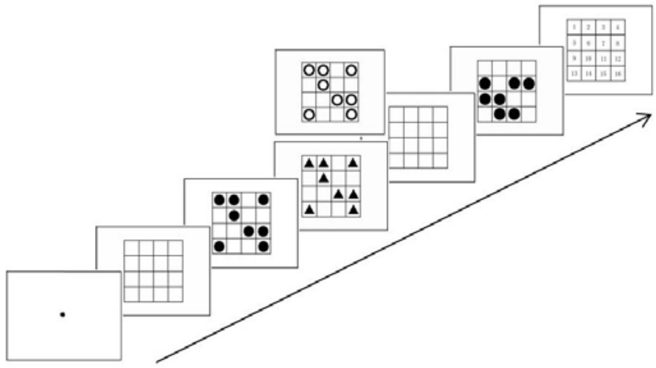
Design and Procedure

In general, the design and procedure were similar to that used by Hollingworth et al (2005). On each trial, two dot arrays [eight dots (triangle or cirques) and seven dots, respectively] were presented sequentially within an enclosed square grid separated by a variable ISI. There were four blocks of trials totally, with each combination between pattern complexity and topological property (simple pattern and topological property invariant, simple pattern and topological property variant, complex pattern and topological property invariant, complex pattern and topological property variant) comprising a block. On any given trial, one cell within the grid was never filled and the participants were instructed to identify the position of the empty cell.

The procedure was illustrated in Figure 2 and each trial consisted of the following events. Firstly, the black point was presented in the center of the screen. When ready to begin, participants fixated the black point and pressed ‘5’ on the Eye Link Button Controller to start the trial. There was the empty grid (superimposed over the gray background) which was presented for 500 ms delay before presentation of Array1. Array 1 was then presented within the grid. The elements of Array 1 would change from dots to triangles or cirques after 23 ms duration, but the positions of the objects would not change. The new elements would be displayed for 12 ms. The variable ISI between the offset of Array 1 and the onset of Array 2 was 100 ms, 750 ms, 1500 ms, or 2500 ms. During the ISI, the blank grid was displayed. Following the ISI, Array 2 was presented within the grid for 35 ms. Array 2 was followed by the grid with the 16 numbers from ‘1’ to ‘16’ presented in the center of each cell. Participants identified the location of the empty cell by speaking out the number standing for the cell. Then participants pressed ‘5’ on the Eye Link Button Controller to start the next trial. Participants were asked to respond as accurately as possible and that they were under no speed stress. Eye movement behavior of participants was monitored during duration of array 1, array 2 and ISI.



(a) simple pattern condition



(b) complex pattern condition

Figure 2: Sequence of events in a trial of experiment (simple pattern condition and complex pattern condition were illustrated respectively in a and b). The participants pressed '5' key on the Eye Link Button to begin the trial, followed by the events illustrated in the figure. When the final blank grid with number appeared, the participants should speak out the number in the empty cell.

RESULTS

The results were reported in two parts. First, overall accuracy and error rates for different error types in the information integration task were reported. Second, various aspects of eye movement behavior were examined. Variables of interest included fixation number, fixation duration, pupil size, fixation location and saccadic amplitude.

Integration Task Accuracy and Error Rates

A response was classified as correct, an Array 1 error (erroneously selecting a position occupied by the first array), or an Array 2 error (erroneously selecting a position occupied by the second array) and were measured in terms of the percentage of trials on which they occurred. The accuracy, percentage of Array 1 error and percentage of Array 2 error in the empty cell localization task were examined as a function of pattern complexity of Array 1, topological property of objects in the first array and ISI.

Accuracy. There were a reliable main effect of pattern complexity [F (1, 11) = 227.239, p < 0.001] and a reliable main effect of ISI [F (1, 11) = 66.568, p < 0.001]. Other main effects and interactions were not reliable. These results were summarized in Table 1.

Table 1: Localization accuracy as a function of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	0.60	0.75	0.83	0.82
	complex	0.22	0.40	0.38	0.39
Topological Variant	simple	0.59	0.78	0.83	0.82
	complex	0.23	0.42	0.42	0.41

Array 1 Error. The results of array 1 error were similar to the results of accuracy. There were a reliable main effect of pattern complexity [F (1, 11) = 268.444, p < 0.001] and a reliable main effect of ISI [F (3, 33) = 55.905, p < 0.001]. Other main effects and interactions were not reliable. These results were summarized in Table 2.

Table2: Array 1 error rates at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	0.32	0.15	0.08	0.09
	complex	0.67	0.45	0.48	0.49
Topological Variant	simple	0.34	0.10	0.08	0.10
	complex	0.66	0.41	0.45	0.45

Array 2 Error. There was only one reliable main effect of complexity [F (1, 11) = 9.970, p < 0.01]. Other main effects and interactions were not reliable. These results were summarized in Table 3.

Table 3: Array 2 error rates at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	0.08	0.10	0.09	0.09
	complex	0.11	0.15	0.14	0.12
Topological Variant	simple	0.07	0.11	0.09	0.09
	complex	0.11	0.17	0.13	0.14

Eye Movement Behavior

To some extent, the locus of attention is indicated by the location in space that is fixated. Thus an analysis of modes in the distribution of fixations during the ISI separating the arrays can give insight into the manner in which attention is used during VSTM consolidation. In this section, fixation number, total fixation duration, average duration, average pupil size, fixation location and saccadic amplitude were analyzed.

Fixation Number. ANOVA showed that there were a significant main effect of ISI [F (3, 33) = 36.260, p < 0.001], a significant interaction between topological property and pattern complexity [F (1, 11) = 5.963, p < 0.05] and a significant three-order interaction among topological property, pattern complexity and ISI [F (3, 33) = 6.396, p < 0.01]. Simple effect showed that under the topological property invariant and 2500 ms-ISI condition, fixation number under the simple pattern condition was less than that under the complex pattern condition (p < 0.05). Other main effects and interaction were not significant. These results were summarized in Table 4.

Table 4: Fixation number on the each trial at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	1.01	1.64	2.22	3.08
	complex	1.04	1.71	2.55	3.70
Topological Variant	simple	1.02	1.67	2.44	3.42
	complex	1.02	1.70	2.46	3.44

Total Fixation Duration. Average total fixation durations on each trial were summarized in Table 5 as a function of topology property, pattern complexity and ISI. The results of total fixation duration were similar to the results of fixation number. An overall main effect of ISI was observed, since fixation durations generally increased with increases in ISI. ANOVA revealed that there was a significant main effect of ISI [F (3, 33) = 53.115, p < 0.001]. Simple effect showed that under the topological property invariant and 2500 ms-ISI condition, total fixation duration under the simple pattern condition was longer than that under the complex pattern condition (p < 0.05). Other main effects and interaction were not significant.

Table 5: Fixation duration (ms) on the each trial at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	228.54	625.21	951.60	1211.35
	complex	224.11	596.76	846.33	1012.03
Topological Variant	simple	227.62	620.51	858.99	1123.38
	complex	226.08	589.14	860.03	1077.92

Pupil Size. The results of pupil size, measured by pupil diameter, under all experimental conditions were summarized in Table 6. ANOVA revealed that there was a reliable main effect of ISI [F (3, 33) = 42.399, $p < 0.001$]. Other main effects and interactions were not significant.

Table 6: Pupil size (mm) on the each trial at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	2.26	2.34	2.38	2.42
	complex	2.36	2.42	2.48	2.53
Topological Variant	simple	2.27	2.32	2.38	2.43
	complex	2.17	2.20	2.28	2.32

Fixation Location. Fixation location under the conditions of topological property, pattern complexity and ISIs was summarized in Table 7. ANOVA showed that there was a reliable main effect of pattern complexity [F (1, 11) = 6.131, $p < 0.05$]. Other main effects and interaction were not significant. The data revealed that the percentage of fixations on Array 1 dots was lower than chance level (50%) at any conditions [| ts(11) | > 4, $ps < 0.01$]. Simple effects revealed that under the simple pattern condition, the rate of fixating the location of empty cell in the array 1 was not different between topological invariant and topological variant and under the complex pattern condition, the rate of fixating the location of empty cell in the array 1 under topological invariant was more than that under topological variant, which was illustrated in Figure 3

Table 7: The percentage of fixating on the object position in the first array on the each trial at the combined conditions of topological property, pattern complexity and ISI in the experiment

		ISI			
		100	750	1500	2500
Topological Invariant	simple	0.39	0.43	0.41	0.41
	complex	0.46	0.40	0.40	0.41
Topological Variant	simple	0.41	0.42	0.39	0.39
	complex	0.51	0.44	0.46	0.43

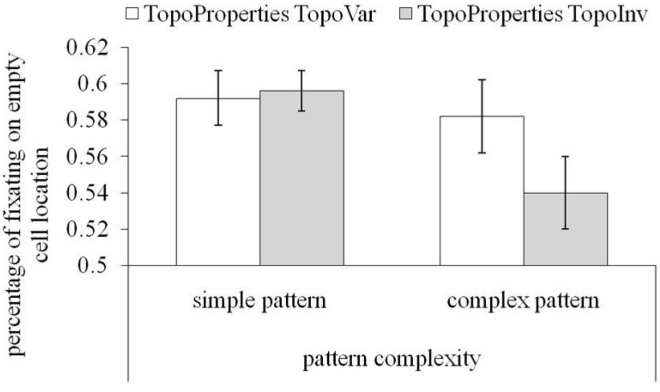


Figure 3 fixation locations on the empty position in the first array on the each trial as a function of topological property and pattern complexity (Topo Inv represented for topological invariant and Topo Var represented for topological variant).

Saccadic Amplitude. There were not saccade under the 100 ms ISI and eleven participants' data were valid. So saccadic amplitude were analyzed under two topological property, two pattern complexities and three-ISI levels (750 ms, 1500 ms and 2500ms) conditions. Saccadic amplitude under the conditions of different topological property, pattern complexity and ISIs was summarized in Table 8. The data revealed that there were a reliable main effect of pattern complexity [F (1, 10) = 5.481, $p < 0.05$] and a reliable main effect of ISI [F (2, 20) = 5.229, $p < 0.05$]. Other main effects and interaction were not significant.

Table 8: Saccadic amplitude on the each trial at the combined conditions of topological property, pattern complexity and ISI in the experiment.

		ISI			
		100	750	1500	2500
Topological Invariant	simple	—	1.92	1.68	1.63
	complex	—	2.23	2.15	2.17
Topological Variant	simple	—	1.99	1.85	1.67
	complex	—	2.19	2.15	1.92

DISCUSSION

Mechanism in the integration of sequential arrays and information representation in the VSTM during the integrating process were studied in the present study.

Our study showed that the accuracy in the simple pattern condition was higher than that in the complex condition. Meanwhile, the array 1 error and the array 2 error also showed the similar trends. But objects' topological property had no impact on the accuracy, array 1 error and array 2 error. These findings supported the figural grouping hypothesis in VSTM (Hollingworth, Hyun, & Zhang, 2005; Ren, Xuan, & Fu, 2007). The effect of pattern complexity provided a means to reconcile apparently high-capacity memory at long ISIs with evidence that VSTM has a limited capacity of three or four objects (Luck & Vogel, 1997). At longer ISIs, Array 1 is likely represented in VSTM as one or more higher order objects, each containing information from more than one array element. It is to say that during the integration of sequential arrays the information in the first array could be represented in VSTM as one or more pattern which containing information of several elements. These results were similar to the findings of Hollingworth et al (2005).

It could be seen from the Table 4 that participants did have eye movements during ISI. The results showed that average fixation number on each trial was positively correlated with ISI, since longer ISI afforded more time for participants to make more eye movements. Simple effect analysis showed that under the topological property invariant condition, at 2500 ms ISI, fixation number was less in the simple pattern than that in the complex pattern.

Fixation duration had been considered to reflect the amount of processing (Just, & Carpenter, 1980; Rayner, 1998). It could be also seen from the Table 5 that fixation duration had similar results to the fixation number. Simple effect analysis showed that under the topological property invariant condition, at 2500 ms ISI, fixation duration were longer in the simple pattern than that in the complex pattern. These two findings suggested that the topological property of objects in the first array was represented in some degree in the VSTM.

It could be seen from Table 6 that average pupil size (e.g. pupil diameter) became larger with the delay of duration of ISI. This finding was probably due to pupil adaption to lightness of screen with the delay of duration of ISI.

More importantly, our results showed that the percentage of fixating on locations originally occupied by objects in Array 1 was less than chance level (0.50) under any conditions (see Figure 3). This finding suggested that the participants were more likely to pay attention to empty cell locations rather than locations originally occupied by object to retain array 1. These findings suggested that participants were more likely to try to retain locations of empty cells than object locations in array 1 during ISI. From aspect of eye movements, these results offer the evidences supporting convert-and-compare hypothesis (Jiang, Kumar, & Vickery, 2005). Brockmole and Irwin (2005) also monitored the participants' eye movement and found that the percentage that participants fixate the grid position occupied by dots of array 1 was on the random level. The reasons for the difference between their results and the present study were not clear yet. One possible explanation could be the manipulation of the pattern complexity in the present study.

Besides, the saccadic amplitude was larger under the complex pattern condition than that under the simple pattern (see Table 7). This finding also suggested that pattern information in the first array was represented in the VSTM.

NOTES

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