Independent Learning of Spatial and Nonspatial Sequences

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A small number of studies have examined whether learning the structures of two uncorrelated sequences can proceed independently of one another. Limitations in those studies have left their results open to alternative explanations. The present study addressed the limitations. The visuospatial serial reaction time task, initially introduced by Mayr (1996), was used to examine whether learning the structure of a sequence of visuospatial target locations (spatial sequence) and learning the structure of a sequence of target identities and responses (nonspatial sequence) can proceed independently of one another. Employing a dual-sequence/single-sequence paradigm, learning a nonspatial sequence did not affect learning a spatial sequence. This suggests that spatial sequence learning and nonspatial sequence learning can proceed independently of one another.

Keywords: implicit sequence learning, serial reaction time task, spatial sequence, nonspatial sequence, visuospatial attention

Learning that is not the result of conscious, intentional processes is called implicit learning. Implicit learning of the structure of a sequence is called implicit sequence learning. The serial reaction time task (SRTT) has been used extensively to study implicit sequence learning. Participants performing the SRTT are exposed to a sequence of stimuli, presented one stimulus at a time, and must react to the stimuli as the stimuli are presented. Unbeknownst to participants, the sequence of stimuli has an underlying structure. Reaction times (RTs) are used to determine whether participants have learned the sequence structure, and awareness measures are used to determine whether participants were aware of the structure. Learning the sequence structure in the absence of awareness of the structure suggests that learning the structure was implicit (if learning the structure had been the result of conscious, intentional processes, then this would have presumably lead to an awareness of the structure). A number of SRTT studies suggest that people can implicitly learn the structure of a sequence (e.g., Reed & Johnson, 1994; Remillard, 2008a; Vaquero, Jiménez, & Lupianez, 2006).

Numerous variations of the SRTT have been developed. The visuospatial SRTT (vsSRTT) was developed to study learning of the structure of a sequence of visuospatial locations. On each trial of the vsSRTT, a target appears at one of a number of possible spatial locations on a monitor and participants respond to the target's identity. The sequence of target locations is structured and the sequence of target identities (and hence responses), which may or may not be structured, is uncorrelated with the sequence of target locations. Many vsSRTT studies suggest that people can learn the structure of a sequence of visuospatial locations (e.g.,

D'Angelo, Jiménez, Milliken, & Lupianez, 2013; Deroost & Soetens, 2006a, 2006b; Helmuth, Mayr, & Daum, 2000; Mayr, 1996; Price & Shin, 2009). However, some vsSRTT studies have failed to find evidence of such learning (Deroost & Soetens, 2006a; Kemény & Lukacs, 2011; Meier & Cock, 2010, Experiment 2; Rüsseler, Munte, & Rosler, 2002; Willingham, Nissen, & Bullemer, 1989, Experiment 3).

Studies using the vsSRTT suggest that (a) people can learn sequence structures as complex as fourth-order probabilities (Remillard, 2011), (b) people can use their knowledge of the sequence structure to guide visuospatial attention to an anticipated target location and process information at that location in advance of the target (Remillard, 2003), (c) the orienting of visuospatial attention is an important component of the learning process (Remillard, 2009), (d) eye movements are not necessary for learning the sequence structure (Coomans, Deroost, Vandenbossche, Van den Bussche, & Soetens, 2012; Remillard, 2003), and (e) learning the sequence structure is not affected by the perceptual load of the display, but expressing knowledge of the structure is more difficult with low perceptual load displays (e.g., displays for which target locations are marked with short lines or outline boxes) than with high perceptual load displays (e.g., displays for which target locations are marked with distracting stimuli; Coomans, Deroost, Zeischka, & Soetens, 2011).

Mayr (1996, Experiment 2) developed the vsSRTT to examine whether learning the structure of a sequence of visuospatial locations (henceforth, "spatial sequence") and learning the structure of a sequence of target identities and responses (henceforth, "nonspatial sequence") could proceed independently of one another. On each trial, one of three targets (a square, a triangle, or a circle) appeared at one of three locations on a monitor (the corners of an imaginary triangle), and participants responded to the identity (i.e., shape) of the target with a corresponding keypress. There were two groups of participants. The dual-sequence group received a structured spatial sequence and a structured nonspatial sequence. The spatial sequence was ABCACB (in which different letters represent different corners of the imaginary triangle) and the nonspatial

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sequence was ABCACBC (in which different letters represent different target shapes). Both sequences repeated across trials. Also, the two sequences were of different lengths and so were not correlated with one another (i.e., elements of the spatial sequence were not predictive of elements of the nonspatial sequence and vice versa). The single-sequence group received a structured spatial sequence identical to that in the dual-sequence group and an unstructured (i.e., pseudorandom) nonspatial sequence. In both groups, the magnitude of spatial sequence learning was assessed by replacing the structured spatial sequence with an unstructured spatial sequence and noting the increase in RT. In the dualsequence group, the magnitude of nonspatial sequence learning was assessed by replacing the structured nonspatial sequence with an unstructured nonspatial sequence and noting the increase in RT. Mayr found that the dual-sequence group learned the spatial and nonspatial sequences, and the single-sequence group learned the spatial sequence. Crucially, the magnitude of spatial sequence learning was equivalent in the two groups. Thus, learning a nonspatial sequence did not affect learning of a spatial sequence, suggesting that learning a spatial sequence and learning a nonspatial sequence proceed independently of one another.

Mayr (1996) tested for spatial sequence learning by replacing the structured spatial sequence with an unstructured spatial sequence and noting the increase in RT. Because the nonspatial sequence remained unchanged, the testing condition for the dualsequence group was not identical to that for the single-sequence group. This is an important limitation because different testing conditions can produce differences in the expression of sequence knowledge (e.g., Abrahamse, van der Lubbe, & Verwey, 2009; Coomans et al., 2011; Deroost, Coomans, & Soetens, 2009; Frensch, Lin, & Buchner, 1998). It is conceivable that spatial sequence learning was greater in the single-sequence group than in the dual-sequence group, but that expressing spatial sequence knowledge during the test was more difficult with an unstructured nonspatial sequence (single-sequence group) than with a structured nonspatial sequence (dual-sequence group).

When the structured spatial sequence was replaced with an unstructured spatial sequence to test for spatial sequence learning, the unstructured spatial sequence was randomly generated with the constraints that each element (A, B, C) occurred twice across every six trials and that there were no immediate repetitions (e.g., AA). Thus, the unstructured sequence matched the structured sequence with respect to individual element frequencies. However, it is not clear whether the unstructured sequence matched the structured sequence with respect to sequential biases. One sequential bias is people's tendency to respond more slowly to reversals than to nonreversals. For example, if 1, 2, and 3 each represent a target location, then responding to the target is slower when the target's current location is a reversal (i.e., its current location matches its location two trials earlier [e.g., 1-2-1 or 3-1-3]) than when the target's current location is not a reversal (e.g., 1-2-3 or 3-1-2; Lee, Beesley, & Livesey, 2016; Vaquero et al., 2006). If a greater percentage of unstructured than structured sequence trials are reversals, then an increase in RT upon introduction of the unstructured sequence could be the result of the different percentages of reversals and not the result of learning of the structured sequence. A number of authors have stressed the importance of equating structured and unstructured (or control) sequences with respect to various sequential biases when testing for sequence learning (e.g.,

Anastasopoulou & Harvey, 1999; Reed & Johnson, 1994; Vaquero et al., 2006). In the Mayr (1996) study, the extent to which the unstructured spatial sequence matched the structured spatial sequence with respect to sequential biases is not clear.

Deroost and Soetens (2006a) also compared spatial sequence learning in a dual-sequence group with that in a single-sequence group using the vsSRTT. On each trial, one of four targets (a red, green, blue, or yellow circle) appeared at one of four locations on a monitor, and participants responded to the identity (i.e., colour) of the target with a corresponding keypress. The dual-sequence group (Experiment 1) received a structured spatial sequence and a structured nonspatial sequence. The spatial sequence was ABACDBCADCBD (in which different letters represent different locations on the monitor) and the nonspatial sequence was CACDBADCBDABD (in which different letters represent different target colours). Both sequences repeated across trials. Also, the two sequences were of different lengths and so were not correlated with one another. The single-sequence group (Experiment 3) received a structured spatial sequence identical to that in the dualsequence group and an unstructured (i.e., random) nonspatial sequence. In both groups, the magnitude of spatial sequence learning was assessed by replacing the structured spatial sequence with an unstructured spatial sequence and noting the increase in RT. In the dual-sequence group, the magnitude of nonspatial sequence learning was assessed by replacing the structured nonspatial sequence with an unstructured nonspatial sequence and noting the increase in RT. Deroost and Soetens found that the dual-sequence group learned the spatial and nonspatial sequences, and the singlesequence group failed to learn the spatial sequence. Thus, contrary to Mayr's (1996) results, learning a nonspatial sequence seemed to facilitate learning of a spatial sequence. This suggests that learning a spatial sequence and learning a nonspatial sequence may not proceed independently of one another.

However, Deroost and Soetens's (2006a) study did have a number of limitations. First, for reasons unknown, the four locations on the monitor were arranged in two dimensions (i.e., the corners of an imaginary square) for the dual-sequence group and along a single dimension (i.e., a horizontal row) for the singlesequence group. Learning a spatial sequence or expressing spatial sequence knowledge may be easier when the sequence involves two dimensions than when it involves a single dimension. Second, awareness of the structure of the spatial sequence was not assessed. Perhaps the dual-sequence group had greater awareness of the spatial sequence structure than did the single-sequence group, and used this awareness to consciously anticipate the next target location thereby shortening RTs. Third, Deroost and Soetens tested for spatial sequence learning by replacing the structured spatial sequence with an unstructured spatial sequence and noting the increase in RT. Because the nonspatial sequence remained unchanged, the testing condition for the dual-sequence group was not identical to that for the single-sequence group. It is conceivable that expressing spatial sequence knowledge during the test was more difficult with an unstructured nonspatial sequence (singlesequence group) than with a structured nonspatial sequence (dualsequence group). Finally, when the structured spatial sequence was replaced with an unstructured spatial sequence to test for spatial sequence learning, the unstructured spatial sequence was randomly generated with no constraints. Thus, the unstructured sequence did not match the structured sequence with respect to various sequential biases. For example, a greater percentage of unstructured than structured sequence trials was reversals. If sequential biases in a spatial sequence involving two dimensions differ from those in a spatial sequence involving one dimension (e.g., the RT difference between reversals and nonreversals is greater in two dimensions than in one dimension), then the difference in sequential biases between the structured and unstructured spatial sequences could account for the greater increase in RT in the dual-sequence group than in the single-sequence group when the structured spatial sequence was replaced with an unstructured spatial sequence.

The Present Study

Only two studies have examined whether learning a spatial sequence and learning a nonspatial sequence can proceed independently of one another when the two sequences are presented concurrently and are uncorrelated. The two studies have produced conflicting results. However, both studies had limitations that left their results open to alternative explanations. The present study addressed the limitations.

Mayr (1996) and Deroost and Soetens (2006a) used deterministic (i.e., fixed, repeating) spatial and nonspatial sequences. In the present study, I chose to use probabilistic sequences over deterministic sequences for a number of reasons. First, probabilistic sequences have been used to study spatial sequence learning in the vsSRTT (e.g., Coomans et al., 2011; D'Angelo et al., 2013; Remillard, 2003, 2009). Second, one can better manipulate the type of information to be learned with probabilistic sequences than with deterministic sequences (e.g., Remillard, 2008a, 2011). Third, the mechanisms responsible for learning probabilistic sequences are also likely responsible for learning deterministic sequences (Cleeremans & Jiménez, 1998; Jiménez, Méndez, Pasquali, Abrahamse, & Verwey, 2011). Finally, and perhaps most importantly, instructing people to try to learn the structure of the sequence or explicitly providing people with the structure of the sequence has no effect on RT measures of sequence learning when the sequence is probabilistic, but does have a beneficial effect when the sequence is deterministic (Cleeremans & Jiménez, 1998; Destrebecqz, 2004; Du, Prashad, Schoenbrun, & Clark, 2016; Howard & Howard, 2001; Jiménez, Méndez, & Cleeremans, 1996; Stefaniak, Willems, Adam, & Meulemans, 2008). Thus, when the sequence is probabilistic, RT measures of sequence learning are not affected by attempts to become aware of the sequence structure or by awareness of the sequence structure.

The present study used the vsSRTT to examine whether learning a spatial sequence and learning a nonspatial sequence can proceed independently of one another. There was a dual-sequence group and a single-sequence group. There was also a training phase and a transfer phase. The transfer phase addressed the limitations of prior studies.

On each trial in the training phase, one of four targets (the letter n, s, v, or z) appeared at one of six horizontally arranged locations on a monitor, and participants responded to the identity of the target with a corresponding keypress. For the dual- and single-sequence groups, the spatial sequence was structured in that first-order probabilities varied. Specifically, given the target location on Trial t - 1, there was one high-probability (.67) and one low-probability (.33) successor on Trial t. For example, if the target appeared in Location 1 on Trial t - 1, then, on Trial t, the target

appeared in Location 4 with a probability of .67 and Location 3 with a probability of .33. Shorter RTs on high- than on lowprobability successors would indicate learning of the spatial sequence. For the dual-sequence group, the nonspatial sequence was structured in that first-order probabilities varied. Specifically, given the target identity on Trial t - 1, there was one highprobability (.73) and three low-probability (.09) successors on Trial t. For example, if the target on Trial t - 1 was the letter n, then, on Trial t, the target was the letter v with a probability of .73 and the letters n, s, and z, each with probability .09. Shorter RTs on high- than on low-probability successors would indicate learning of the nonspatial sequence. For the single-sequence group, the nonspatial sequence was unstructured in that all first-order probabilities were .25. In the dual- and single-sequence groups, the spatial and nonspatial sequences were uncorrelated (i.e., the identity of the target on Trial t could not be predicted from the locations of the target on preceding trials and the location of the target on Trial t could not be predicted from the identities of the target on preceding trials).

On each trial in the transfer phase, one of two targets (the bigram ox or xo) appeared at one of six horizontally arranged locations on the monitor (the same locations as in the training phase), and participants responded to the identity of the target with a corresponding keypress. For the dual- and single-sequence groups, the structure of the spatial sequence was identical to that in the training phase, and the nonspatial sequence was unstructured in that all first-order probabilities were .50. Thus, the dual- and single-sequence groups experienced identical conditions. Consequently, there should have been no group differences in the ability to express spatial sequence knowledge. To show that shorter RTs on high- than on low-probability successors in the dual- and single-sequence groups was the result of spatial sequence knowledge acquired in the training phase, and not the result of spatial sequence knowledge acquired in the transfer phase or sequential biases differentially affecting high- and low-probability successors, a third group of participants was exposed only to the transfer phase. This transfer-only group was not exposed to the training phase. Also, the transfer-only group was exposed to the same spatial and nonspatial sequences as the dual- and single-sequence groups. Therefore, if the magnitude of spatial sequence learning (i.e., the RT difference between high- and low-probability successors) is greater in the dual- and single-sequence groups than in the transfer-only group, then this would suggest that, in the transfer phase, the dual- and single-sequence groups used spatial sequence knowledge that had been acquired in the training phase. Additionally, if the magnitude of spatial sequence learning is equivalent in the dual- and single-sequence groups, then this would suggest that both groups acquired equivalent spatial sequence knowledge in the training phase and that for the dual-sequence group, learning the nonspatial sequence in the training phase did not affect learning of the spatial sequence in the training phase (i.e., learning the spatial sequence and learning the nonspatial sequence proceeded independently of one another).

On each trial in the training phase, each of the six locations was marked with one of two bigrams, *ox* or *xo*, chosen randomly with the constraint that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams (see Figure 1). This ensured that there were three of each bigram and that high- and low-probability successors were marked with different bigrams. The

until response ОX хo хn ОX ОX ΧО XO ОX ХO ОX ХO ОX 400 ms хо VX хо ОX ХО ОX until response хо хо хо ОX оx 400 ms ОX хо хо хo ОX ОX sх until response

Figure 1. An example sequence of events in the training phase. Participants responded to the identity of the underlined target with a corresponding keypress.

latter follows from the fact that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were complements; that is, given the target location on Trial t - 1, if one location (e.g., Location 4) was the highprobability successor on Trial t, then its complement (e.g., Location 3) was the low-probability successor. After a 400-ms delay, the next target in the nonspatial sequence replaced the letter o in the bigram marking the next location in the spatial sequence (e.g., nx or xn), and an underline appeared below the altered bigram. Immediately following a correct response to the identity of the underlined target, the next trial began. The six locations were marked with the bigrams ox and xo to keep the display in the training phase identical to that in the transfer phase and to create a high perceptual load display. The targets n, s, v, and z were the same height as the letters o and x and shared some features with o and x (e.g., n and s have curvature like o, and v and z have diagonal lines like x). A high perceptual load display can enhance the expression of spatial sequence knowledge (Coomans et al., 2011).

On each trial in the transfer phase, each of the six locations was marked with one of two bigrams, *ox* or *xo*, chosen randomly with the constraint that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams (see Figure 2). After a 400-ms delay, an underline appeared below the bigram marking the next location in the spatial sequence. Immediately following a correct response to the identity of the underlined target, the next trial began. Remillard (2003) showed that conditions like those in the transfer phase are sensitive to spatial sequence knowledge. This is because during the 400-ms delay, participants orient to the anticipated target location (i.e., high-probability successor) and process the bigram marking that location. The result is an RT benefit, if the underline appears at the unanticipated location (i.e., low-probability successor), marked with a different bigram.

There were four sessions in the training phase and two sessions in the transfer phase, and each session was composed of 1,808 trials. The first session of the transfer phase was of particular interest because it was most indicative of the amount of spatial sequence knowledge that had been acquired in the training phase. Consequently, the transfer-only group was exposed only to the first session of the transfer phase. Following the transfer phase, awareness of the structure of the spatial sequence was assessed.

Method

Participants

The participants were 96 introductory psychology students ranging in age from 18 to 26 years. There were 24 participants in the dual-sequence group (11 men, 13 women), 24 in the singlesequence group (six men, 18 women), and 48 in the transfer-only group (nine men, 39 women). For participating, participants in the dual- and single-sequence groups received course credit and \$20, and participants in the transfer-only group received course credit.

vsSRTT

The vsSRTT was run on a desktop computer that was connected to an LCD monitor and a standard keyboard. The six target locations were horizontally arranged and each location was marked with the bigram ox or xo. Each bigram was 0.7 cm (width) \times 0.3 cm (height) and displayed in Courier New font. Adjacent bigrams were separated by an interval of 2.1 cm. The bigrams were white and the background was black. The viewing distance was approximately 60 cm. In the training phase, the response keys D, F, J, and K, on which were placed the left middle, left index, right index, and right middle fingers, corresponded to the targets n, s, v, and z, respectively. Each target was white, displayed in Courier New font, and of the same size as the letters o and x in the bigrams ox and xo. In the transfer phase, the response keys V and M, on which were placed the left index and right index fingers, corresponded to the targets ox and xo, respectively. All response keys were covered with white stickers.

A trial in the training phase began with the next target in the nonspatial sequence replacing the letter o in the bigram marking the next location in the spatial sequence, and a white underline appearing 0.2 cm below the altered bigram (see Figure 1). The underline was 0.7 cm \times 0.05 cm. Participants pressed the key corresponding to the identity of the underlined target. Immediately following a correct response, the underline was erased and the

OX	XO	<u>×0</u>	OX	OX	XO	until response
XO	OX	XO	OX	XO	OX	400 ms
XO	<u>ox</u>	XO	OX	XO	OX	until response
xo	XO	XO	OX	OX	OX	400 ms
хо	XO	XO	OX	OX	ox	until response

Figure 2. An example sequence of events in the transfer phase. Participants responded to the identity of the underlined target with a corresponding keypress.

location markers were changed as follows: The bigram, ox or xo, marking each location was chosen randomly with the constraint that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams. This ensured that there were three of each bigram and that low- and high-probability successors were marked with different bigrams (see the Structure of the Spatial Sequences section). After a 400-ms delay, the next trial began with the next target in the nonspatial sequence replacing the letter o in the bigram marking the next location in the spatial sequence, and the appearance of the underline below the altered bigram.

A trial in the transfer phase began with a white underline appearing 0.2 cm below the bigram marking the next location in the spatial sequence (see Figure 2). The underline was 0.7 cm imes0.05 cm. Participants pressed the key corresponding to the identity of the underlined target. Immediately following a correct response, the underline was erased and the location markers were changed as follows: If the target location and identity on the next trial were Location X and Bigram Y, respectively, then Bigram Y marked Location X. The bigram, ox or xo, marking each of the remaining locations was chosen randomly with the constraint that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams. After a 400-ms delay, the next trial began with the appearance of the underline below Bigram Y marking Location X. In the training and transfer phases, RT was measured as the time between the appearance of the underline and the first response, regardless of the response's correctness. Only RTs on correct trials (i.e., trials for which the first response was correct) were analysed.

The dual- and single-sequence groups performed the vsSRTT over six sessions. Sessions 1 to 4 were the training phase and Sessions 5 to 6 were the transfer phase. Each session was composed of 16 blocks of trials with 113 trials per block. Sessions 1 and 5 began with a practice block of 100 trials. On a given day, there were one or zero sessions. There were never more than two consecutive zero-session days. The six sessions were completed in 6 to 9 days. The transfer-only group performed only Session 5.

A performance history was provided at the end of each block of trials in a session. The numbers 1 to 16, corresponding to the number of blocks in a session, appeared vertically on the left side of the monitor. Beside the number for a completed block, one of two types of information was displayed. If 6% or more of the trials in the block were incorrect trials, the message "too many errors" and the error percentage were displayed. Otherwise, a horizontal line, its length proportional to the average RT on correct trials, and the average RT were displayed. After a 10-s break, participants initiated the next block of trials at their discretion by pressing a key in response to a prompt on the monitor.

Structure of the Spatial Sequences

Letting the numbers 1 to 6 represent the six target locations from left to right, respectively, Table 1 presents the first-order probabilities that were inherent in the spatial sequences. For example, if the target appeared in Location 6 on Trial t - 1, then, on Trial t, the target appeared in Location 3 with a probability of .67 (high-probability successor, H) and Location 4 with a probability of .33 (low-probability successor, L). If the target appeared in Location 1 with a probability of .50 (medium-probability successor, M) and

Table 1First-Order Probabilities in the Spatial Sequences

	Target location	Successor (<i>t</i>)						
Tier	(t-1)	1	2	3	4	5	6	
1	1	_		L-W	H-B		_	
	6	_	_	H-B	L-W	_		
2	2	M-W	_				M-B	
	5	M-B	_				M-W	
3	3	_	H-W			L-B		
	4		L-B	—	—	H-W	_	

Note. t - 1 refers to Trial t - 1; t refers to Trial t; H = high-probability successor; L = low-probability successor; M = medium-probability successor; W = within-half transition; B = between-half transition.

Location 6 with a probability of .50 (medium-probability successor, M). The target appeared in each of the six locations equally often. Thus, shorter RTs on H than on L successors would indicate learning of the first-order probabilities.

Locations 1 to 3 and 4 to 6 formed the left and right halves of the display, respectively. H and L successors in the first tier of Table 1 involved between-half (B; 1–4, 6–3) and within-half (W; 1–3, 6–4) transitions, respectively. H and L successors in Tier 3 involved W (3–2, 4–5) and B (3–5, 4–2) transitions, respectively. I have found RTs to be shorter on W transitions than on B transitions. To ensure that RTs on H and L successors were equally affected by type of transition, RTs were calculated separately for H-W and H-B successors, and then averaged, as were RTs for L-W and L-B successors.

The spatial sequences were generated in a manner analogous to that in Remillard (2009, 2011). Each location had two possible successors and so there were 48 (6 \times 2³) possible contexts of Length 4 each followed by two possible successors. Eight of the contexts ended with Location 1 (e.g., 1-3-2-1 and 6-4-5-1) and were followed by successors 4 (H) and 3 (L). For each of the eight contexts, every 12 occurrences of the context were followed 8 times by the H successor and 4 times by the L successor. The process was similar for the contexts ending with Locations 6, 3, and 4 and that were followed by H and L successors. For the contexts ending with Locations 2 and 5 and that were followed by M successors, every 12 occurrences of a context were followed 6 times by each of the two M successors. For each participant in the dual- and single-sequence groups, a 10,468-element spatial sequence was randomly generated with the context constraints noted in the three preceding sentences. Elements 1 to 113, 110 to 222, 219 to 331, and so forth to 10,356 to 10,468 each constituted a block of 113 trials for a total of 96 blocks (6 sessions \times 16 blocks per session). The spatial sequence for the practice block of 100 trials at the beginning of Session 1 was randomly generated with the constraint that each of the 48 contexts of Length 4 was followed by each of its two possible successors once. Thus, the spatial sequence was unstructured in that all first-order probabilities were .50. The spatial sequence for the practice block of 100 trials at the beginning of Session 5 was a copy of the first 100 elements of the spatial sequence that was presented in the 11th block of Session 5. Thus, the spatial sequence was structured. For each participant in the transfer-only group, the spatial sequence for Session 5 was a copy of the Session 5 spatial sequence of a yoked participant from the dual- or single-sequence group.

There were six versions of Table 1. Version 1 was Table 1. Version 2 was formed from Version 1 by exchanging H and L successors. Version 3 was created by having Tiers 1, 2, and 3 of Table 1 describe M, H/L, and H/L successors, respectively. Version 4 was formed from Version 3 by exchanging H and L successors. Version 5 was created by having Tiers 1, 2, and 3 of Table 1 describe H/L, H/L, and M successors, respectively. Version 6 was formed from Version 5 by exchanging H and L successors.

Structure of the Nonspatial Sequences (Training Phase)

Table 2 presents the first-order probabilities that were inherent in the nonspatial sequences for the dual-sequence group. For example, looking at Version 1 of the structure, if the target on Trial t-1 was z, then, on Trial t, the target was n, s, v, and z, with a probability of .09 (low-probability successor, 1), .73 (highprobability successor, h), .09 (1 successor), and .09 (1 successor), respectively. Across all trials, each target occurred equally often. Because the targets n, s, v, and z required responses using the left middle, left index, right index, and right middle fingers, respectively, there were four types of finger transitions. These were finger repetition (rep), homologous finger transition (hom; e.g., left middle to right middle, right index to left index), within-hand transition (w; e.g., left index to left middle, right middle to right index), and between-hand transition not involving homologous fingers (b; e.g., left index to right middle, right index to left middle). Successors 1-w and 1-b were matched to successors h-w and h-b, respectively, with respect to type of finger transition. To ensure that RTs on h and l successors were equally affected by type of finger transition, RTs were calculated separately for h-w and h-b successors and then averaged, as were RTs for l-w and l-b successors. Shorter RTs on h than on 1 successors would indicate learning of the first-order probabilities. Version 2 of the structure was identical to Version 1, except that h-w, h-b, l-w, and l-b successors in Version 1 were, respectively, l-w, l-b, h-w, and h-b successors in Version 2.

For the single-sequence group, the nonspatial sequences were unstructured in that all first-order probabilities were .25. For

Table 2

First-Order Probabilities in the Nonspatial Sequences of the Training Phase for the Dual-Sequence Group

	Target $(t-1)$	Successor (t)					
Version		n	S	v	Z		
1	п	l-rep	l-w	h-b	l-hom		
	S	h-w	l-rep	1-hom	l-b		
	v	l-b	l-hom	l-rep	h-w		
	z	l-hom	h-b	l-w	l-rep		
2	n	l-rep	h-w	l-b	l-hom		
	S	l-w	l-rep	l-hom	h-b		
	v	h-b	l-hom	l-rep	l-w		
	z	1-hom	1-b	h-w	l-rep		

Note. Targets *n*, *s*, *v*, and *z* required responses using the left middle, left index, right index, and right middle fingers, respectively. t - 1 refers to Trial t - 1; *t* refers to Trial *t*; h = high-probability successor; l = low-probability successor; w = within-hand transition; b = between-hand transition; rep = repetition; hom = homologous finger transition.

example, if the target on Trial t - 1 was z, then, on Trial t, the target was n, s, v, and z, each with a probability of .25. For the purpose of comparing performance in the single-sequence group with that in the dual-sequence group, successors in the single-sequence group were labelled like those in the dual-sequence group (i.e., like that outlined in Table 2). Thus, in the single-sequence group, one would expect RTs on h successors to be similar to RTs on l successors.

For each participant in the dual- and single-sequence groups, a 7,232-element nonspatial sequence was randomly generated with the first-order probability constraints noted in the two preceding paragraphs. Elements 1 to 113, 114 to 226, 227 to 339, and so forth to 7,120 to 7,232 each constituted a block of 113 trials for a total of 64 blocks (4 sessions \times 16 blocks per session). The nonspatial sequence for the practice block of 100 trials at the beginning of Session 1 was randomly generated with the constraint that all first-order probabilities were .25. Thus, the nonspatial sequence was unstructured.

To verify that the spatial and nonspatial sequences were not correlated, a computer program determined, for each participant in the dual-sequence group, the probability of the target appearing in each of the six locations on Trial t given the target's identity on Trial t - 1, on Trial t - 2, and on Trials t - 1 and t - 2 combined. All conditional probabilities were approximately .167. Thus, participants in the dual-sequence group could not use the target's identity on preceding trials to predict the location of the target on the next trial. The computer program also determined the probability of the target being n, s, v, and z on Trial t given the location of the target on Trial t - 1, on Trial t - 2, and on Trials t - 1 and t - 2 combined. All conditional probabilities were approximately .25. Thus, participants in the dual-sequence group could not use the target's location on preceding trials to predict the identity of the target on the next trial.

Structure of the Nonspatial Sequences (Transfer Phase)

For the dual- and single-sequence groups, the nonspatial sequences in the transfer phase were unstructured in that all first-order probabilities were .50. For example, if the target on Trial t - 1 was *ox*, then, on Trial *t*, the target was *ox* with a probability of .50 and *xo* with a probability of .50.

For each participant in the dual- and single-sequence groups, a 3,616-element nonspatial sequence was randomly generated with the first-order probability constraints noted in the preceding paragraph. Elements 1 to 113, 114 to 226, 227 to 339, and so forth to 3,504 to 3,616 each constituted a block of 113 trials for a total of 32 blocks (2 sessions \times 16 blocks per session). The nonspatial sequence for the practice block of 100 trials at the beginning of Session 5 was a copy of the first 100 elements of the nonspatial sequence that was presented in the 11th block of Session 5. For each participant in the transfer-only group, the nonspatial sequence of a yoked participant from the dual- or single-sequence group. Software developed by Remillard (2008b) was used to generate all of the spatial and nonspatial sequences.

Awareness Survey

The survey to assess awareness of the first-order probabilities in the spatial sequence was a six-item paper-and-pencil test. The items were $1 \rightarrow 34$, $5 \rightarrow 16$, $3 \rightarrow 25$, $6 \rightarrow 34$, $2 \rightarrow 16$, and $4 \rightarrow 25$ (in which the pairs of numbers following the arrows were arranged vertically in the survey and not horizontally as shown here). For each item, numbers represented target locations, and participants had to choose the high-probability successor. For example, the first item required participants to imagine the underline appearing in Location 1, and then to indicate whether the underline was more likely to have appeared next in Location 3 or Location 4. For participants' reference while they completed the survey, each of the six locations on the monitor was marked with the bigram *ox* or *xo*, chosen randomly, with the constraint that Locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams.

Four items pertained to H/L successors and two to M successors. If participants become aware of the first-order probabilities, then the percentage of the four items pertaining to H/L successors receiving a correct response should exceed random guessing performance (i.e., 50%). Also, if learning of the first-order probabilities is the result of conscious, intentional processes, then greater conscious, intentional processing would presumably lead to greater learning and awareness of the first-order probabilities. Consequently, one should observe a positive correlation between the RT difference between H and L successors and the percent correct on the awareness survey. Remillard (2009, Experiment 2) found that with six sessions of training, people can become aware of firstorder probabilities of .67 versus .33 in spatial sequences. However, he also found that the RT difference between H and L successors was independent of level of awareness, suggesting that learning of the first-order probabilities was implicit (see also Remillard, 2003, Experiment 3).

Procedure

Two participants were randomly assigned to each of the 24 cells created by crossing group (dual-sequence, single-sequence), spatial sequence version (1-6), and nonspatial sequence version (1, 1)2). Thus, there were 24 participants in the dual-sequence group and 24 in the single-sequence group. At the beginning of Session 1, participants were given 1 min to study a sheet of paper showing each target (n, s, v, and z) and its corresponding response key. Participants were then shown eight stimuli (*nx*, *xn*, *sx*, *xs*, *vx*, *xv*, *zx*, and xz) presented one at a time in random order. For each stimulus, participants had to point to the corresponding response key. Corrective feedback was provided if participants pointed to the wrong key. The sequence of eight stimuli was repeated until participants were able to get through the entire sequence without error. Participants then performed a practice block of 100 trials of the vsSRTT. Following the practice block, participants were informed that they would be performing 16 additional blocks of trials and that they would receive RT or error rate feedback following each block. Participants were instructed to try to improve their RT across blocks while keeping their error rate below 6%. At the beginning of Session 5, participants in the dual- and single-sequence groups were informed of the new targets (ox and xo) and response keys, and that, aside from the targets and response keys, all other aspects of the task remained unchanged. Participants then performed a practice block of 100 trials. The structure underlying the spatial and nonspatial sequences was never mentioned to participants. Immediately following the last block of Session 6, the awareness survey was administered.

There were 48 participants in the transfer-only group. Different participants in the transfer-only group were yoked to different participants in the dual- or single-sequence groups. Yoked participants had identical Session 5 spatial and nonspatial sequences. The transfer-only group was run immediately after the dual- and single-sequence groups had been run. For participants in the transfer-only group, the awareness survey was administered immediately following the last block of Session 5. Finally, a participant was replaced if, in any session, median RT exceeded 1,200 ms or error rate exceeded 12%. On the basis of these criteria, four participants in the dual-sequence group, and one in the transfer-only group were replaced.¹

Results and Discussion

Training Phase

For each participant in the dual- and single-sequence groups, median RT was calculated for each of the 144 cells created by crossing session (1–4), spatial combination of successor probability and display-half transition (H-W, H-B, L-W, L-B, M-W, M-B), and nonspatial combination of successor probability and finger transition (h-w, h-b, l-w, l-b, l-hom, l-rep). RTs on incorrect trials and the first three trials of each block were excluded from all analyses.

To determine whether participants in the dual-sequence group learned the first-order probabilities in the nonspatial sequences, RTs were averaged across the six spatial combinations for each of the four nonspatial combinations h-w, h-b, l-w, and l-b. Then, an analysis of variance (ANOVA) with session (1–4), successor (h, l), and transition (w, b) as within-subject factors, and nonspatial sequence version (1, 2) as a between-subjects factor, was performed on the averaged RTs. Analyses involving the session factor focused on the linear component of session (session-linear) because increases in the RT difference between h and l successors across sessions were of interest. Alpha was .05 for all analyses. The relevant means appear in Figure 3.

In the dual-sequence group, there was an effect of successor, F(1, 22) = 492.48, MSE = 3,421.21, p < .001, and a Successor × Session-Linear interaction, F(1, 22) = 22.16, MSE = 1,068.99, p < .001. Thus, averaging across transition, RT was shorter on h

¹ It became apparent during the experiment that participants whose median RT in a session exceeded 1,200 ms (in all cases in Session 1) or whose error rate in a session exceeded 12% (typically Session 1) had great difficulty performing the vsSRTT. Their performances on the vsSRTT exceeded the mean performance of participants who were not replaced by more than four standard deviations. For participants in the dual- and single-sequence groups who were not replaced, the largest median RT in a session (in all cases in Session 1) ranged from 718 ms to 1,007 ms (N = 48; M = 823 ms, SD = 74.85 ms), and the largest error rate in a session ranged from 3.8% to 9.4% (N = 48; M = 6.35%, SD = 1.37%). To minimize bias when deciding which participants to replace, RTs on H, L, h, and 1 successors were never computed for participants who were replaced and were computed for participants who were not replaced only after all participants had been run.



Figure 3. The left and middle panels plot RT as a function of session (1-4), nonspatial successor (h = high-probability, l = low-probability), and finger transition (w = within-hand, b = between-hand) for the dualand single-sequence groups, respectively. The right panel plots the RT difference between h and l successors (i.e., the mean of l-w and l-b minus the mean of h-w and h-b) as a function of session (1-4) and group (dual-sequence, single-sequence).

than on 1 successors, and the RT difference increased across sessions (see Figure 3, right panel). This indicates that participants in the dual-sequence group learned the first-order probabilities in the nonspatial sequences. There was considerable learning in the first session with additional learning across sessions. In the single-sequence group, the effect of successor, F(1, 22) = 0.02, MSE = 377.69, p = .888, and the Successor × Session-Linear interaction, F(1, 22) = 0.68, MSE = 234.25, p = .419, were not significant. Thus, averaging across transition, RT on h successors was not significantly different from that on 1 successors (see Figure 3, right panel). This was expected given that the nonspatial sequences for the single-sequence group were unstructured in that all first-order probabilities were .25.²

To determine whether participants learned the first-order probabilities in the spatial sequences, RTs were averaged across the six nonspatial combinations for each of the four spatial combinations H-W, H-B, L-W, and L-B. Then, an ANOVA with session (1–4), successor (H, L), and transition (W, B) as within-subject factors, and spatial sequence version (1–6) as a between-subjects factor, was performed on the averaged RTs. Analyses involving the session factor focused on the linear component of session (sessionlinear) because increases in the RT difference between H and L successors across sessions were of interest. When comparing the dual- and single-sequence groups, group (dual-sequence, singlesequence) was introduced as a between-subjects factor. The relevant means appear in Figure 4.

In the dual-sequence group, there was an effect of successor, F(1, 18) = 34.32, MSE = 675.14, p < .001, and a nonsignificant Successor × Session-Linear interaction, F(1, 18) = 0.29, MSE = 696.18, p = .596. Thus, averaging across transition, RT was shorter on H than on L successors, and the RT difference did not change significantly across sessions (see Figure 4, right panel). This indicates that participants in the dual-sequence group learned

the first-order probabilities in the spatial sequences and that much of the learning occurred in the first session. In the single-sequence group, there was an effect of successor, F(1, 18) = 10.82, MSE =2,216.67, p = .004, and a nonsignificant Successor × Session-Linear interaction, F(1, 18) = 0.16, MSE = 576.51, p = .692. Thus, averaging across transition, RT was shorter on H than on L successors, and the RT difference did not change significantly across sessions (see Figure 4, right panel). This indicates that participants in the single-sequence group learned the first-order probabilities in the spatial sequences and that much of the learning occurred in the first session.

When group was introduced as a between-subjects factor, the Successor \times Group interaction, F(1, 36) = 0.00, MSE = 1,445.91, p = .961, and Successor \times Session-Linear \times Group interaction,

² There is evidence that learning the structure of a sequence is greater when the sequence is executed with fingers from the same hand than when it is executed with fingers from both hands (Berner & Hoffmann, 2009). To determine whether this was the case in the present study, analyses were limited to h successors. If RT is shorter for h-w than h-b combinations, and the difference is greater in the dual-sequence group than in the singlesequence group (the latter group used to establish a baseline difference in RT between w and b transitions), then this would suggest that learning of the first-order probabilities was greater when a high-probability successor and its immediate predecessor were executed with fingers from the same hand than when they were executed with fingers from different hands. Limiting the analysis to h successors, an ANOVA with transition (w, b) and session (1-4) as within-subject factors, and nonspatial sequence version (1, 2) and group (dual-sequence, single-sequence) as between-subjects factors, revealed an effect of transition, F(1, 44) = 26.31, MSE = 3,211.04, p < .001, a Transition × Group interaction, F(1, 44) = 8.39, MSE = 3,211.04, p = .006, and a nonsignificant Transition \times Session-Linear \times Group interaction, F(1, 44) = 0.57, MSE = 656.59, p = .454. Thus, RT was shorter for h-w than h-b combinations, and the difference was greater in the dual-sequence group than in the single-sequence group (see Figure 3, left and middle panels).



Figure 4. The left and middle panels plot RT as a function of session (1-4), spatial successor (H = high-probability, L = low-probability), and display-half transition (W = within-half, B = between-half) for the dual- and single-sequence groups, respectively. The right panel plots the RT difference between H and L successors (i.e., the mean of L-W and L-B minus the mean of H-W and H-B) as a function of session (1-4) and group (dual-sequence, single-sequence).

F(1, 36) = 0.02, MSE = 636.35, p = .899, were not significant. Thus, there was no evidence that the RT difference between H and L successors differed across the two groups. Indeed, when averaging across the four sessions, the RT difference between H and L successors in the dual-sequence group (M = 16 ms) was identical to that in the single-sequence group (M = 16 ms).³

The preceding results would seem to suggest that the magnitude of spatial sequence learning was equivalent in the two groups. However, one cannot be certain of this. The two groups were exposed to different nonspatial sequences, which may have created differences in the expression of spatial sequence knowledge. For example, it is conceivable that spatial sequence learning was greater in the single-sequence group than in the dual-sequence group, and that expressing spatial sequence knowledge was more difficult with an unstructured nonspatial sequence (singlesequence group) than with a structured nonspatial sequence (dual-sequence group). To better assess whether the magnitude of spatial sequence learning was equivalent in the dual- and singlesequence groups, one must examine performance in the transfer phase in which the dual- and single-sequence groups experienced identical conditions and, consequently, in which there should have been no group differences in the ability to express spatial sequence knowledge.

Transfer Phase (Session 5)

divided into four epochs, with each epoch spanning four blocks of trials. For each participant, median RT was calculated for each of the 48 cells created by crossing epoch (1–4), spatial combination of successor probability and display-half transition (H-W, H-B, L-W, L-B, M-W, M-B), and finger transition (repetition, alternation). RTs on incorrect trials and the first three trials of each block were excluded from all analyses.

To examine learning of the first-order probabilities in the spatial sequences, RTs were averaged across the two finger transitions for each of the four spatial combinations H-W, H-B, L-W, and L-B. Then, an ANOVA with epoch (1-4), successor (H, L), and transition (W, B) as within-subject factors, and spatial sequence version (1-6) as a between-subjects factor, was performed on the

Because the targets *ox* and *xo* required responses using the left and right index fingers, respectively, there were two types of finger transitions. These were finger repetition (e.g., left index, left index) and finger alternation (e.g., left index, right index). As in the training phase, RT was calculated as a function of finger transition. Also, to examine learning of the first-order probabilities at various points in Session 5, the 16 blocks of trials in Session 5 were

 $^{^{3}\}ensuremath{\,\mathrm{Error}}$ rates were analyzed in a manner analogous to that for RTs. The mean error rate differences between h and 1 successors (i.e., 1 - h) in Sessions 1 to 4 were, respectively, 5.7%, 10.1%, 14.0%, and 16.3% in the dual-sequence group, and -0.6%, 0.0%, -0.3%, and -0.4% in the singlesequence group. In the dual-sequence group, error rate, averaged across the four sessions, was smaller for h than 1 successors (p < .001), and the error rate difference increased across sessions (p < .001). In the single-sequence group, neither result was significant. Thus, the error rate results were similar to the RT results. The mean error rate differences between H and L successors (i.e., L - H) in Sessions 1 to 4 were, respectively, 0.1%, 0.2%, 1.6%, and 1.4% in the dual-sequence group, and 0.8%, 0.0%, 0.2%, and -0.3% in the single-sequence group. In the dual-sequence group, error rate, averaged across the four sessions, was smaller for H than L successors (p = .037), and the error rate difference increased marginally across sessions (p = .080). In the single-sequence group, neither result was significant. The error rate difference between H and L successors was greater in the dual-sequence group than in the singlesequence group in Session 4 (p = .036), and marginally so in Session 3 (p = .067). Unlike the RT results, the error rate results suggest that the dual-sequence group may have better learned the first-order probabilities in the spatial sequences than the single-sequence group.

averaged RTs. Analyses involving the epoch factor focused on the linear component of epoch (epoch-linear) because increases in the RT difference between H and L successors across epochs were of interest. The relevant means appear in Figures 5 and 6.

In the dual-sequence group, there was an effect of successor, F(1, 18) = 33.06, MSE = 1,582.50, p < .001, and a nonsignificant Successor × Epoch-Linear interaction, F(1, 18) = 1.12, MSE = 155.05, p = .303. Thus, averaging across transition, RT was shorter on H than on L successors, and the RT difference did not change significantly across epochs (see Figure 6, left panel). The conclusion was similar for the single-sequence group, in which there was an effect of successor, F(1, 18) = 17.97, MSE = 2,838.44, p < .001, and a nonsignificant Successor × Epoch-Linear interaction, F(1, 18) = 3.20, MSE = 259.34, p = .091, and for the transfer-only group, in which there was an effect of successor, F(1, 42) = 16.81, MSE = 770.28, p < .001, and a nonsignificant Successor × Epoch-Linear interaction, F(1, 42) = 3.59, MSE = 328.75, p = .065.

When group (dual-sequence, single-sequence) was introduced as a between-subjects factor, the Successor × Group interaction, F(1, 36) = 0.00, MSE = 2,210.47, p = .966, and Successor × Epoch-Linear × Group interaction, F(1, 36) = 0.59, MSE =207.19, p = .448, were not significant. Thus, there was no evidence that the RT difference between H and L successors differed across the two groups (see Figure 6, left panel). Indeed, when averaging across the four epochs, the RT difference between H and L successors in the dual-sequence group (M = 23 ms) was identical to that in the single-sequence group (M = 23 ms).

To determine whether the dual- and single-sequence groups used spatial sequence knowledge that had been acquired in the training phase, the RT difference between H and L successors in the dual- and single-sequence groups was compared with that in the transfer-only group. Because the RT difference between H and L successors in the dual-sequence group was similar to that in the single-sequence group, the two groups were combined into a single group called the trained group. When group (trained, transfer-only) was introduced as a between-subjects factor, there was a Successor × Group interaction, F(1, 84) = 14.80, MSE = 1,456.88, p < .001, and a nonsignificant Successor × Epoch-Linear × Group interaction, F(1, 84) = 0.04, MSE = 273.48, p = .843. Thus, the RT difference between H and L successors was greater in the trained group than in the transfer-only group, and the group difference did not change significantly across epochs. This suggests that the dual- and single-sequence groups used spatial sequence knowledge that had been acquired in the training phase.

The dual- and single-sequence groups experienced identical conditions in the transfer phase, and so there should have been no group differences in the ability to express spatial sequence knowledge. Also, in the transfer phase, both groups used spatial sequence knowledge that had been acquired in the training phase. Thus, the similar transfer phase RT difference between H and L successors in the dual- and single-sequence groups strongly suggests that both groups acquired equivalent spatial sequence knowledge in the training phase. This, in turn, suggests that in the dual-sequence group, learning the nonspatial sequence in the training phase (i.e., learning of the spatial sequence and learning the nonspatial sequence proceeded independently of one another).

Although Session 5 was of primary interest, the right panel in Figure 6 summarizes the results from Session 6. The RT difference between H and L successors was similar in the dual- and single-sequence groups in Epochs 1 and 2, but then appeared to become larger in the dual- than single-sequence group in Epochs 3 and 4. Despite appearances, the Successor \times Group interaction was not



Figure 5. RT in Session 5 as a function of group (dual-sequence, single-sequence, transfer-only), epoch (1-4), spatial successor (H = high-probability, L = low-probability), and display-half transition (W = within-half, B = between-half).



Figure 6. The RT difference between high-probability (H) and low-probability (L) successors (i.e., the mean of L-W and L-B minus the mean of H-W and H-B) as a function of session (5, 6), epoch (1-4), and group (dual-sequence, single-sequence, transfer-only).

significant in the overall analysis (p = .451), nor in analyses limited to each epoch separately (four ps > .221). The Successor × Epoch-Linear × Group interaction was not significant (p = .173).⁴

Bayesian Analysis (Session 5)

An important result in Session 5 was the nonsignificant Successor (H, L) \times Group (dual-sequence, single-sequence) interaction. Averaging across transition (W, B) and epoch (1-4), the RT difference between H and L successors in the dual-sequence group was not significantly different from that in the single-sequence group. Some investigators have argued that a nonsignificant result does not necessarily support the null hypothesis, even in situations with high power, and that a Bayes factor can better evaluate whether the data support the null hypothesis (e.g., Dienes, 2014, 2016). The Bayes factor, B_{01} , is the probability of the data given the null hypothesis (H_0) divided by the probability of the data given the alternative hypothesis (H_1) , and indicates how many times more likely the data are under H_0 than under H_1 . Typically, H_0 is that there is no effect and H_1 is a distribution of effect sizes called a prior. A value of B_{01} greater than 1 indicates that the data are more likely under H_0 than H_1 , and a value greater than 3 is considered good evidence for H_0 . The inverse of B_{01} (i.e., $1/B_{01}$ and denoted B_{10} indicates how many times more likely the data are under H_1 than H_0 .

The statistical package JASP can provide Bayes factors for the various effects in an ANOVA (Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2016). JASP (Version 0.7.5.6) was used to obtain a Bayes factor for the Successor \times Group interaction. To simplify the analysis, RTs on H and L successors were first averaged across transition (W, B) and epoch (1–4). Then, the averaged RTs were submitted to a Bayesian repeated measures ANOVA with successor (H, L) as a within-subject factor, and spatial sequence version (1–6) and group (dual-sequence, single-sequence) as between-subjects factors. The null model was composed of two of the three main effects (i.e., successor and group) and no interactions. The alternative model was composed of the null model plus the Successor × Group interaction. B_{OI} was 3.63, indicating that the data were 3.63 times more likely in the absence of a Successor × Group interaction than in the presence of an interaction. This is good evidence for the absence of an interaction.

Another important result in Session 5 was the nonsignificant Successor (H, L) \times Epoch-Linear \times Group (dual-sequence, single-sequence) interaction. JASP was used to obtain a Bayes factor for the interaction. First, RTs on H and L successors were averaged across transition (W, B). Then, for each participant, the slope of the regression line through the four H successor RTs (one for each epoch) and the slope of the regression line through the four L successor RTs (one for each epoch) were calculated. Finally, the slopes were submitted to a Bayesian repeated measures ANOVA with successor (H, L) as a within-subject factor, and spatial sequence version (1-6) and group (dual-sequence, singlesequence) as between-subjects factors. The null model was composed of two of the three main effects (i.e., successor and group) and no interactions. The alternative model was composed of the null model plus the Successor \times Group interaction. B_{01} was 2.92, indicating that the data were 2.92 times more likely in the absence of a Successor \times Epoch-Linear \times Group interaction than in the presence of an interaction. This is relatively good evidence for the absence of an interaction.

For RTs and slopes, I also created a null model composed of the three main effects and two of the three two-way interactions (i.e., Successor \times Version and Version \times Group), and an alternative model composed of the null model plus the Successor \times Group interaction. B_{OI} was 3.87 for RTs and 3.02 for slopes. Again, there was good evidence for the absence of a Successor \times Group Interaction and a Successor \times Epoch-Linear \times Group interaction.

Awareness of the First-Order Probabilities

The awareness survey assessed awareness of the first-order probabilities in the spatial sequence. The percentage of the four items pertaining to H/L successors receiving a correct response was determined for each participant. The mean percentages for the dual- and single-sequence groups were 60.4% and 44.8%, respec-

⁴ Error rates were analyzed in a manner analogous to that for RTs. In Session 5, the mean error rate differences between H and L successors (i.e., L-H) in Epochs 1 to 4 were, respectively, 0.3%, 0.2%, 0.2%, and 1.3% in the dual-sequence group; 0.3%, 0.3%, 0.5%, and 0.6% in the single-sequence group; and 0.9%, 0.2%, 0.2%, and 0.3% in the transfer-only group. All of the analyses that were reported for RTs were not significant in the case of error rates. In Session 6, the mean error rate differences between H and L successors in Epochs 1 to 4 were, respectively, -0.2%, 0.5%, 1.5%, and 0.7% in the dual-sequence group, and 0.5%, 1.8%, 1.4%, and 1.2% in the single-sequence group. Error rate, averaged across the four epochs, was smaller for H than L successors in the single-sequence group (p = .006), but not significantly so in the dual-sequence group (p = .122). The error rate difference between H and L successors in the dual-sequence group (p = .295).

tively. These values did not differ significantly from what would be expected by random guessing performance (i.e., 50%), F(1, 23) = 2.83, MSE = 919.38, p = .106, and F(1, 23) = 0.55, MSE = 1,194.52, p = .468, respectively. Thus, there was no evidence of awareness of the first-order probabilities.

To determine whether the RT difference between H and L successors was correlated with percent correct on the awareness survey, each participant was assigned to a high- or low-awareness group. In the dual- and single-sequence groups, four participants had been assigned to each of the six versions of the spatial sequence. For each of the 12 quadruplets (six from each group), the two members scoring lowest on the awareness survey were assigned to the low-awareness group and the two members scoring highest were assigned to the high-awareness group. If a clear assignment to awareness group was not possible for some members of a quadruplet, then those members were randomly assigned to an awareness group with the constraint that there were two members in each awareness group. The mean percentages correct on the awareness survey were 77.1% and 43.8% in the dualsequence high- and low-awareness groups, respectively, and 70.8% and 18.8% in the single-sequence high- and low-awareness groups, respectively. Not surprisingly, percent correct was greater in the high-awareness group than in the low-awareness group for the dual-sequence group, F(1, 22) = 10.13, MSE = 658.14, p =.004, and the single-sequence group, F(1, 22) = 31.98, MSE = 509.00, p < .001.

In the dual-sequence group, RT differences between H and L successors (averaged across transition and epoch) in the high- and low-awareness groups were, respectively, 21 ms and 25 ms in Session 5, and 34 ms and 32 ms in Session 6. An ANOVA with epoch (1–4), successor (H, L), and transition (W, B) as within-subject factors, and spatial sequence version (1–6), and awareness (high, low) as between-subjects factors, revealed a nonsignificant Successor × Awareness interaction in Session 5, F(1, 12) = 0.38, MSE = 1,094.43, p = .551, and in Session 6, F(1, 12) = 0.01, MSE = 3,110.68, p = .909. Thus, RT differences between H and L successors in the high-awareness group.

In the single-sequence group, RT differences between H and L successors (averaged across transition and epoch) in the high- and low-awareness groups were, respectively, 27 ms and 19 ms in Session 5, and 32 ms and 22 ms in Session 6. An ANOVA revealed a nonsignificant Successor × Awareness interaction in Session 5, F(1, 12) = 0.52, MSE = 3,148.53, p = .484, and in Session 6, F(1, 12) = 0.74, MSE = 3591.37, p = .408. Thus, RT differences between H and L successors in the high-awareness group were not significantly different from that in the low-awareness group.

The preceding results suggest that in the dual- and singlesequence groups, the RT difference between H and L successors was independent of the percent correct on the awareness survey. This, in turn, suggests that the RT difference between H and L successors was the result of implicit learning.

Remillard (2003, 2009), who trained participants for three or six sessions under conditions very similar to the present study's Session 5, and who assessed awareness of the first-order probabilities in a manner very similar to that in the present study, found that RT differences between H and L successors in the high-awareness group were almost identical to that in the low-awareness group

(the differences between the two groups never exceeding 2 ms). The results for the dual-sequence group and, to a somewhat lesser extent, the single-sequence group are consistent with the results of Remillard (2003, 2009).

Given the importance of the nonsignificant Successor \times Awareness interactions. JASP was used to obtain Bayes factors for the interactions. To simplify the analyses, RTs on H and L successors were first averaged across transition (W, B) and epoch (1-4). Then, the averaged RTs were submitted to Bayesian repeated measures ANOVAs with successor (H, L) as a within-subject factor, and spatial sequence version (1-6) and awareness (high, low) as between-subjects factors. The null model was composed of two of the three main effects (i.e., successor and awareness) and no interactions. The alternative model was composed of the null model plus the Successor \times Awareness interaction. In the dualsequence group, B_{01} was 2.59 and 2.76 for Sessions 5 and 6, respectively. In the single-sequence group, B_{01} was 2.53 and 2.15 for Sessions 5 and 6, respectively. Thus, there was some, albeit weak, evidence for the absence of a Successor \times Awareness interaction. When the dual- and single-sequence groups were combined into a single group to double the number of participants in each awareness group, B_{01} was 3.57 for Session 5 and 3.01 for Session 6. This is good evidence for the absence of a Successor \times Awareness interaction. The results were similar when I created a null model composed of the three main effects and two of the three two-way interactions (i.e., Successor \times Version and Version \times Awareness) and an alternative model composed of the null model plus the Successor \times Awareness interaction.

General Discussion

Only two studies have examined whether learning a spatial sequence and learning a nonspatial sequence can proceed independently of one another when the two sequences are presented concurrently and are uncorrelated. However, as reviewed in the introduction, both studies had limitations that left their results open to alternative explanations. The present study used the dual-/ single-sequence paradigm, as did prior studies, and addressed the limitations of prior studies. In the training phase, the dualsequence group received a structured spatial sequence and a structured nonspatial sequence, and the single-sequence group received a structured spatial sequence and an unstructured nonspatial sequence. In the subsequent transfer phase, both groups still received the structured spatial sequence. However, unlike the training phase, the nonspatial sequence involved two targets rather than four, and was unstructured for both groups. Thus, the dual- and single-sequence groups experienced identical conditions in the transfer phase, and so there should have been no group differences in the ability to express spatial sequence knowledge. In the transfer phase, both groups used spatial sequence knowledge that had been acquired in the training phase, as indicated by a greater RT difference between H and L successors in the dual- and singlesequence groups than in the transfer-only group, which had been exposed only to the transfer phase and not to the training phase. Consequently, the equivalent transfer phase RT difference between H and L successors in the dual- and single-sequence groups strongly suggests that both groups acquired equivalent spatial sequence knowledge in the training phase. This, in turn, suggests that in the dual-sequence group, learning the nonspatial sequence in the training phase did not affect learning of the spatial sequence in the training phase (i.e., learning the spatial sequence and learning the nonspatial sequence proceeded independently of one another).

In the dual- and single-sequence groups, the RT difference between H and L successors in the transfer phase was independent of the percent correct on the awareness survey. This suggests that learning of the first-order probabilities in the spatial sequence was implicit. Regarding the nonspatial sequence, the dual-sequence group's awareness of the structure of the nonspatial sequence was not assessed immediately following the final session of the training phase, so as to not encourage participants to search for structure in the spatial or nonspatial sequence in the transfer phase. Thus, one might argue that nonspatial sequence learning in the training phase did not affect spatial sequence learning in the training phase because the former was explicit (i.e., the result of conscious, intentional processes) and the latter was implicit. If nonspatial sequence learning had been implicit, then it might have affected spatial sequence learning. It is unlikely that nonspatial sequence learning was exclusively explicit. Explicit learning of a sequence is accompanied by implicit learning of the sequence and the magnitude of implicit learning is equivalent to that when there is no explicit learning (Sanchez & Reber, 2013; Song, Howard, & Howard, 2007; Song, Marks, Howard, & Howard, 2009; Willingham & Goedert-Eschmann, 1999; Willingham, Salidis, & Gabrieli, 2002). Also, when a sequence is probabilistic (like the nonspatial sequence in the dual-sequence group), performance on RT measures of sequence learning is independent of performance on measures of awareness of the structure of the sequence, suggesting that learning of the structure of the sequence is implicit (Remillard, 2003, 2009; Stefaniak et al., 2008).

An important assumption underlying the dual-/single-sequence paradigm is that nonspatial sequence learning does not occur in the single-sequence group (i.e., nonspatial sequence learning mechanisms are not engaged when the nonspatial sequence is unstructured). When spatial sequence learning is equivalent in the dualand single-sequence groups, the assumption allows one to infer that in the dual-sequence group, learning the nonspatial sequence did not affect learning of the spatial sequence. The results of brain imaging studies showing greater activity for structured than unstructured sequences in certain brain regions are consistent with the assumption (e.g., Daselaar, Rombouts, Veltman, Raaijmakers, & Jonker, 2003; Rauch et al., 1997; Rieckmann, Fischer, & Backman, 2010; Schendan, Searl, Melrose, & Stern, 2003).

Reducing the number of targets and responses in the singlesequence group might reduce the likelihood of engaging nonspatial sequence learning mechanisms. For example, rather than having participants respond to the targets n, s, v, and z with corresponding keypresses, one could have participants respond to the target nwith a keypress and withhold responding to the target s. Targets nand s might occur on 85% and 15% of trials, respectively. Under these circumstances, when there is predominantly a single target and response (with occasional catch trials), nonspatial sequence learning mechanisms might be minimally engaged. This approach is certainly worth investigating. Remillard (2003, Experiment 1) employed a spatial sequence identical in structure to that in the present study and an unstructured nonspatial sequence between H and L successors was 15 ms, which is nearly identical to the 16 ms in the training phase of the present study. Thus, reducing the number of targets and responses may have little impact on spatial sequence learning. Of course, participants in Remillard (2003, Experiment 1) and those in the present study were exposed to different nonspatial sequences, which may have created differences in the expression of spatial sequence knowledge.

The present study used the dual-/single-sequence paradigm to obtain evidence that learning a spatial sequence and learning a nonspatial sequence can proceed independently of one another. There is also evidence that the expression of spatial and nonspatial sequence knowledge can proceed independently of one another. Using the vsSRTT, D'Angelo et al. (2013) found that the occurrence of a nonspatial l successor on the current trial, relative to an h successor, reduced the expression of nonspatial (but not spatial) sequence knowledge on the next trial and that the occurrence of a spatial L successor on the current trial, relative to an H successor, reduced the expression of spatial (but not nonspatial) sequence knowledge on the next trial.

The independence of spatial and nonspatial sequence learning suggests that learning a spatial sequence involves mechanisms that are distinct from those involved in learning a nonspatial sequence. The literature offers some suggestions as to the nature of the mechanisms involved in spatial and nonspatial sequence learning. Spatial sequence learning appears to involve the visuospatial attention orienting system. The presence of a distractor that captures visuospatial attention impairs spatial sequence learning (Remillard, 2009). Also, eye movements are not necessary for learning, which suggests that covert orienting of visuospatial attention is sufficient for learning (Coomans et al., 2012; Remillard, 2003). Finally, spatial sequence learning, in which people implicitly learn the relationship between the location of the target on Trial t - 1 and the location of the target on Trial t, is conceptually similar to learning in the visuospatial attention-cueing paradigm, in which people implicitly learn the relationship between the location of a cue and the location of a subsequent target (Lanthier, Wu, Chapman, & Kingstone, 2015; López -Ramon, Chica, Bartolomeo, & Lupianez, 2011; Risko & Stolz, 2010).

Nonspatial sequence learning does not appear to involve the visuospatial attention orienting system. The presence of distractors that capture visuospatial attention does not impair nonspatial sequence learning (Jiménez & Vazquez, 2008). Sequence learning in the traditional SRTT, in which individuals respond to the location of the target with a corresponding keypress, is also unimpaired by the presence of attention-capturing distractors (Rowland & Shanks, 2006). Some studies suggest that sequence learning in the traditional SRTT involves response selection processes (Schumacher & Schwarb, 2009; Schwarb & Schumacher, 2009, 2010). It is likely that response selection processes would also be involved in nonspatial sequence learning. Recent evidence suggests that orienting of visuospatial attention involves mechanisms that are distinct from those involved in response selection (Reimer, Strobach, Frensch, & Schubert, 2015). This could explain why spatial and nonspatial sequence learning can proceed independently of one another.

Two studies have examined the independence of spatial and nonspatial sequence learning (Deroost & Soetens, 2006a; Mayr, 1996). An equally small number of studies have examined the independent learning of other types of sequences. Schmidtke and Heuer (1997, Experiment 1) used the dual-/single-sequence paradigm to examine whether learning a manual-response sequence and learning a tone sequence could proceed independently of one another. The dual-sequence group received a structured manualresponse sequence and a structured tone sequence. The singlesequence group received a structured manual-response sequence and an unstructured tone sequence. The dual-sequence group learned the manual-response and tone sequences, and the singlesequence group learned the manual-response sequence. The magnitude of manual-response sequence learning was equivalent in the two groups. Thus, learning a tone sequence did not affect learning of a manual-response sequence, suggesting that learning a manualresponse sequence and learning a tone sequence proceed independently of one another.

Schmidtke and Heuer (1997) tested for manual-response sequence learning in a transfer phase in which the tone was no longer presented. The RT increase in an unstructured sequence block relative to two surrounding structured sequence blocks was the index of sequence learning. Because the tone was no longer presented, the test conditions were identical for the dual- and single-sequence groups. A limitation of the study, though, was the absence of a transfer-only group exposed only to the transfer phase. One explanation of the results is that knowledge of the manual-response sequence acquired in the training phase (and which may have been greater in the single- than dual-sequence group or vice versa) was not used in the transfer phase, and the shorter RT on structured than unstructured sequence blocks was the result of manual-response sequence knowledge acquired in the transfer phase, or the result of differences in sequential biases between the structured and unstructured sequence blocks. Without a transfer-only group, the preceding explanation of the results cannot be ruled out.

Goschke and Bolte (2012, Experiment 3) exposed participants to a structured letter sequence and to a structured manual-response sequence. For participants in the letter-distractor group, a distractor letter was inserted after each element of the letter sequence, thereby disrupting the structure of the sequence. The structure of the manual-response sequence was not disrupted. For participants in the manual-distractor group, a distractor manual-response was inserted after each element of the manual-response sequence, thereby disrupting the structure of the sequence. The structure of the letter sequence was not disrupted. In a test phase in which the distractors were removed, there was evidence that the letterdistractor group had learned the manual-response sequence (but not the letter sequence), and that the manual-distractor group had learned the letter sequence (but not the manual-response sequence). The authors concluded that because the distractor letters and distractor manual-responses did not disrupt learning of the manual-response and letter sequences, respectively, learning a letter sequence and learning a manual-response sequence proceed independently of one another. Unfortunately, the authors did not compare learning of the sequences in the two groups with that in a third group in which distractors had not been presented during training. Without this third group, it is not clear what effect the distractor letters had on learning the manual-response sequence or what effect the distractor manual-responses had on learning the letter sequence. It is conceivable that, in the letter-distractor group, the distractor letters did impair learning of the manual-response sequence despite not having completely eliminated learning of the sequence or that, in the manual-distractor group, the distractor

manual-responses did impair learning of the letter sequence despite not having completely eliminated learning of the sequence. In their study, the authors effectively had two single-sequence groups without a comparison dual-sequence group.

Only four studies have examined whether learning two different types of sequences can proceed independently of one another when the two sequences are presented concurrently and are uncorrelated. All of the studies had limitations that left their results open to alternative explanations. The present study addressed the limitations and provides the best evidence to date that learning two different types of sequences can proceed independently of one another.

Résumé

Un petit nombre d'études ont examiné si les structures d'apprentissage de deux séquences non corrélées pouvaient s'effectuer indépendamment l'une de l'autre. Les limites de ces études ont donné lieu à des explications alternatives de leurs résultats. La présente étude s'est penchée sur ces limites. La tâche de temps de réaction sériel visuo-spatial, introduite initialement par Mayr (1996), a été utilisée pour déterminer si la structure d'apprentissage d'une séquence d'emplacements cibles visuospatiaux (séquence spatiale) et la structure d'apprentissage d'une séquence de réponses et d'identités cibles (séquence non-spatiale) pouvaient s'effectuer indépendamment l'une de l'autre. Employant un paradigme séquence double/séquence simple, l'apprentissage d'une séquence non-spatiale n'a pas affecté l'apprentissage d'une séquence spatiale. Cela suggère que l'apprentissage séquentiel spatial et l'apprentissage séquentiel non-spatial peuvent s'effectuer indépendamment l'un de l'autre.

Mots-clés : apprentissage séquentiel implicite, temps de réaction sériel, séquence spatiale, séquence non-spatiale, attention visuo-spatiale.

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