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Sequential Processing Facilitates Hebb Repetition Learning in Visuospatial Domains

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Exposure to the same information improves auditory/verbal short-term memory performance, but such improvement is not always observed in visual short-term memory. In this study, we demonstrate that sequential processing makes visuospatial repetition learning efficient in a paradigm that employs a similar design previously used for an auditory/verbal domain. When we presented sets of color patches simultaneously in Experiments 1–4, recall accuracy did not increase with repetition; however, once color patches were presented sequentially in Experiment 5, accuracy did increase rapidly with repetition, even when participants engaged in articulatory suppression. Moreover, these learning dynamics matched those in Experiment 6, which used verbal materials. These findings suggest that (a) sequential focus on each item facilitates a repetition learning effect, indicating a temporal bottleneck is involved early in this process and (b) repetition learning is mechanistically similar across sensory modalities even though these modalities differently specialize in processing spatial or temporal information.

Public Significance Statement

We acquire knowledge of the world by learning the regularities of what occurs repeatedly. Such learning has been shown to occur in a variety of modalities, including visual and verbal, from early ages, even if one is not aware of the regularity. However, it has also been noted that the learning effect is small or absent in some situations. As the majority of evidence for regularity learning is associated with temporal sequence processing, it is possible that a temporal bottleneck exists during the early stages of the learning. This study provides insight into learning mechanisms that operate in the visuospatial domain and presents avenues for further investigation of the interaction between short-term and long-term memory.

Keywords: statistical learning, visual short-term memory, domain generality, temporal processing, simultaneous presentation

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The extraction of statistical properties and regularities from sensory inputs forms a fundamental basis of human cognition. With such information, human behaviors and the corresponding neural activities in the brain can be changed or modified to adjust cognitive processes to a particular environment. In a study of verbal statistical learning using the head-turn preference procedure, Saffran et al. (1996) showed that, after 2 min of exposure to a sequence of consonant–vowel syllables, 8-month-old infants prefer novel artificial words that contain syllable sequences (combinations) with low transitional probability over artificial words that have been repeatedly presented in the sequence (i.e., with high-transitional-probability syllable combinations). Since infants have a novelty preference, the observed preference toward novel sequences indicated that the transitions between syllables were accumulated. In other words, the probabilities of this co-occurrence (i.e., regularity) could be learned. Inspired by this seminal work, several subsequent laboratory-based studies have demonstrated the acquisition of statistical properties, such as occurrence frequency and transition probability on a variety of tasks (e.g., recognition tasks, recall tasks, preference ratings) with a variety of materials (e.g., tone sequences, Saffran et al., 1999; sequences of shapes, Kirkham et al., 2002; action sequences, Roseberry et al., 2011). Furthermore, recent research analyzing mega-data from the real world also indicates strong impacts of occurrence frequency and frequency distribution of linguistic elements (e.g., phonemes, syllables, digits; Jones & Macken, 2018; Nakayama et al., 2015), objects (Clerkin et al., 2017), and faces (Jayaraman et al., 2015) on our cognitive processes (in this case, memory, learning, and perception). These results suggest that human cognition is largely based on sensory experiences and extracted regularities (or statistical properties such as occurrence frequency and transition probability) embedded in environments.

Although previous studies have shown that statistical learning emerges in multiple domains, they do not provide strong evidence that only a single process is operated regardless of domain. Examining the learning mechanisms at work across multiple domains offers two benefits. First, if learning characteristics differ by domain, this supports the possibility that domain-specific processes are in operation. Second, examining learning characteristics in different domains can provide insight into the detailed learning algorithm or principles. This is because the primary features to be processed differ across domains. For example, temporal sequences and their contents (e.g., syllables) are the primary focus in the verbal domain, whereas spatial locations, their contents (e.g., color and shape), and simultaneity are dominant and easily manipulated in the visuospatial domain.

The literature on laboratory-based statistical learning experiments often employed a two-phase paradigm (e.g., Saffran et al., 1996), but such a paradigm does not allow for a detailed examination of the temporal dynamics of statistical learning because it does not keep tracking the entire learning process. In this paradigm, participants are first exposed to a stimulus sequence (familiarization phase), followed by a two-alternative forced-choice (2AFC) task (test phase). In the test phase, participants are presented with two stimuli, each of which has been or has not been presented during the familiarization phase. Participants are asked to judge which is more familiar or preferred. This method can be utilized with adults and infants with preferences indicated by head turns or eye fixations. The 2AFC method is used to investigate whether participants learn stimuli even if they do not explicitly recognize them. Despite its popularity, one major disadvantage is that it cannot be used to track participants' changes in performance over time, that is, it cannot reveal the temporal dynamics of learning. To overcome this disadvantage, other methods have been developed (e.g., the serial reaction time task and the Hebb repetition paradigm; for details, see Siegelman et al., 2017). Such approaches allow comparison of the underlying learning dynamics across different domains.

To track participants' progress in learning, this study employed the Hebb repetition paradigm; this enables a direct investigation of short-term retention, which is the first step in learning from experience or acquiring long-term knowledge. This paradigm was first developed by Hebb (1961), in which participants were asked to perform an immediate serial recall of sequences of digits. Random sequences were generated in most trials, but one fixed sequence (referred to as the Hebb list hereafter) was repeatedly presented every three trials. Typically, recall performance for the Hebb list would gradually improve with repetition to a greater extent than the performance for the other sequences. Although most studies on the Hebb repetition effect have targeted phenomena in tasks involving digits or words/syllables (see Hurlstone et al., 2014), it is not limited to the verbal domain. For example, Couture and Tremblay (2006) also observed a Hebb repetition effect in visuospatial short-term memory using a task in which dots were sequentially presented at specific spatial locations and participants were asked to perform an immediate recall of the serial order of the presented dots (see also Horton et al., 2008; Johnson et al., 2017; Johnson & Miles, 2019a, 2019b; Page et al., 2006; Sukegawa et al., 2019 for other materials).

These studies suggest that the Hebb repetition effect can be observed in both the verbal and visuospatial domains, and they all adopted temporal sequences as their learning materials. In fact, it is the case for the vast majority of studies showing the Hebb repetition effect, regardless of whether the stimuli are in the verbal or visuospatial domains (e.g., Bower & Winzenz, 1969; Couture et al., 2008; Cumming et al., 2003; Fastame et al., 2005; Hitch et al., 2009; Page et al., 2006, 2013). Suppose the Hebb repetition effect is merely based on previous experiences in which participants have encountered the relevant items (in other words, on extracting regularities from past environments). In that case, this effect should also be observed when all items appear simultaneously. However, visual short-term memory performance does not improve with simply numerous repetitions of the same displays when all items are presented simultaneously (color: Fukuda & Vogel, 2019; shape: Olson & Jiang, 2004; location: Olson et al., 2005; Olson & Jiang, 2004; color, shape, and location bindings: Logie et al., 2009; Shimi & Logie, 2019). Rather, visual short-term memory performance was improved only when probes in the exact location on display changed across repetitions (Olson et al., 2005), when verbal labels were recalled for visual features (Logie et al., 2009), and when individual features were selected from a set of colors, shapes, and locations and reconstructed the display. Based on these results, Shimi and Logie (2019) proposed that visually presented objects are retained in domain-specific short-term visual stores (called *visual cache*, the contents of which are replaced by new representations after stimuli change), which is separate from long-term memory and verbal short-term memory. Then, they could become available as episodic long-term memory through verbalization and reconstruction of the contents of the visual cache. The same may be true when stimuli related to the visuospatial domain (e.g., Couture & Tremblay, 2006; Sukegawa et al., 2019) are presented sequentially. That is, since attention is directed to individual items with sequence presentation, awareness of the contents of the visual cache makes the episodic long-term memory available, which may produce Hebb repetition learning.

So far, previous studies in the visuospatial domain only compared Hebb arrays to filler arrays. Yet, Saito et al. (2020) have pointed to three types of learning involved in the Hebb repetition paradigm in the verbal domain: (a) position–item association learning, which is pertinent to the frequency with which each item appears in a given serial position; (b) item-to-item association learning, which is based on the co-occurrence frequency of two successive items; and (c) whole list learning, which is assumed to be a primary source of the Hebb repetition effect and is based on either combined learning of the first two types, or episodic learning of the whole sequence.

Nakayama and Saito (2017) attempted to separate the position–item association learning from the other two types in a verbal Hebb repetition paradigm. In their experiment, five of a set of 10 nonwords were sequentially presented in each list, each at a particular temporal position more frequently than other temporal positions (e.g., "to-nu" was frequently presented in the first position in sequences, whereas "re-chi" was frequently presented in the third position). There were three types of lists. Hebb lists were repeatedly presented as wholes within an experimental block. Consequently, all items in the lists were presented in their most frequent positions (e.g., "to-nu" was presented first in these lists, raising its occurrence frequency in this position), with fixed presentation order. Filler lists were generated individually for every trial. They consisted of items that were presented in infrequent positions (e.g., "re-chi" was presented in the fourth position in one list but in the second position in another list; thus, the occurrence frequency of this item at a certain position is low). Fixed-frequency lists consisted of a mixture of items presented repeatedly in their most frequent positions and those in less frequent positions. Therefore, every mixed-frequency list was unique within a block (e.g., "to-nu" in the first position and "re-chi" in the second position; see Nakayama & Saito, 2017 for more details). Following repetitions, participants' recall performance was best for the Hebb lists compared with the other lists. Notably, the Hebb repetition effect was obtained with only four repetitions, as reported in previous studies (e.g., Hitch et al., 2009). It was also confirmed that the performance was better for frequent-position items in the mixed-frequency lists than for infrequent-position items in the mixed-frequency and filler lists. However, speed was much slower for the position–item learning than for the whole list learning. These results suggest that participants learned from statistical information relating to position–item frequency statistics by extracting statistical information from their experiences. This learning mechanism might be different from the whole list of learning. Hence, although Hebb learning was not consistently found in the literature, other types of statistical learning may still be occurring in the visuospatial domain. To evaluate this, we would need to include not only Hebb lists but also lists including variations in the frequency of item-position co-occurrences.

The present study aimed to provide empirical evidence concerning the effectiveness of repetition learning in the visual domain, in which multiple items can be processed simultaneously or sequentially, and to show the possibility that the learning mechanisms of the visuospatial domain involved in the frequency of item-position co-occurrence. In Experiment 1, we adapted Nakayama and Saito's (2017) paradigm to a visual short-term memory task with items presented simultaneously (i.e., Luck & Vogel, 1997) to examine whether repetition is a necessary but not a sufficient condition for improving visual short-term memory, as observed by previous studies (Fukuda & Vogel, 2019; Logie et al., 2009; Olson et al., 2005; Olson & Jiang, 2004; Shimi & Logie, 2019). In Experiments 2–4, we extended Experiment 1 to examine further the simplified recall procedure (using the single probe method used by Wheeler & Treisman, 2002), foveal to parafoveal attention, as well as a longer encoding time (1,200 ms) for inducing Hebb repetition learning, respectively. In Experiment 5, we presented items sequentially rather than simultaneously to compare our results in the visual domain with those reported by Nakayama and Saito (2017) in the verbal domain, such as whether the effect size of whole list learning was larger than that of position–item learning. Finally, in Experiment 6, we replaced the colored patches with verbal nonwords while maintaining the same presentation method as in Experiment 5. It allowed a direct comparison between the visuospatial domain and verbal domains. Note that "position" in experiments of this study refers to spatial position (i.e., location) rather than serial order position, as our task required participants to remember the spatial locations of items. See Table 1 for the summary of the experiments.

Experiment 1: Simultaneous Presentation With Whole-Probe Recall

To investigate the learning dynamics underlying the Hebb repetition effect in visual short-term memory, we adopted Nakayama and Saito's (2017) learning schedule to the task proposed by Luck and Vogel (1997). To adapt Nakayama and Saito's method to our concerns, we changed the task from the detection of changes between an encoding display and a probe display to the recollection of all items; that is, participants were simultaneously presented with multiple color patches and then asked to immediately recall all of them (i.e., reconstruction of color and location).

The first research question in Experiment 1 was whether immediate recall performance for Hebb lists would improve with repetition. Since statistical learning is observed in multiple domains, we expected performance to improve more for Hebb lists than for filler lists. However, following previous studies (Fukuda & Vogel, 2019; Logie et al., 2009; Olson et al., 2005; Olson & Jiang, 2004; Shimi & Logie, 2019), it would not necessarily be observed.

If recall performance could be improved with repetition, the second question would concern the mechanisms of the repetition effect; that is, whether individuals made use of location–item frequency in a learning task targeting visual short-term memory and whether the whole list repetition effect shows higher memory performance than the location-item frequency effect. According to Nakayama and Saito (2017), recall performance was expected to be highest for Hebb lists and better for frequent-location items in mixed-frequency lists than for infrequent-location items in mixed-frequency and filler lists.

In terms of visual short-term memory performance, Luck and Vogel (1997) showed that three color patches could be memorized with near-perfect performance. However, performance declined with the presentation of more than three items and reached a chance level of six items. This result suggests a smaller capacity than that observed in the case of verbal short-term memory (i.e., Luck & Vogel, 1997). Considering together with the results of the pilot study, although five items were presented to participants in Nakayama and Saito (2017), we decided to present only four items in this study. We expected to observe improvement in participants' performance and avoid a decrease in motivation due to the task's difficulty. We selected a sample size of $N = 30$ for this series of experiments based on Nakayama and Saito (2017).

The Hebb lists in Nakayama and Saito (2017) showed a detectable increase in memory performance within a block. Each experimental block of 16 lists contained a unique Hebb list, which was presented only 4 times within the block, and the result indicated robust and

Table 1
An Overview of Experiments Indicating in Which Variable(s) They Differ

Variable	Experiment 1	Experiment 2	Experiment 3	Experiment 4a	Experiment 4b	Experiment 5a	Experiment 5b	Experiment 6
Memory item	Color	Color	Color	Color	Color	Color	Color	Nonword
Presentation mode	Simultaneous	Simultaneous	Simultaneous	Simultaneous	Simultaneous	Sequential	Sequential	Sequential
Presentation duration	200 ms	200 ms	200 ms	1,200 ms	1,200 ms	300 ms each (+500 ms blank)	300 ms each (+500 ms blank)	300 ms each (+500 ms blank)
Stimulus size/location	Large/sparse	Large/sparse	Small/dense	Large/sparse	Large/sparse	Large/sparse	Large/sparse	Large/sparse
Recall item	Whole	Single	Whole	Whole	Whole	Whole	Whole	Whole
Eye movements	Unrestricted	Unrestricted	Unrestricted	Unrestricted	Restricted	Unrestricted	Unrestricted	Unrestricted
Articulately suppression	No	No	No	Yes	Yes	No	Yes	No

rapid learning of the Hebb lists. In contrast, the high-frequency location items were presented frequently in the same locations across blocks. Thus, location–item association learning could be accumulated throughout the experiment. The arrangement of this learning schedule was based on the prediction that position–item association learning would be slower than whole-list learning (see Saito et al., 2020, for discussions on this issue). Note that their Hebb lists were always constructed with high-frequency position items. For example, a high-frequency position item "to-nu" that appeared at the first serial position in a mixed-frequency list in one block was presented at the first serial position in a Hebb list in another block. With these list structures, Nakayama and Saito confirmed the advantage of the whole list learning over position–item association learning. Adopting their learning schedule, we investigate repetition learning characteristics in the visuospatial domain.

Method

Participants

Thirty undergraduate and graduate students at Kyoto University participated, 12 of whom were women. Their ages ranged from 18 to 25 years ($M = 21.0$, $SD = 1.9$). All participants had normal or corrected-to-normal vision and reported not being colorblind. The internal review board of Kyoto University (CPE-227) approved the procedures and written informed consent (after informing participants of the study purpose, methodology, risks, their right to withdraw, the duration of the experiment, handling of individual information, and the voluntary nature of participation) was obtained from all participants prior to testing. Participants were naïve to the purpose of the study and were paid 1,000 JPY for their participation in the experiment, which lasted 1 hr.

Stimuli and Apparatus

Ten colored squares, subtending 1.7° (width) × 1.7° (height) of the visual angles, were used as items for memorization. Colors were determined to be clearly discriminable, and no participants reported confusing them with each other (RGB values for the color patches were [64, 0, 63], [254, 128, 192], [128, 128, 192], [128, 128, 64], [181, 229, 29], [185, 122, 87], [255, 255, 129], [129, 255, 254], [255, 128, 65], and [64, 128, 128]). Four placeholders were distributed evenly around the circumference of a circle with a diameter of 4.6° of the visual angles, placed at the center of the monitor; these placeholders were invisible to participants, and their locations varied across participants. The background color was gray. The task was presented using MATLAB (The MathWorks, Inc., Natick, MA, USA) with the Psychtoolbox extension (Brainard, 1997; Pelli, 1997). All stimuli were presented on a cathode ray tube monitor with 1024 × 768-pixel resolution, 75 cm away from the participant's head, in a dimly lit room.

Presentation Schedule

To examine the effects of whole list repetition and location–item repetition, we constructed learning lists following Nakayama and Saito (2017). Table 2 shows part of the planned schedule, and Table 3 shows the total numbers of each item presented, indicating that high-frequency location–item combinations were presented 4 times more often than low-frequency location–item combinations. Based on this design, three types of four-item lists were constructed. Hebb lists ("HEBB") consisted of fixed combinations of only high-frequency location–item combination items, repeated 4 times within each block. A Hebb list was presented once every four trials. Mixed location–item frequency lists ("MIX") consisted of a combination of two high-frequency items and two low-frequency items. The high-frequency combinations were repeated within each block. In contrast, the low-frequency combinations differed every time. Filler lists ("FILLER") consisted only of low-frequency location–item combination items, meaning that different items were presented every time.

As shown in Table 2, each block consisted of four sub-blocks, presenting MIX, HEBB, MIX, and FILLER lists in sequence. Sixteen blocks (i.e., 64 sub-blocks or 256 trials) were designed with the following constraints: (a) no lists except the Hebb lists were repeated, (b) each Hebb list was presented no more than 4 times, and (c) no item was repeated within a list. There were 16 Hebb lists, 128 mixed-frequency lists, and 64 filler lists. The order of all the items was fixed across participants. A set of colors were randomly assigned to items 0 to 9 for each participant.

Procedure

Participants were asked to memorize the presented colors and their locations in each trial and immediately recall all colors in the correct locations. During the experiment, participants began each trial by clicking the mouse, whereupon a fixation cross was presented at the center of the monitor for 500 ms, followed by simultaneous presentation of the four color patches for 200 ms (see Figure 1). Subsequently, a blank screen was presented for 2,000 ms, during which participants were required to maintain the items for subsequent recall.

After the 2,000 ms maintenance interval, a recall display and mouse cursor were presented to the participants. In this display, there were four placeholders; 10 colors were presented around each placeholder (see Figure 1). Participants were asked to click on the color that had been presented at each location during the

Table 2
Example of Part of the Planned Learning Schedule

Block	Sub-block	Trial	List type	Position 1	Position 2	Position 3	Position 4
1	1	1	MIX	1	3	0	2
		2	HEBB	0	2	4	6
		3	MIX	2	6	5	7
		4	FILLER	6	4	9	5
	2	5	MIX	1	3	8	0
		6	HEBB	0	2	4	6
		7	MIX	3	9	5	7
		8	FILLER	7	5	3	1
	3	9	MIX	1	3	7	8
		10	HEBB	0	2	4	6
		11	MIX	4	0	5	7
		12	FILLER	5	7	1	3
	4	13	MIX	1	3	2	9
		14	HEBB	0	2	4	6
		15	MIX	8	1	5	7
		16	FILLER	9	8	6	4
2	5	17	MIX	0	3	7	8
		18	HEBB	1	2	4	6
		19	MIX	2	1	5	7
		20	FILLER	9	4	0	5
		.	.	.	.	.	.
		.	.	.	.	.	.
		.	.	.	.	.	.

Note. The numbers 0–9 in the columns denoting Positions 1, 2, 3, and 4 represent colors; positions and colors were allocated randomly to these numbers for each participant. Gray cells indicate high-frequency color-position associations. HEBB, MIX, and FILLER indicate Hebb list, mixed-frequency list, and filler list, respectively.

presentation period. Once they had clicked on a color, the corresponding placeholder was filled with this color, and they could not change their response. Participants were able to recall the items in arbitrary order. The positions of the colors within the array of response options were randomly decided on each trial, but within a given trial, they were consistent across all placeholders.

Table 3
Presentation Frequencies for Position–Item Combinations in a Single Block

Color	Position 1	Position 2	Position 3	Position 4	Total
Item 0	4	1	1	1	7
Item 1	4	1	1	1	7
Item 2	1	4	1	1	7
Item 3	1	4	1	1	7
Item 4	1	1	4	1	7
Item 5	1	1	4	1	7
Item 6	1	1	1	4	7
Item 7	1	1	1	4	7
Item 8	1	1	1	1	4
Item 9	1	1	1	1	4
Total	16	16	16	16	

Note. Items 0–9 represent colors, which were each randomly allocated to an item number for each participant. Gray cells indicate high-frequency color-position combinations. Two colors, which were assigned to items 8 and 9, were not frequently presented throughout the experiment. Each block was repeated 16 times in the experiment.

After the participant had provided responses for all four color patches, a blank display appeared, and they could begin the next trial by clicking the mouse again. Participants were not given any feedback on whether their responses were correct.

Data

All data in this study are available online (https://osf.io/gr5hq/). The experiments were not preregistered.

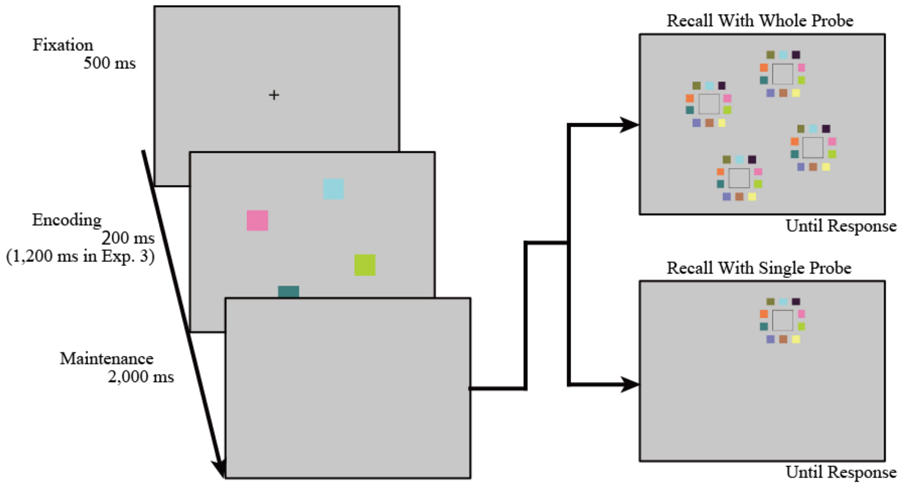
Results

Average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks are shown in Figure 2. We conducted a 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian analysis of variance (ANOVA; Love et al., 2015; Morey & Rouder, 2015; Rouder et al., 2012) with default prior scales (JASP 0.14.1.0). The results are shown in Table 4. It revealed that any models containing main effects and interaction were not preferred against a null model by a Bayes factor of 0.40–4.36 × 10^{-8} (HEBB: 63.5%; high-frequency MIX: 61.3%; low-frequency MIX: 62.6%; FILLER: 60.7%). The data thus did not provide positive evidence of any repetition effect in this visual short-term memory task.

Discussion

Experiment 1 showed no improvement with repetition in a visual short-term memory task. Although this result differs from the

Figure 1
The Procedure of Experiments 1–3



Note. In Experiments 1 and 3, participants were asked to recall all four patches (top right); in Experiment 2, they were asked to recall one of the four patches (bottom right). See the online article for the color version of this figure.

findings of Nakayama and Saito (2017), who examined the speech version of the same paradigm, it is consistent with the results of the previous experiments in the visual domain (Fukuda & Vogel, 2019; Logie et al., 2009; Olson et al., 2005; Olson & Jiang, 2004; Shimi & Logie, 2019). Note that not only the whole list learning effect (Hebb repetition learning) but also other position–item learning was not observed. One possible explanation for the apparent lack of a repetition effect in Experiment 1 is that some materials might have been forgotten from short-term memory during the recall process, where participants had to recall all the color patches. To examine this possibility, in Experiment 2, we again presented four color patches to participants during the encoding period but asked them to recall only one color patch (i.e., a single-probe method, as proposed by Wheeler & Treisman, 2002).

Experiment 2: Simultaneous Presentation With Single-Probe Recall

In Experiment 1, participants were required to recall all color patches on each trial. Therefore, their memory for any given color might have been subjected to decay or interference during the recall of colors in the other locations. If this was the case, there is a possibility that participants could have successfully encoded the items and improved their ability to do so through learning over the experiment. Still, they could not demonstrate this because the information was lost during maintenance and retrieval. To prevent this type of effect from whole-array probes, Wheeler and Treisman (2002) proposed a single-probe task in which a single item is selected out of all encoded items, and the participant is asked to recall (or recognize) only this item. Using this method in Experiment 2, we again examined whether immediate recall performance for Hebb lists improves with repetition and whether learning based on both whole list learning and location–item association learning can be observed in visual short-term memory.

Method

Participants

A group of 30 undergraduate and graduate students at Kyoto University, 16 of whom were women, participated in Experiment 2. Their ages ranged from 18 to 29 years ($M = 21.4$, $SD = 2.5$). None of them had participated in Experiment 1. Vision-related exclusion criteria, ethical considerations, and payment were similar to those in Experiment 1.

Stimuli, Apparatus, and Presentation Schedule

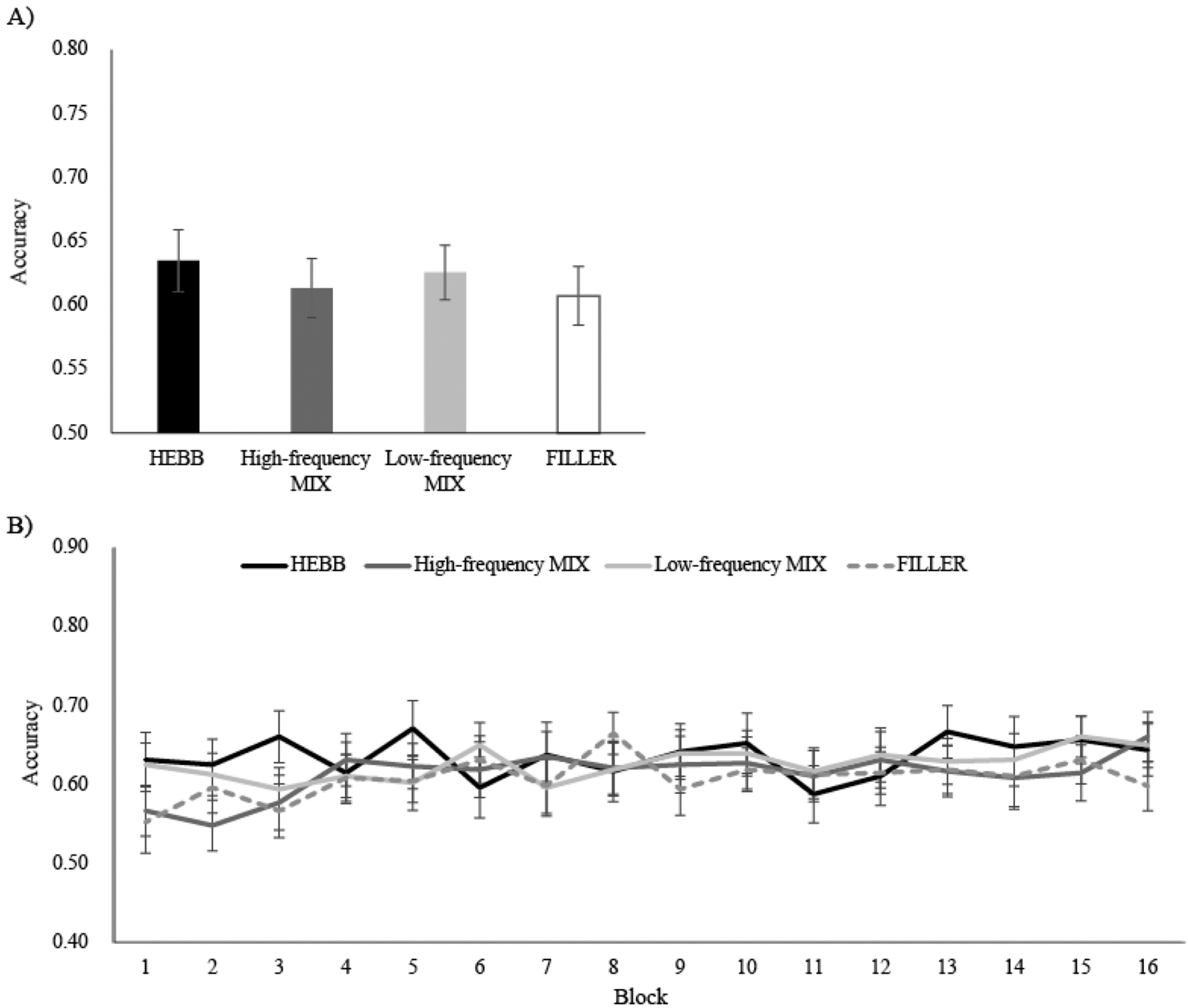
These were identical to those used in Experiment 1.

Procedure

Almost all aspects of the protocol were identical to those used in Experiment 1; the only difference was in the recall phase. In Experiment 2, the 10 candidate colors for a response were presented around only one placeholder (see Figure 1). The recall location was selected using the following rules. During the first and second trials in each sub-block, in which MIX and HEBB lists were presented, respectively, the recall location was chosen randomly. On the third trial in each sub-block, in which a second MIX list was presented, the recall location was selected from those of the two high-frequency items if one of the low-frequency items had been selected for recall in the first trial, in which the first MIX list was presented. Conversely, the third trial recall location was selected from those of the two low-frequency items if one of the high-frequency items had been selected for recall in the first trial. This procedure enabled us to investigate recall performance for the same number of trials in each condition. On the fourth trial in each sub-block, in which a FILLER list was presented, one of the recall locations

Figure 2

Mean Recall Accuracy (A) Over the Entire Experiment and (B) in Each Block of Experiment 1 (Simultaneous Presentation With Whole-Probe Recall)



Note. Error bars represent the standard error of the mean.

was chosen, and it was fixed throughout the experiment.[1] No participants reported discerning how the recall locations had been selected.

Table 4

Results of Bayesian ANOVA in Experiment 1

Models	BF_{10}
Null model	**1.00**
List	0.40
Block	8.33×10^{-4}
List + Block	3.48×10^{-4}
List + Block + List × Block	4.36×10^{-8}

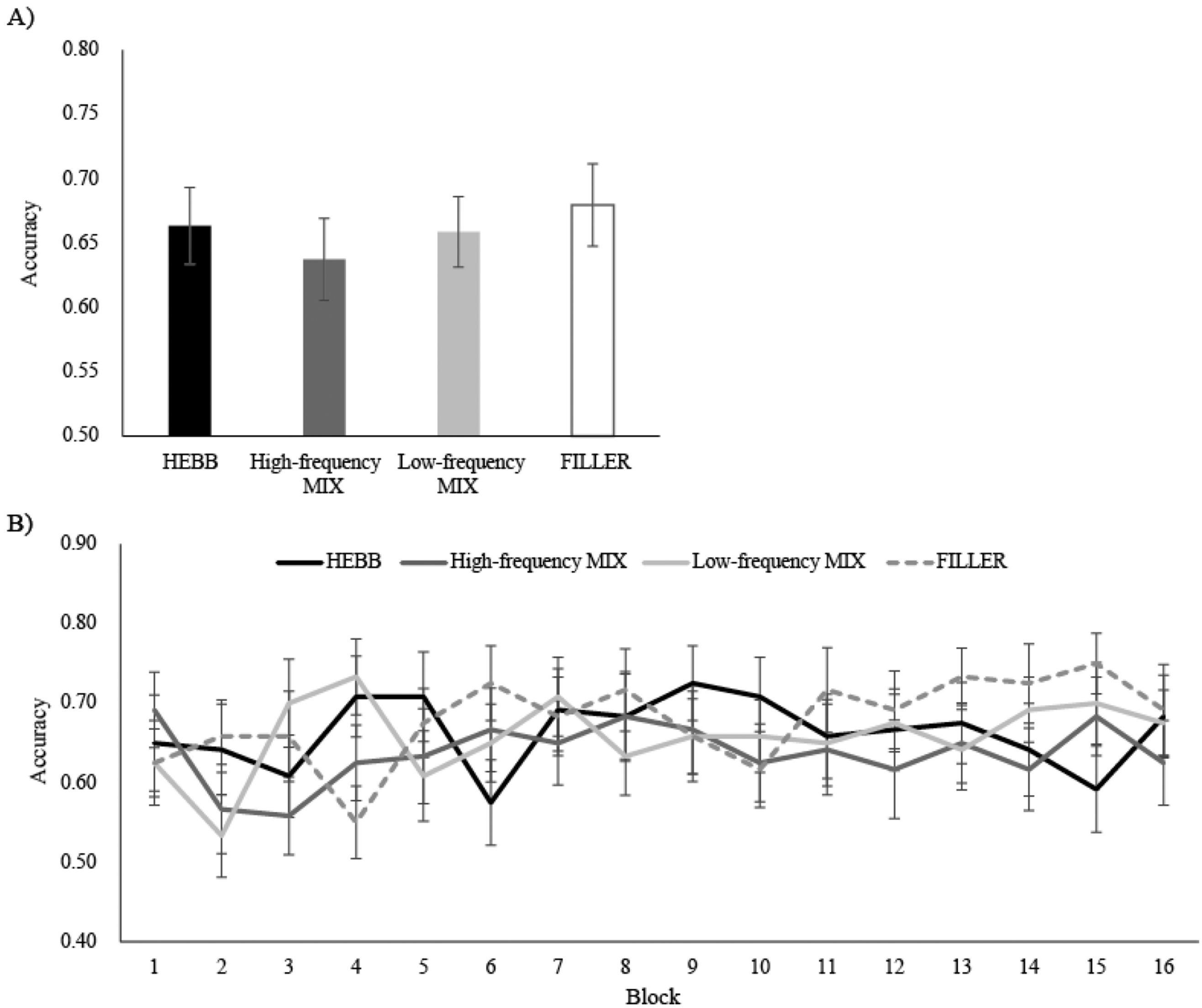
Note. The bold indicates the best model.

Results

Figure 3 shows the average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks. A 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA with default prior scales was performed, and the results are shown in Table 5. It provided strong evidence that any models containing main effects and interaction effects were not preferred to the null model by a Bayes factor of 0.05–6.36×10^{-9} (HEBB: 66.4%; high-frequency MIX: 63.8%; low-frequency MIX: 65.9%; FILLER:

[1] Due to a program error, the recall location of the FILLER lists was fixed. The effects of the fixed recall location were thus analyzed with post hoc tests.

Figure 3
Mean Recall Accuracy (A) Over the Entire Experiment and (B) in Each Block of Experiment 2 (Simultaneous Presentation with Single-Probe Recall)



Note. Error bars represent the standard error of the mean.

68.0%). These results suggest that no improvement was observed with repetition, even when participants were asked to recall only a single item.

Table 5
Results of Bayesian ANOVA in Experiment 2

Models	BF_{10}
Null model	**1.00**
List	0.05
Block	5.97×10^{-5}
List + Block	3.04×10^{-6}
List + Block + List × Block	6.36×10^{-9}

Note. The bold indicates the best model.

The probability that a probe would appear at a particular location was slightly higher than at other locations across the experiment because all probes for the FILLER lists were presented at a fixed location.[2] It might have led to a tendency for participants to focus their attention and intentionally remember an item presented at that location. This could be a possible reason why the FILLER condition showed a (numerically) slightly higher accuracy rate. It is probable that in other types of lists (HEBB, high-frequency MIX, and low-frequency MIX), performance could have been higher at that location. For this reason, in a post hoc analysis, we calculated recall performance only

[2] see footnote 1.

with the location where a probe was presented in the FILLER condition. The recall accuracy rates in HEBB list items, high-frequency MIX list items, low-frequency MIX list items, and FILLER list items were 65.9%, 63.3%, 66.8%, and 68.0%, respectively. A one-way Bayesian ANOVA (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) with default prior scales provided strong evidence that models with a main effect were not preferred against the null model by a Bayes factor of 0.093. These results were similar to the previous (main) analysis.

Since the recall location of the FILLER lists was fixed, there is a possibility that participants paid attention to only one location, whether or not they were aware of it. Therefore, we compared the recall performance of HEBB list items, high-frequency MIX list items, and low-frequency MIX list items, which were presented in the remaining three probe locations (i.e., except for the location where the FILLER list items were recalled). These recall performances were similar to those presented at the location where a probe in the FILLER condition was presented: 66.6% in HEBB list items, 64.2% in high-frequency MIX list items, and 65.4% in low-frequency MIX list items. A one-way Bayesian ANOVA (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) with default prior scales provided moderate evidence that models with a main effect were dispreferred to the null model by a Bayes factor of 0.197.

Discussion

Experiment 2 yielded similar findings as Experiment 1; that is, repetition did not improve recall performance in a visual short-term memory task. In Experiment 2, we employed a single-probe method in which participants were asked to recall only one item presented in a particular location. The results suggest that the lack of a repetition effect observed in Experiment 1 was not due to participants' loss of stored information from memory during the recall of other color patches.

Experiment 3: Simultaneous Presentation in Parafoveal Vision

Another possible reason for the absence of a repetition effect in Experiments 1 and 2 was the considerable distance between items, which might have been potentially impaired encoding of individual items due to low resolution in perifoveal vision and that of the whole-array display. To examine this, in Experiment 3, we moved color patches closer to the center of the monitor (i.e., to be picked up by parafoveal vision) to obviate the need for larger eye movements. This may facilitate participants' easier simultaneous encoding of color patches than Experiments 1 and 2 (see Brady & Störmer, 2022).

Method

Participants

A group of 30 undergraduate and graduate students participated at National Taiwan University, 13 of whom were women. Their ages ranged from 19 to 26 years ($M = 21.3$, $SD = 2.2$). Vision-related exclusion criteria and ethical considerations were the same as those in Experiment 1. Participants were paid 140 NTD for their participation in the experiment.

Apparatus, Stimuli, and Presentation Schedule

Although this experiment was conducted at National Taiwan University, almost all aspects were identical to Experiment 1; the only differences other than the instruction language were the distance between the monitor and the participants, stimulus size, and presentation locations. To present stimuli in the parafoveal vision, the size of the colored squares subtended 0.8° (width) × 0.8° (height) of the visual angles, and four placeholders were distributed evenly around the circumference of a circle with a diameter of 2.8° of the visual angles, placed at the center of the monitor. The distance between the monitor and the participants was 60 cm.

Procedure

The protocol was identical to that of Experiment 1; that is, participants were asked to recall all four color patches.

Results

Figure 4 shows the average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks. A 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA with default prior scales was performed, and the results are shown in Table 6. It provided very strong evidence that the model including a main effect of the block was best preferred. The data thus indicated that recall performance increased with a practice effect, but did not indicate that a repetition effect was observed (HEBB: 67.5%; high-frequency MIX: 65.5%; low-frequency MIX: 67.4%; FILLER: 66.8%).

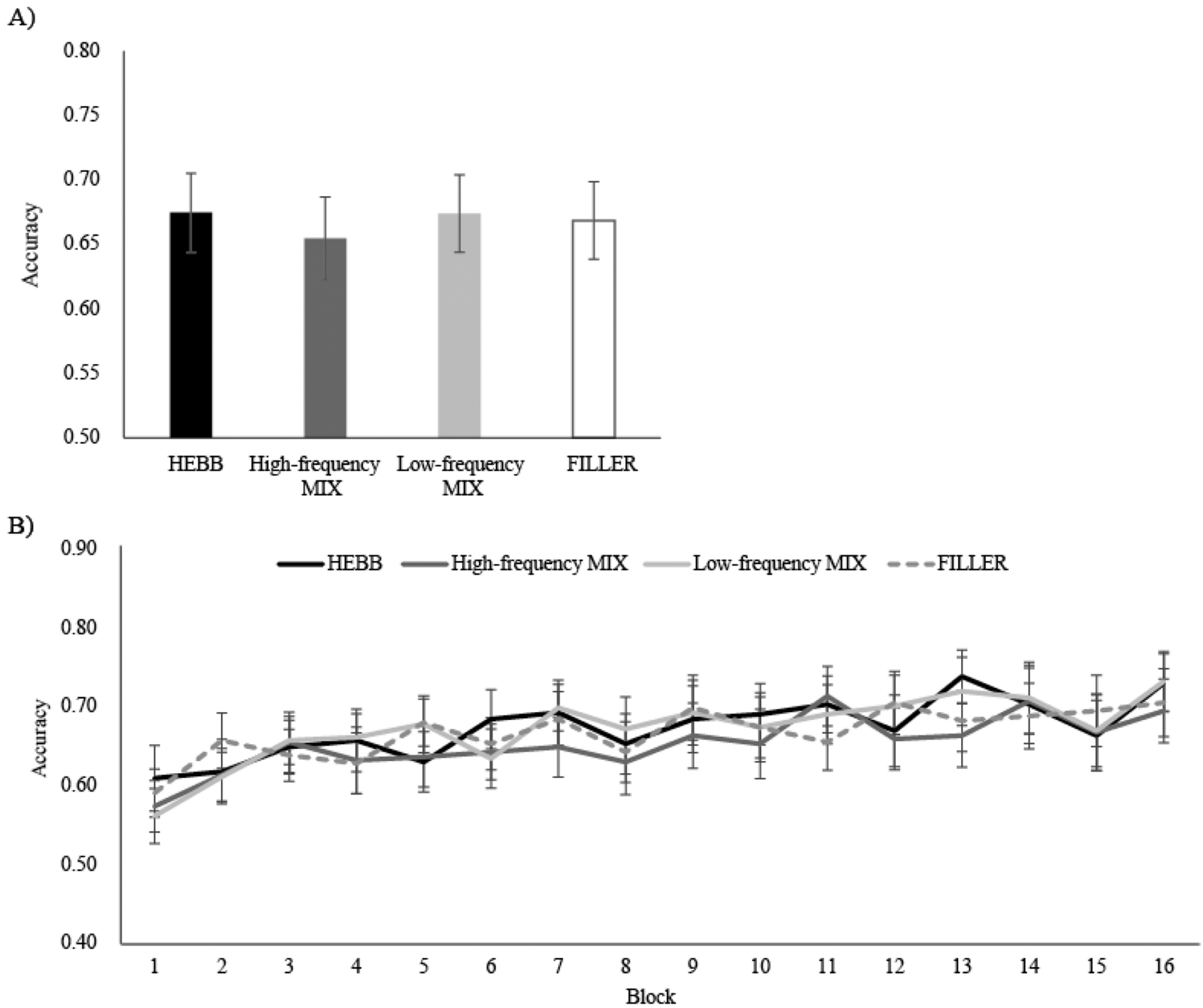
Discussion

The repetition effect was not observed even when stimuli were presented in the parafoveal vision, within which participants could see all the items at a glance more easily as compared with Experiments 1 and 2.

An interim summary of the findings through Experiments 1–3 is that the Hebb repetition effect was not observed with simultaneous item presentation in the visuospatial domain, even though the repetition number is capable of inducing the Hebb repetition effect in the verbal domain. In paradigms eliciting a Hebb repetition effect in the verbal domain, participants listen to linguistic materials that are sequentially presented (e.g., Hebb, 1961; Majerus et al., 2004, 2012). As mentioned in the Introduction, this might be a key factor for Hebb repetition learning. Another possibility might be to increase the amount of information that can be stored by extending the encoding time of the item and thus gain the benefit of repeated presentation.

In the following experiments, we examined each of the two factors (longer presentation duration and sequential presentation) separately. In Experiment 4, we investigated the first factor by increasing the presentation duration of the stimuli.

Figure 4
Mean Recall Accuracy (A) Over the Entire Experiment and (B) in Each Block of Experiment 3 (Simultaneous Presentation in Parafoveal Vision)



Note. Error bars represent the standard error of the mean.

Experiments 4a and 4b: Simultaneous Presentation With a Longer Encoding Duration and Restricted or Unrestricted Eye Movements

In this experiment, we extended the encoding time for the color patches from 200 to 1,200 ms. To prevent participants from encoding them using verbal information with a longer presentation time, we asked participants to say aloud "dadadada…" (i.e., to engage in articulatory suppression) during the encoding phase. To match the visual field locations where the items were presented to those in Experiments 1–3, we conducted both cases where the gaze was fixed in the fixation cross (Experiment 4a) and where no such restriction was applied (Experiment 4b).

Method

Participants

Two groups of 30 undergraduate and graduate students participated at Kyoto University (Experiment 4a) included 13 women, and participants' ages ranged from 18 to 29 years with $M = 22.2$ and $SD = 2.5$, while Experiment 4b included 16 women, and participants' ages ranged from 18 to 26 years with $M = 21.1$ and $SD = 2.0$). None of them had participated in any previous experiments in this study. Vision-related exclusion criteria and ethical considerations were the same as in Experiment 1. Participants were paid 1,500 JPY for participating in the experiment, which lasted 1.5 hr. The duration was longer than previous experiments because of calibration and recording of participants' eye movements during the experiment.

Table 6
Results of Bayesian ANOVA in Experiment 3

Models	BF_{10}
Null model	1.00
List	0.02
Block	$\mathbf{2.06 \times 10^{10}}$
List + Block	4.91×10^{8}
List + Block + List × Block	2.36×10^{3}

Note. The bold indicates the best model.

Apparatus

In addition to the apparatus used in previous experiments, an Eyelink 1,000 with a 500 Hz sampling rate was used to record participants' eye movements. The Eyelink was operated via MATLAB with the Psychtoolbox extension, which includes the Eyelink Toolbox (Kleiner et al., 2007).

Stimuli and Presentation Schedule

All aspects were identical to Experiment 1.

Procedure

The protocol was almost identical to that of Experiment 1. The only differences were that the encoding time was extended from 200 to 1,200 ms, and the fixation cross remained visible during the encoding phase. Participants were asked to say the syllable "da" twice per second to prevent them from relying on verbal information, and a calibration procedure for the Eyelink system was conducted at the beginning of every block. Eye movements were monitored online by the experimenter.

Results

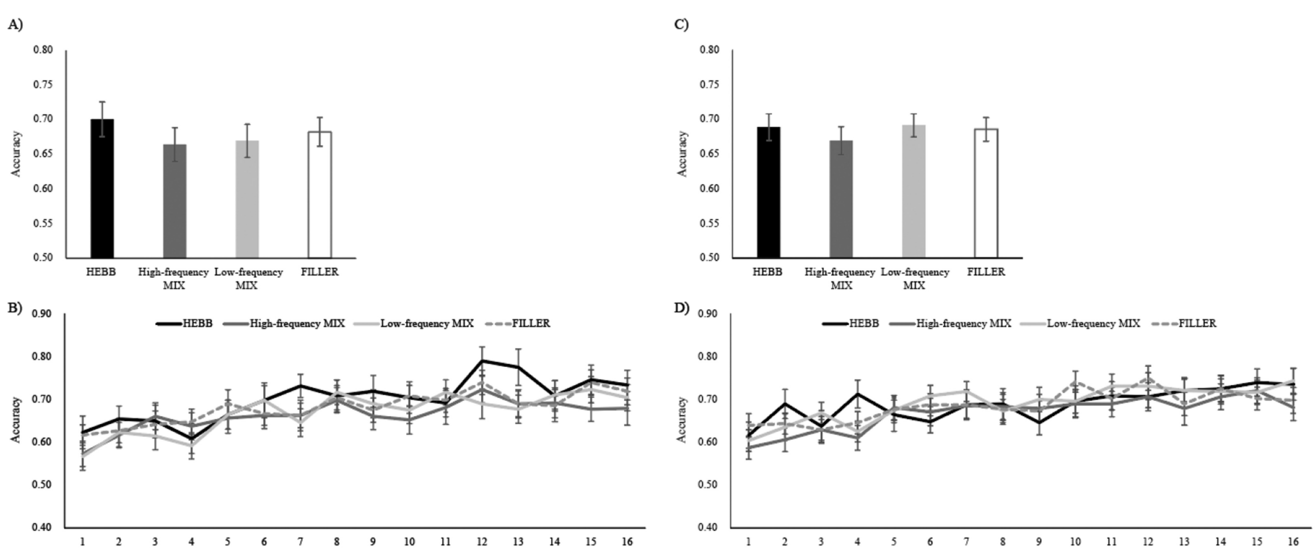
Figure 5 shows the average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks. A 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA with default prior scales was performed, and the results are shown in Table 7.

Experiment 4a (without eye movements) provided very strong evidence that the model including the main effects of list item and block was best preferred. For the main effect of the list item, the post hoc test showed evidence that recall accuracy differs between Hebb (70.0%) and high-frequency MIX list items (66.4%), and that recall accuracy differs between Hebb and low-frequency MIX list items (66.9%), respectively (i.e., $BF_{10,\ U}$ of 101.05 and 30.40). However, the data indicated that other differences in the list item, including Hebb and FILLER conditions (68.2%), were regarded as the same (i.e., $BF_{10,\ U}$ were less than 1.31).

In Experiment 4b (with eye movements), Bayesian ANOVA provided strong evidence that the model including a main effect of the block was best preferred. These results were consistent with those of Experiment 4a, and we can conclude that no Hebb repetition effect was observed in this paradigm (HEBB: 68.9%; high-frequency MIX: 66.9%; low-frequency MIX: 69.2%; FILLER: 68.6%).

These results suggest that recall performance improved over the course of repeated trials but that this was not due to the repetition of whole lists or particular position–item associations. Specifically, we cannot observe a significant difference in performance between the HEBB lists and the FILLER lists. Therefore, we conclude that no Hebb repetition effect was observed in Experiments 4a and 4b, even when the encoding time was increased to more than 1 s.

Figure 5
Mean Recall Accuracy (A and C) Over the Entire Experiment, and (B and D) in Each Block, in Experiments 4a (Simultaneous Presentation With a Longer Encoding Duration and Restricted Eye Movements) and 4b (Simultaneous Presentation With a Longer Encoding Duration and Unrestricted Eye Movements), Respectively



Note. Error bars represent the standard error of the mean.

Table 7
Results of Bayesian ANOVA in Experiments 4a and 4b

Models	Experiment 4a BF_{10}	Experiment 4b BF_{10}
Null model	1.00	1.00
List	32.42	0.06
Block	1.50×10^{22}	$\mathbf{1.95 \times 10^{13}}$
List + Block	$\mathbf{1.11 \times 10^{24}}$	1.36×10^{12}
List + Block + List × Block	9.57×10^{19}	1.07×10^{7}

Note. The bold indicates the best model.

A post-hoc analysis of Experiments 4a and 4b using a 2 (experiment: 4a vs. 4b) × 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA provided strong evidence that the model including main effects of list item and block. For the main effect of the list item, recall accuracy differs between Hebb and high-frequency MIX list items, and high-frequency MIX list items and FILLER. However, the performance of the Hebb and FILLER lists was comparable. Therefore, we conclude that the Hebb repetition effect was not observed in Experiment 4.

Discussion

Experiment 4 elicited no repetition effects from the use of whole list representations or location–item frequency, like the previous experiments, suggesting that shorter presentation duration was not a factor precluding the detection of such an effect in Experiments 1–3. The instruction concerning eye movement limitations did not affect the results. To examine the second potential factor, namely, the allocation of attention to each object, or sequential processing, we presented the items sequentially in Experiment 5.

Experiments 5a and 5b: Sequential Presentation

In Experiment 5, items were presented to the participants sequentially rather than simultaneously. The aim was to examine whether sequential processing plays an important role in the Hebb repetition effect.

Method

Participants

Two groups of 30 undergraduate and graduate students participated at Kyoto University (Experiment 5a included 15 women and participants' ages ranged from 18 to 34 years with $M = 21.8$ and $SD = 3.1$, while Experiment 5b included 14 women and participants' ages ranged from 18 to 27 years with $M = 20.7$ and $SD = 2.1$). None of them had participated in any previous experiments in this study. Vision-related exclusion criteria, ethical considerations, and payment were the same as in Experiment 1. The experiment took 1 hr.

Stimuli, Apparatus, and Presentation Schedule

All aspects were identical to Experiment 1. Participants' eye movements were not recorded.

Procedure

During the experiment, participants began each trial by clicking the mouse, after which a fixation cross was presented at the center of the monitor for 500 ms, followed by sequential presentations of four color patches, one at a time, with the presentation of duration 300 and 500 ms inter-stimulus intervals (see Figure 6). After the presentation of the last color patch, a blank screen was presented for 2,000 ms, and then the recall display appeared. This was the same as in Experiments 1, 3, and 4 (i.e., whole-probe recall). The order in which item location was presented was randomly decided across participants but fixed for each individual participant. In Experiment 5a, articulatory suppression was not used while in Experiment 5b, participants were asked to engage in articulatory suppression during the encoding period (see the Method section for Experiment 4). All other aspects of the procedure were identical to those used in the previous experiments.

Results

Figure 7 shows the average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks. A 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA with default prior scales was performed, and the results are shown in Table 8.

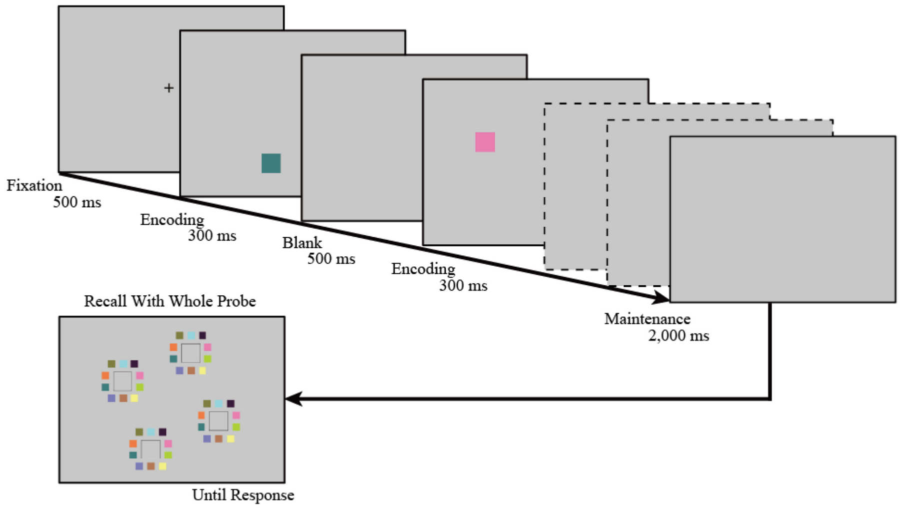
Experiment 5a provided extreme evidence that the model including the main effects of the list item and the block was best preferred. For a main effect of the list item, the post hoc test showed evidence that recall accuracy for HEBB list items (72.8%) was higher than for low-frequency MIX list items (67.6%) and FILLER list items (66.8%) by $BF_{10,\ U}$ of 6.10×10^5 and 1.36×10^7, respectively. Moreover, evidence that the recall accuracy for high-frequency MIX list items (72.3%) was also higher than for low-frequency MIX and FILLER list items by $BF_{10,\ U}$ of 3.93×10^5 and 6.94×10^7, respectively. The data indicated that recall accuracy for HEBB and high-frequency MIX list items and for low-frequency MIX and FILLER list items were the same (i.e., $BF_{10,\ U}$ were 0.06 and 0.08, respectively).

In Experiment 5b, Bayesian ANOVA provided strong evidence that the model including the main effects of list item and block was best preferred. For a main effect of the list item, the post hoc test indicated that recall accuracy for HEBB list items (68.0%) was higher than for low-frequency MIX list items (62.5%) and FILLER list items (63.8%) by $BF_{10,\ U}$ of 2.63×10^6 and 385.98, respectively. Moreover, the recall accuracy for high-frequency MIX list items (66.3%) was also higher than for low-frequency MIX and FILLER list items by $BF_{10,\ U}$ of 720.05 and 4.51, respectively. The data indicated that recall accuracy for HEBB and high-frequency MIX list items and for low-frequency MIX and FILLER list items were respectively the same (i.e., $BF_{10,\ U}$ were 0.15 and 0.15, respectively).

As a post-hoc analysis, we compared the results of Experiments 5a and 5b. A 2 (experiment: 5a vs. 5b) × 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA provided strong evidence that the model including main effects of list item and block, but not the main effect of experiment and interaction including this factor, was preferred rather than the null model ($BF_{10} = 1.69 \times 10^{90}$). However, evidence that the best model was preferred over the model including all main effects was anecdotal (the best model's $BF_{10} = 0.56$ compared with a model including all main effects). In any case, evidence of

Figure 6

The Procedure of Experiment 5



Note. Participants were asked to engage in articulatory suppression in Experiment 5b but not in Experiment 5a. See the online article for the color version of this figure.

interaction was weak; we can consider that the patterns were the same across experiments.

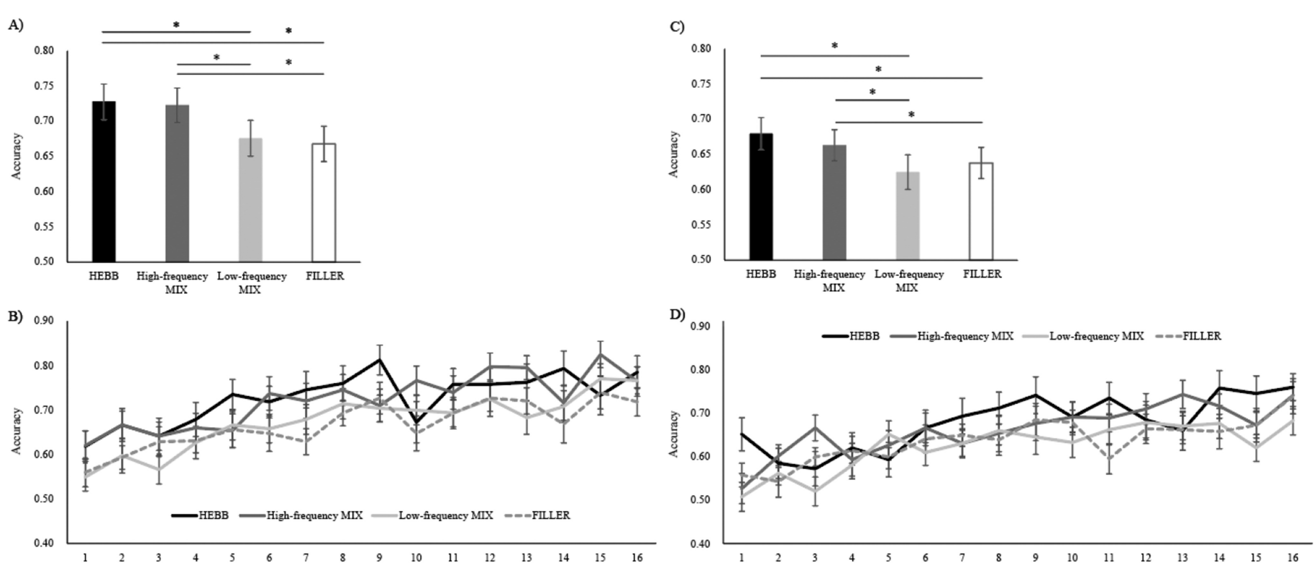
Discussion

The results indicated that recall accuracy improved with repetition when items were presented sequentially. However, recall accuracy did not significantly differ between HEBB list items and high-frequency items in the MIX list, suggesting that the Hebb repetition effect in the visual domain can be attributed mainly to the use of location–item frequency statistics and not to the use of whole list representation or item-to-item co-occurrence statistics. This result could be replicated even with articulatory suppression (Experiment 5b).

Nakayama and Saito (2017) showed that both whole list learning and position–item association learning contributed to the Hebb repetition effect in the verbal domain. In contrast, the current experiment did not show any additional effect of whole list repetition over location–item repetition, despite using the same learning schedule. This

Figure 7

Mean Recall Accuracy (A and C) Over the Entire Experiment, and (B and D) in Each Block, in Experiments 5a (Sequential Presentation Without Articulatory Suppression) and 5b (Sequential Presentation With Articulatory Suppression)



Note. Error bars represent the standard error of the mean. Asterisks in the figure indicate that post hoc tests provided strong evidence supporting a difference.

Table 8
Results of Bayesian ANOVA in Experiments 5a and 5b

	Experiment 5a	Experiment 5b
Models	BF_{10}	BF_{10}
Null model	1.00	1.00
List	8.39×10^{9}	4.60×10^{4}
Block	3.50×10^{37}	2.81×10^{27}
List + Block	$\mathbf{1.19 \times 10^{49}}$	$\mathbf{6.79 \times 10^{32}}$
List + Block + List × Block	2.21×10^{46}	2.65×10^{31}

Note. The bold indicates the best model.

discrepancy might be due to differences between the principal features of the domains: in the verbal domain, both whole-sequence knowledge and item-to-item association knowledge are important in addition to position–item association knowledge because a word or sentence is an aggregation of syllables that are always in sequences containing item-to-item transitions in language. In contrast to the verbal domain, learning information about item-to-item co-occurrence probability might not always be necessary for the visual domain. However, individuals might be able to learn item-to-item co-occurrence probability statistics even in the visual domain. For example, Biederman et al. (1982) demonstrated that people could perceive the "gist" of scenes, including spatial-positional relationships between items, at a glance (e.g., if a fire hydrant is on a post, performance in recognition of the scene is impaired).

Yet, it might not be fair to compare the experiments conducted in this study with those of Nakayama and Saito (2017) because the stimuli, presentation methods, and task difficulty were different. In the final experiment, we replicated Experiment 5 by changing the items to be memorized to verbal stimuli and examining the Hebb repetition effect in the verbal domain.

Experiment 6: Sequential Presentation With Verbal Materials

Experiment 5 showed that the Hebb repetition effect in the visuospatial domain is observed with a sequential presentation. Still, contrary to previous studies using verbal materials, this effect was based solely on learning location-item associations. To investigate whether this result depends on differences in item domain (visual or verbal) or methods employed in this study, we used verbal materials (four-mora Japanese nonwords) instead of color patches in Experiment 6. If differential results between the previous study (i.e., Nakayama & Saito, 2017) and Experiment 5 in the current study depend on item modality, the advantage of whole list learning over location-item learning would be observed with verbal materials; that is, recall accuracy for HEBB lists would be larger than that for high-frequency MIX lists.

Method

Participants

A group of 30 undergraduate and graduate students participated at Kyoto University, 16 of whom were women. Their ages ranged from 18 to 21 years ($M = 19.1$, $SD = 0.8$). None of them had participated in any of the previous experiments in this study. Exclusion criteria, ethical considerations, and payment were the same as those in Experiment 1.

Stimuli

Ten four-mora Japanese nonwords (ka-te-ku-yo, ka-te-ku-ki, ka-te-ki-ku, ka-ku-te-yo, ka-ku-te-ki, ku-ka-te-yo, ku-ka-te-ki, te-ka-ku-yo, te-ka-ku-ki, and te-ka-ki-ku) were used as items for memorization. The item-to-item similarity and task difficulty were adjusted to match those of previous experiments (i.e., Experiments 1–5) through the pilot study. To ensure that the presentation method was the same as in Experiments 1–5, we presented these words visually, subtending 3.4° (width) × 1.7° (height) of the visual angles. The places of word appearance were also the same as in the previous experiments (see Figure 8).

Apparatus and Presentation Schedule

All were identical to those used in Experiment 1.

Procedure

All procedures were identical to those used in Experiment 5a, indicating that items sequentially appeared one-by-one and participants were not required to engage in articulatory suppression.

Results

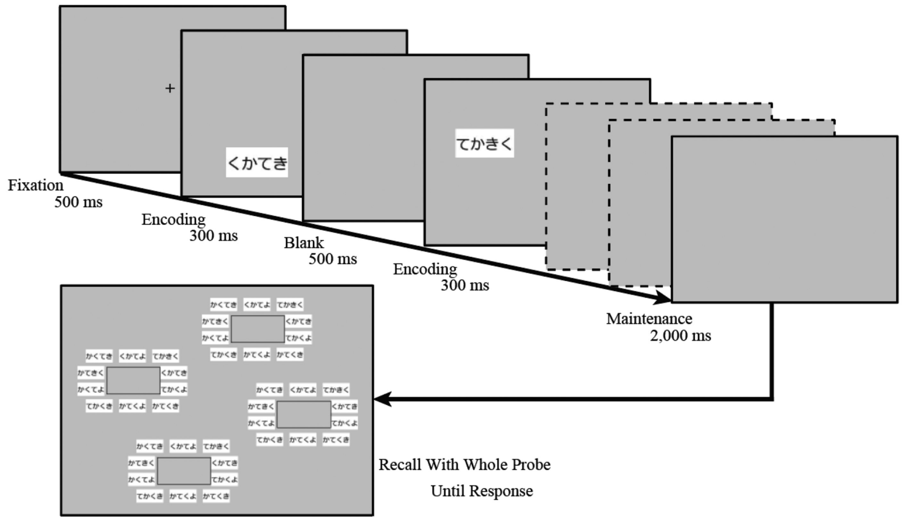
Figure 9 shows the average recall accuracy for the entire experiment and participants' progress over the course of the experimental blocks. A 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA with default prior scales was performed, and the results are shown in Table 9. It provided strong evidence that the model, including the main effects of list item and block, was best preferred. For the main effect of the list item, the post hoc test indicated that recall accuracy for HEBB list items (50.7%) was higher than for low-frequency MIX list items (45.8%) and FILLER list items (44.6%) by $BF_{10,\ U}$ of 1.29×10^{5} and 7.15×10^{7}, respectively. Moreover, the recall accuracy for high-frequency MIX list items (50.5%) was also higher than for low-frequency MIX and FILLER list items by $BF_{10,\ U}$ of 5.93×10^{4} and 2.18×10^{8}, respectively. The data indicated that recall accuracy for HEBB and high-frequency MIX list items and for low-frequency MIX and FILLER list items were respectively the same (i.e., $BF_{10,\ U}$ were 0.05 and 0.14, respectively).

Furthermore, as a post-hoc analysis, we compared the results of Experiments 5a, 5b, and 6. A 3 (experiment: 5a, 5b, or 6) × 4 (list item: HEBB, high-frequency MIX, low-frequency MIX, or FILLER) × 16 (block: first to 16th) Bayesian ANOVA provided strong evidence that the model including main effects of the experiment, list item, and block, but not interactions including experiment, was best preferred ($BF_{10} = 2.91 \times 10^{145}$). This indicated that although overall performances were different among the experiments (Experiment 6 was the worst and Experiment 5a was the best), the effect of the list item was the same across experiments.

Discussion

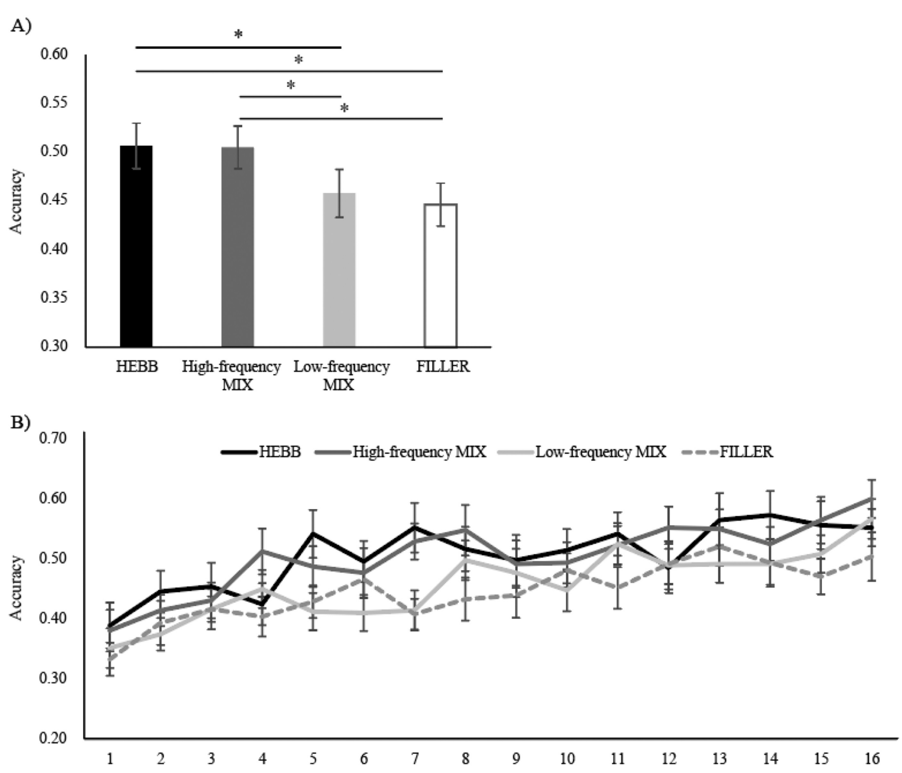
Although the overall performance was lower in Experiment 6 than in Experiment 5, it showed repetition-related improvement in

Figure 8
The Procedure of Experiment 6, in Which Japanese Nonwords Were Visually Presented



performance in a verbal short-term memory task, replicating the pattern of results in Experiment 5. Nakayama and Saito (2017) showed higher recall accuracy for a HEBB sequence than for high-frequency items in a MIX sequence, but no evidence for the difference between these item types was observed in the current study. Nakayama and Saito (2017) presented five two-mora Japanese nonwords to participants. In contrast, the present experiment presented four four-mora Japanese nonwords to match the presentation method and difficulty

Figure 9
Mean Recall Accuracy (A) Over the Entire Experiment and (B) in Each Block of Experiment 6 (Sequential Presentation Using Verbal Items)



Note. Error bars represent the standard error of the mean. Asterisks in the figure indicate that post hoc tests provided strong evidence supporting a difference.

Table 9
Results of Bayesian ANOVA in Experiment 6

Models	BF_{10}
Null model	1.00
List	1.71×10^9
Block	6.06×10^{27}
List + Block	$\mathbf{1.53 \times 10^{38}}$
List + Block + List × Block	6.46×10^{34}

Note. The bold indicates the best model.

level with Experiments 1–5 in this study. It might have increased the difficulty level compared with the previous study and led to insufficient whole list learning. Another possibility is that the spatial nature of the task requirement (item-serial position association in the previous study while item-spatial position association in this study) weakened the whole list learning.

Although the procedure of Experiment 6 required to perform participants the item-location bindings, it has been known that in such an experimental setting (verbal-location binding), adults generally use the verbal (phonological) encoding strategy (e.g., Cowan et al., 2006). Therefore, it is expected that Experiment 6 is a test of learning for verbal materials with spatial locations. Nevertheless, repetition-related improvement was observed, and there were no differences in learning dynamics between the visual and verbal domains. This suggests a domain-general algorithm in which the episodic long-term memory process is driven by noticing individual contents stored in a domain-specific cache (e.g., visual cache) by sequential presentations, leading to the Hebb repetition effect.

General Discussion

The series of experiments conducted in this study produced two broad findings. First, sequential processing is critical to the Hebb repetition effect in our visual memory paradigm. Items should be focused on sequentially to elicit an increase in recall accuracy with a small number of repetitions. In the previous study using the auditory/verbal domain, this factor was not investigated because statistical learning and Hebb repetition paradigms in this domain almost exclusively employed sequential presentation procedures. An interesting possibility is that sequential processing might be essential in various kinds of repetition learning, including the one used here. Second, the characteristics of the Hebb repetition learning effect are similar across modalities. Although Experiment 5 showed that visuospatial memory seemed to emphasize where each item appears rather than which items appear together, Experiment 6 demonstrated that this effect depended on the learning schedules employed in this study. These results suggest that recognition of item-position bindings underlies the initial repetition learning of both visuospatial as well as verbal memoranda.

Examination of statistical learning, or the Hebb repetition effect, across various domains allows researchers to answer questions that cannot be addressed in a single domain. In the verbal domain, pieces of input (auditory input in particular), such as syllables, are by nature sequentially presented (e.g., Hebb, 1961; Saffran et al., 1996), meaning that they are strongly associated with sequential processing. By contrast, not only can vision be used to process the spatial location and content (e.g., color) of each item, but it can also easily be used to process multiple items presented simultaneously. The results of simultaneous presentation in the present study were consistent with previous studies investigating the repetition effect in visual working memory (i.e., visual change detection task). Furthermore, the results were replicated by the single-probe method (according to Wheeler & Treisman, 2002), in which only one of the four presented items was recalled.

Recently, Souza and Oberauer (2022) found that Hebb repetition learning is required to recall all memorized items. Furthermore, they showed more learning with sequential than with simultaneous presentations, but the Hebb repetition effect was also observed with simultaneous presentations. The difference between Souza and Oberauer (2022) and the current study may have involved several factors: Souza and Oberauer's experiment had more repetitions of the same item configuration, and the memory display was made with highly discriminative color patches such as red, green, blue, white, black, magenta, yellow, and cyan (compared with theirs, we avoided using typical colors in our experiment to prevent color verbalization). This may have made it easier for participants to notice repetition and to use strategies to answer (see also Musfeld et al., 2022). Indeed, half of the participants in Souza and Oberauer's experiment reported that they noticed repeated sequences. Furthermore, in our experiment, the high-frequent items were intermixed in the list, so there was a possibility that they interfered. Although these differences from Souza and Oberauer (2022) had not been directly compared in this study, we showed differences between simultaneous and serial presentation learning, at least in the early stages of Hebb repetition learning.

Not only were the items presented sequentially, but the consolidation duration (the blank between item presentations) would be important and have influenced the results. Souza and Oberauer (2022) investigated this. They showed more learning with the consolidation durations between items compared with no consolidation durations, suggesting that consolidation duration may also play a significant role. We may infer from this point that Hebb repetition learning also involves a temporal bottleneck process.

The hypothesis that visuospatial repetition learning is associated with attention and temporal bottleneck processing is consistent with previous studies investigating statistical learning in the visuospatial domain. For example, Kirkham et al. (2002) and Roseberry et al. (2011) showed shape and action sequences to participants. In their studies, items that should be learned were presented one by one, and participants could focus on each item in turn, leading to repetition learning. Logie et al. (2009) and Shimi and Logie (2019) reported that the facilitation effect due to repetitions was observed in a reconstruction task in which participants had to access the contents of the cache one by one. Interestingly, the reconstruction procedure (selecting the location, shape, and color for each object individually) is itself sequential. These results are in line with the above-mentioned hypothesis.

Sequential presentation guides the observer's attention. The relevance of attention in learning regularity is consistent with the conclusions of Turk-Browne et al. (2005) in visual statistical learning. From the results of five experiments, they claimed that selective attention is required for visual statistical learning. Another form of implicit learning, the mere exposure effect, in which people show a stronger preference for objects that they have been exposed to than for objects that they have never been exposed to (Zajonc, 1968), is observed only when the object is attended to, and not observed when it is not attended to (Yagi et al., 2009). In almost all studies of statistical learning in the auditory/verbal domain, items are presented sequentially (e.g., number sequences in Hebb, 1961; sequences of syllables in Majerus et al., 2004; tone sequences in Saffran et al., 1999). Daikoku and Yumoto (2017) presented overlapping auditory sequences to participants and observed no evidence of statistical learning when they paid attention to both sequences. Taking these findings together with the results of our study, we further propose that statistical learning in various domains is associated with attention and temporal bottleneck processing. Since we are confronted with too many sensory inputs, it is likely that statistical learning cannot occur for all stimuli we encounter.

Many kinds of regularities (linguistic, social, physical, etc.) are present in any given environment, and humans form long-term knowledge based on statistical learning of such regularities. Immediate recall supported by working memory is the first step in this type of learning and can also be used as a measure of human perceptual and cognitive systems. Many previous studies, such as by Saffran et al. (1996), have demonstrated that statistical learning can be observed in multiple domains (e.g., in learning of language sequences, tone sequences, action sequences, sequences of shapes, and visual scenes; Fiser et al., 2010; Kirkham et al., 2002; Roseberry et al., 2011; Saffran et al., 1999) among both adults and children; however, the domain-generality of statistical learning is still debated. This is in part because domain-generality encompasses two possible scenarios: a general learning mechanism that operates across domains or domain-specific processes that operate in different domains with common underlying learning principles (see Hepner & Nozari, 2019 for this distinction). The results of the present study indicated that participants engaged in statistical learning in a Hebb repetition learning paradigm when each item was sequentially attended. This means, in the words of Shimi and Logie (2019), being aware of the contents input to a domain-specific cache, thereby making the episodic long-term memory accessible. We found that performance based on location–item frequency statistics and whole list (array) statistics were similar across the visuospatial and verbal item domain (see also Majerus et al., 2004, Majerus & Oberauer, 2020; Saito et al., 2020). Musfeld et al. (2022) observed that learning in the visuospatial domain was slower than in the verbal domain. However, in both domains, awareness of the repetition co-occurs with learning: only after becoming aware of the repetition do participants seem to improve in the task. These results were consistent, suggesting that items are represented under each domain-specific cache, and then domain-general learning processes might operate and form long-term knowledge. This will be further activated in later perception or recognition.

One issue that should be further discussed is the amount of repetition used. In this study, we repeatedly presented HEBB lists only 4 times. This repetition might be less than required to achieve statistical learning based on item–item co-occurrence or whole list (array) repetition in the visuospatial domain (e.g., Couture & Tremblay, 2006). One possibility is that further repetition would have elicited a pattern in which the more the sequences are presented, the larger the difference in participants' recall performance between HEBB list items and high-frequency MIX list items, with increasingly better performance in the former case. However, four repetitions have been found in other studies to be capable of yielding a Hebb repetition effect in the verbal domain (e.g., Hitch et al., 2009), and Nakayama and Saito (2017) again with verbal memory materials succeeded in discriminating between learning for whole-sequence knowledge and that for the position–item association knowledge using the same paradigm as employed in this study. The absence of the whole list repetition advantage might be due to the simply spatial nature of the task (item-serial position vs. item-spatial position). However, the important thing is that observed learning dynamics in both the visuospatial item domain (Experiment 5) and the verbal item domain (Experiment 6) were the same.

Conclusion

The extraction of statistical properties and regularities from sensory inputs forms a fundamental basis of human cognition. To track changes in extracting statistical properties over time and reveal the temporal dynamics of learning, we employed the Hebb repetition paradigm. Although many studies reported that the Hebb repetition effect could be observed in verbal and visuospatial domains, many relate to temporal sequences. Studies employing a simultaneous presentation method did not necessarily show the Hebb repetition effect. Over a series of six experiments, we investigate the conditions under which a Hebb repetition effect can be facilitated in a visual short-term memory task and the nature of this effect (i.e., whether it arises from statistical learning based on location-item frequency or whole list representations). Results showed that sequential presentation impacts the ingredient of performance depending on repetition and that Hebb repetition learning in the visuospatial domain happens similar to the verbal domain. This constitutes a significant contribution to the literature, as they provide insight into learning mechanisms that operate in the visuospatial domain and presents avenues for further investigation of the importance of sequential processing more generally.

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