Title

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Abstract

The Serial Reaction Time (SRT) and the Alternating Serial Reaction Time (ASRT) tasks are widely used assessments of sequence learning (SL) wherein repetitive patterning of visual-spatial elements leads participants to anticipate locations of subsequent elements in the series. In the SRT task, the predictive dependencies involve adjacent elements whereas in the ASRT task they involve nonadjacent elements, due to the insertion of random elements into the pattern. We tested college students (N = 74) to explore whether the SRT and the ASRT tasks relied on similar underlying learning mechanisms while also examining associations between task performance and nonverbal fluid intelligence, visual-spatial working memory, and sentence processing ability. There was no correlation in performance across the two SL tasks ($r = -.18$), suggesting distinct learning mechanisms. Whereas 95.9% of participants demonstrated sequence-specific learning in the SRT task, only 64.9% demonstrated learning in the ASRT task. SL in the ASRT but not the SRT task was associated with nonverbal intelligence, visual-spatial working memory, and sentence comprehension. The observed results run counter to the claim that the ASRT relies only on implicit learning mechanisms presumed to be unrelated to executive functioning or general intelligence.

Keywords: sequence learning; implicit statistical learning; working memory; nonverbal intelligence; sentence processing

Introduction

Humans are experts at detecting patterns and regularities in the environment—a skill often referred to as (implicit) *statistical learning,* or *sequence learning* (SL) (e.g., Conway & Christiansen, 2006; Jiménez & Méndez, 1999). Learners' sensitivity to recurring sequences and probabilities of co-occurring events is thought to play a critical role in the acquisition of complex systems of knowledge, such as language (Reber, 1993; Romberg & Saffran, 2010). SL often occurs without any conscious awareness of the sequential patterns in the input; hence, it is viewed as a form of implicit learning (Cleeremans, Destrebecqz, & Boyer, 1998; Perruchet & Pacton, 2006).

Various tasks have been developed to assess SL; here we focus on the Serial Reaction Time (SRT) and the Alternating Serial Reaction Time (ASRT) tasks, which assess sequence-specific learning of visual-spatial patterns. These superficially similar tasks are distinguished by the nature of the underlying sequential rules: In the SRT task, visual-spatial elements follow a fixed order, allowing participants to use the preceding adjacent elements to predict the next element in the series (Nissen & Bullemer, 1987). In the ASRT task, random elements are inserted into the pattern; hence, the learner must rely on non-adjacent dependencies to predict upcoming elements (Howard & Howard, 1997). Although both the SRT and the ASRT tasks rely on SL, to our knowledge there has been no attempt to assess relationships in performance across tasks. However, studies utilizing other SL measures indicate a lack of correlations across various SL tasks (Misyak & Christiansen, 2012; Siegelman & Frost, 2015), suggesting that individuals' sensitivity to statistical regularities may vary as a function of stimulus modality (e.g., auditory vs. visual-spatial) and rule type (e.g., adjacent vs. non-adjacent dependencies).

Studies of artificial grammar learning (AGL) have contrasted the effortless learning of adjacent dependencies with the more challenging task of acquiring non-adjacent dependencies (Braine, 1987; Newport & Aslin, 2004). Vuong, Meyer, and Christiansen (2016) examined simultaneous acquisition of adjacent and non-adjacent dependencies within the same AGL task. Although participants were more sensitive to adjacent than non-adjacent dependencies when making off-line judgements of grammaticality, their reaction times (RTs) in predicting successive elements suggested that they were quite capable of tracking both types of dependencies.

Statistical Learning and Cognitive Abilities

The current study compared performance across the SRT and the ASRT tasks in an effort to shed light on underlying learning mechanisms. Researchers (e.g., Lewicki et al., 1988; Ullman, 2004) have suggested that SL relies on the procedural memory system, as opposed to declarative memory. Hence, SL should be less dependent on general cognitive abilities, such as nonverbal intelligence or working memory capacity, whereas explicit analytical problem solving should be more dependent on these abilities (Gebauer & Mackintosh, 2007; Reber, Walkenfeld, & Hernstadt, 1991). The extant literature indicates a lack of consensus regarding this issue (e.g., Danner et al., 2011; Kaufman et al., 2010). Misyak and Christiansen (2012) reported that performance on two distinct AGL tasks correlated with performance on a verbal working memory task, but not with a measure of nonverbal intelligence. In a review of the literature, Janascek and Nemeth (2013) concluded that the relationship between working memory and SL may be stronger for tasks where SL is more explicit and intentional.

They argued that the ASRT task provides a more implicit measure of SL than the SRT task due to the insertion of random elements preventing participants from noticing the underlying sequential pattern (Janacsek, Fiser, & Nemeth, 2012). Under their view, to the extent that SL is implicit, such that participants are unable to rely on explicit modes of thought to predict upcoming events, performance should be unrelated to individual differences in nonverbal intelligence and working memory capacity.

Statistical Learning and Language Abilities

Previous studies provide mixed evidence of a relationship between SL and language processing skills. Although a recent meta-analysis indicates that children with developmental language disorder (also called specific language impairment) perform poorly on the SRT task relative to age-matched controls (Lum, Conti-Ramsden, Morgan, & Ullman, 2014), efforts to link individual differences in performance on the SRT task with specific language abilities have yielded mixed results (e.g., Kidd, 2012; Kidd & Kirjavainen, 2011; Lum & Kidd, 2012).

Few studies to date have explored links between the ASRT task and language processing. Nemeth et al. (2011) had adult participants perform the ASRT task simultaneously with a sentence comprehension task, a word recognition task, or a math calculation task. Only the sentence comprehension task interfered with SL, suggesting that the mechanisms underlying SL learning of nonadjacent dependencies are utilized in sentence processing. Similarly, in studies of second language learning, relationships between ASRT performance and language learning outcomes have emerged that are suggestive of overlapping learning and/or processing mechanisms (e.g., Granena, 2013; Kaufman et al., 2010).

Research Questions

To further elucidate the mechanisms underlying SL, we addressed the following research questions. (1) Do participants show similar trajectories in learning visual-spatial sequences on the SRT and the ASRT tasks and is performance correlated across tasks? (2) Is performance on the SRT or the ASRT tasks related to individual differences in other nonverbal abilities (general intelligence, visual-spatial working memory)? (3) Is performance on the SRT or the ASRT tasks related to individual differences in sentence processing ability?

Method

Participants

Participants were 74 undergraduates (37 women; age range 18–44) recruited from a psychology department subject pool at a large urban public university. Participation was restricted to native speakers of English.

Tasks and Measures

Serial Reaction Time (SRT) Task We employed the SRT task of Lum and Kidd (2012), adapted from Nissen and Bullemer (1987). On each trial, a yellow smiley face appeared at one of four locations on a computer screen; each location corresponded to a button on a gamepad (see Figure 1a). Participants were instructed to press the corresponding button as quickly and accurately as possible each time the smiley face appeared. After a block of practice trials, participants received four consecutive blocks of trials comprising 6 repetitions of a 10-item sequence of locations. After these four blocks, participants completed a final block of 60 trials with the smiley face appearing in pseudo-randomized locations. To obtain a measure of sequence-specific learning, we calculated the *rebound effect* by subtracting the median RT from Block 4 from the median RT on the final random block. To control for individual differences in processing speed, participants' RTs were transformed to z-scores prior to analysis.

Alternating Serial Reaction Time (ASRT) Task We used the ASRT task of Nemeth et al. (2010), adapted from Howard and Howard (1997). On each trial a picture of a dog appeared in one of four horizontally arranged empty circles on a computer screen. Participants were instructed to "catch the dog" by pressing the corresponding keys on the keyboard as quickly and accurately as possible (see Figure 1b). The sequence of locations consisted of 8 elements (2, R, 4, R, 1, R, 3, R) with locations in a fixed sequence (2, 4, 1, 3) alternating with random locations (R). This 8-element sequence was repeated 10 times per block to create 80 trials in each of 20 blocks. Due to the positions of the random

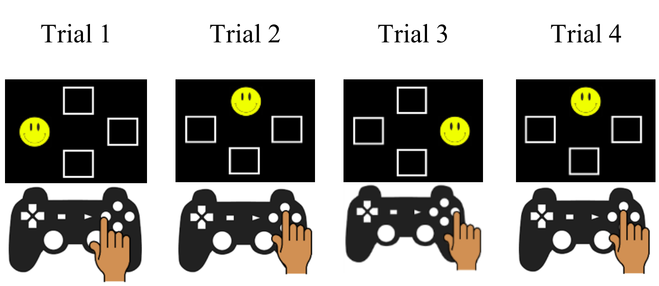

Figure 1a. Example of four consecutive trials on the SRT.

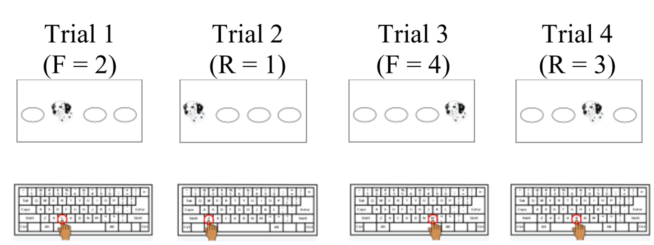

Figure 1b. Example of four consecutive trials on the ASRT task (F = fixed element; R = random element).

elements, sets of three consecutive trials varied in their frequency of occurrence within each block, allowing identification of sets of high frequency triplets (e.g., 2 1 4, generated by 2 R 4) and low frequency triplets (e.g., 1 4 2 generated by R 4 R). To measure of sequence-specific learning, we computed the difference in median RTs for high-frequency triplets vs. low-frequency triplets, with each participant's RTs transformed into z-scores prior to analysis.

Culture Fair Intelligence Test We administered the Culture Fair Test, Scale 3, Form A (Cattell & Cattell, 1973) as a measure of nonverbal intelligence. Participants were given a booklet with four sets of multiple-choice problems (Series, Classification, Matrices, Conditions). Each problem set had three examples followed by 10–14 items of increasing difficulty. Series and Matrices problems required participants to select an option to complete an abstract geometric series or matrix. Classification problems required participants to identify which two out of five stimuli were similar to each other and different from the other three stimuli. Conditions problems required participants to identify which option allowed a dot to be placed within a set of geometric figures where the placement of the dot would match that of a standard figure. Participants attempted to solve as many problems as they could in the allotted time (2.5 to 4 minutes per set). To obtain a measure of nonverbal intelligence, we summed the number of correct responses over the four sets.

Visual-Spatial Working Memory Task We used a visual-spatial working memory task (Ricker & Hardman, 2017) as an assessment of short-term storage capacity. We used this task to avoid any spurious correlations with the language tasks due to overlap in verbal ability and because it allowed us to examine some auxiliary hypotheses related to the decay rate. The task consisted of 10 practice trials and two blocks of 30 experimental trials. On each trial, the participant was shown an array of four rings with a dot at some point along the edge of each ring (see Figure 2). Within each array, the rings appeared at one of eight locations, randomly selected without replacement.

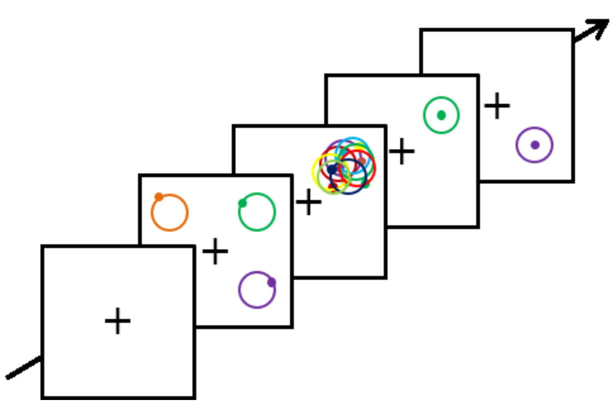

Figure 2. Example of a trial of the Working Memory task. Participants were told to remember the locations of the dots to reproduce at test. The array of 4 rings was presented on the screen for 600ms. Upon offset a masking stimulus was presented for 300ms, followed by a blank retention interval (RI) (750 or 7750 ms), determined randomly on each trial.

To test memory, each ring was re-presented at the end of the retention interval, one at a time, in its prior location, with the dot shown at the center. Participants were instructed to use the computer mouse to move the dot to the location they remembered from the array then click the mouse button to advance to the next item. To obtain a measure of working memory, we calculated response errors in circular degrees for each item.

Sentence Processing Task We administered a self-paced reading task to assess sentence comprehension (Wells, Christiansen, Race, Acheson, & MacDonald, 2009). The task included 9 practice items, 20 test items, and 30 filler items, with test items comprising 10 sentences with a subject relative clause, e.g., *The baker that offended the butcher carried some boxes out to the curb*, and 10 with an object relative clause, e.g., *The representative that the president denounced slammed the door after the meeting.*

At the start of each trial, participants were shown a series of dashes corresponding to each non-space character in the sentence. They were told to press a button to view each successive word. Each button press caused the next word to appear and the previous word to return to dashes. After viewing the last word, participants were given a *yes/no* comprehension question, e.g. *Did the butcher offend the baker*? Comprehension accuracy (% correct) for the 20 test items served an index of sentence processing ability.

Procedure

Participants were tested individually in a quiet testing booth in a two-hour session. Task order was counterbalanced with the constraint that SRT and ASRT tasks were given first and last, with half of the participants completing the SRT task first and the other half completing the ASRT task first.

Results

Individual Outcome Measures

SRT Task Accuracy on the SRT task approached ceiling, M = 97.1% (SD = 4.3; range = 72.3 to 100%). As shown in Figure 3a, RTs decreased across Blocks 1-4 as participants learned the task. A repeated-measures ANOVA confirmed a significant effect of Block on RTs, $F(4, 292) = 65.4$, $p < .001$, η_p^2 = .47. Indicative of sequence-specific learning, participants demonstrated a significant rebound effect, (M = .47, SD = .32, range –.27 to 1.2) between Block 4 and the subsequent random block (p < .001), with considerable variability in its magnitude. Only 4.1% of participants (N = 3) failed to demonstrate sequence-specific learning (i.e., they did not exhibit faster RTs for Block 4 in comparison to the subsequent random block). The magnitude of the rebound effect did not vary by task order.

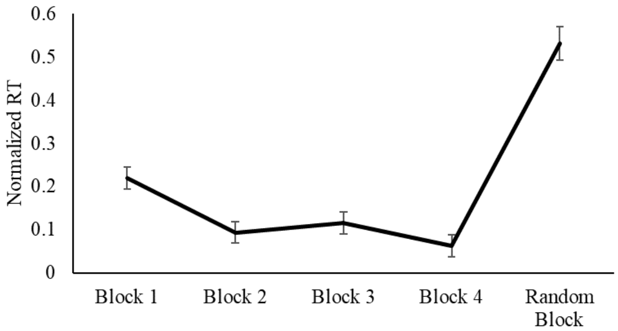

Figure 3a. Normalized RT across blocks for the SRT task.

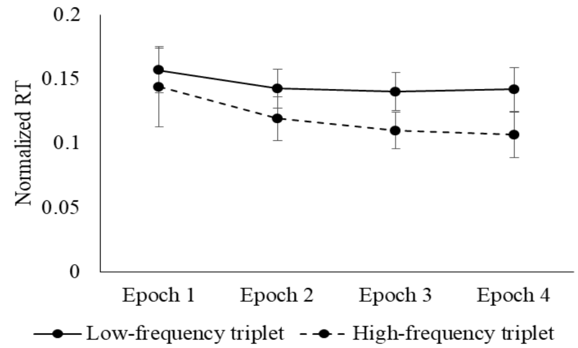

Figure 3b. Normalized RT across epochs for the ASRT task.

ASRT Task Mean accuracy on the ASRT task was 91.8% (*SD* = 5.3; range = 62.4 to 99.3%). For the purpose of statistical analysis, RTs across the 20 blocks of trials were grouped into four epochs of five blocks (i.e., 1–5, 6–10, 11–15, 16–20) and analyzed using repeated-measures ANOVA with Epoch and Triplet Type (high vs. low) as within-subjects factors. The ANOVA revealed a significant main effect of Epoch, $F(3, 219) = 2.94$, p = .03, partial $\eta_p^2 = .04$, confirming a significant decrease in RT as participants learned the task (see Figure 3b).

More importantly, the analysis also revealed a significant main effect of Triplet Type, $F(1, 73) = 9.68$, $p = .003$, partial $\eta_p^2 = .12$, indicating sensitivity to statistical probabilities within the sequence. Note, however, that the mean difference in normalized RTs between high frequency triplets and low frequency triplets was only .02 (*SD* = .06, range –.10 to .21), which suggests that sequence specific learning of non-adjacent dependencies was a relatively weak effect. Indeed, 35.1% of the participants (N = 26) did not demonstrate sequence-specific learning (i.e., they failed to exhibit faster RTs for high frequency triplets as compared to low frequency triplets). The interaction between Epoch and Triplet Type did not approach significance in the ANOVA, $F(3, 219) = 1.18$, $p = .32$, suggesting that the effect of sequence-specific learning did not increase significantly as a function of task exposure. The magnitude of the effect of Triplet Type did not vary as a function of task order.

Culture-Fair Intelligence Test (CFIT) Raw scores were used as a measure of nonverbal intelligence: *M* correct = 21.9, *SD* = 4.9 (range 11 to 34).

Visual-Spatial Working Memory (WM) Task To assess visual-spatial working memory, we calculated the degrees of error in reproducing the position of the dot on each ring. The mean overall error rate was 35.3 degrees (*SD* = 7.9, range 19.9 to 54.7). A two-way repeated-measures ANOVA revealed a main effect of Retention Interval, $F(1, 73) = 18.9$, $p < .001$, partial $\eta_p^2 = .20$, with higher accuracy (smaller error) for the shorter retention interval (*M* = 33.9 degrees; SD = 8.6) than for the longer interval (*M* = 36.7; *SD* = 8.1). A main effect of Serial Position, $F(3, 219) = 35.9$, $p < .001$, partial $\eta_p^2 = .33$, indicated that participants were sensitive to the order of appearance of the probe stimuli as well. Mean error was highly correlated across retention intervals, $r = .79$, $p < .001$, so we use average error in subsequent correlational analyses.

Sentence Processing (SP) Task Mean accuracy in sentence comprehension was 70.3% (*SD* = 12.6%; range 50 to 95%). Comprehension accuracy was not significantly higher for sentences with subject relative vs. object relative clauses, $t(73) = .31$, $p = .76$; accuracy across sentence types was moderately correlated, $r = .47$, $p < .001$.

Associations Between Tasks

Table 1. Correlation coefficients across tasks (N = 74).

	Sequence Learning		Sentence	Working
	SRT	ASRT	Processing	Memory
ASRT	–.18			
SP	.13	.31		
WM	.04	–.29	–.11	
CFIT	.11	.23	.20	–.34

Indices of sequence-specific learning on the SRT and the ASRT tasks were not correlated ($p = .13$); see Table 1. Performance on the ASRT task, but not the SRT task, correlated positively with sentence processing ($p = .008$) and nonverbal intelligence (CFIT) ($p = .04$), and negatively with error on the working memory task ($p = .01$). While error on the working memory task showed a significant negative correlation with CFIT ($p = .003$), neither measure was associated with sentence processing. (Note, however, that *p*-values are uncorrected for multiple comparisons.)

As suggested by a reviewer, we removed the 29 participants who failed to show sequence-specific learning on the SRT and/or ASRT tasks and recalculated the correlations. In the reduced sample (N=45), the SRT and ASRT tasks were significantly negatively correlated ($r = –.36$, $p = .014$). SRT was unrelated to all other variables. ASRT was positively associated with sentence processing ($r = .32$, $p = .033$) and negatively associated with working memory ($r = –.33$, $p = .028$), but no longer associated with CFIT, ($r = .14$, $p = .36$). CFIT remained significantly correlated with working memory ($r = –.30$, $p = .046$).

Discussion

SL has been defined as the implicit detection of complex patterns in the environment (Reber, 1993). Although SL is presumed to underlie the acquisition of complex systems of knowledge such as language, there is little consensus on how to assess SL as an ability (Kaufman et al., 2010; Siegelman, Bogaerts, & Frost, 2017). In this study, we asked whether learning of sequence-specific information across two perceptually similar SL tasks would provide evidence of shared underlying learning mechanisms. The SRT and the ASRT tasks are both widely used as indices of procedural learning, yet differ with respect to the underlying sequential rules. The absence of a positive correlation in sequence learning across the two tasks suggests distinct learning mechanisms for tracking adjacent vs. nonadjacent dependencies, which runs counter to the view that the ASRT task is simply a more implicit version of the SRT task, where intervening elements prevent sequences from entering awareness. In line with prior research that indicated the relative difficulty of detecting nonadjacent dependencies (cf. Braine, 1987), over a third of our participants (35.1%) did not exhibit sequence-specific learning in the ASRT task. This contrasted with markedly superior performance on the SRT task, where only 4.1% of participants failed to exhibit learning. Differences in task performance were also evident in the effect sizes for sequence-specific learning (Z-score units for SRT: .47 vs. ASRT: .02). Although we interpreted the results as due to task differences in dependency learning, the SRT and ASRT tasks also differed in the layout of the response pad and the time course of learning captured (the last two blocks for SRT; all epochs for ASRT). It remains possible that these superficial differences contributed to the differential pattern of correlations we observed.

Our results support proposals that view computations of sequential dependencies as constrained by the input modality and the types of distributional probabilities and contingencies present in the input (Conway & Christiansen, 2006; Frost et al., 2015). Daltrozzo and Conway (2014) have proposed a dual-route hypothesis that SL consists of “basic” and “expert” systems. The basic system captures modality-specific sequences, extracts recurring chunks of input, and registers transitional probabilities in a bottom-up fashion. The expert system, in contrast, utilizes top-down processing dependent on attention and working memory to construct abstract representations of sequential patterns that transcend specific stimuli or stimulus modalities. The basic system seems to emerge early in life, as evidenced by studies of SL in infancy (Romberg & Saffran, 2010), and may bootstrap development of the expert system (Saffran & Wilson, 2003). Under this view, the two systems interact in hierarchical fashion, with extraction of concrete contiguous sequences serving as an initial step in SL (Thiessen et al., 2013). Although it seems plausible that the SRT task taps into the basic system, it remains unclear how performance on ASRT task relates to this account.

In the current study, performance on the ASRT task, but not the SRT task, correlated with nonverbal intelligence and visual-spatial working memory. This pattern of results failed to match Janascek and Nemeth’s (2013) prediction that working memory resources are more strongly associated with explicit than implicit SL. The observed associations between the ASRT and visual-spatial working memory undermine the view that the ASRT task represents a “pure” measure of implicit SL. If this were the case then we should not have observed a significant correlation between working memory and sequence-specific learning on the ASRT task. Alternatively, having greater memory capacity may allow learners to register difficult non-contiguous patterns because more elements can be concurrently held in working memory at the same time. Given Nemeth et al.’s (2011) findings that simultaneous sentence processing is disruptive of learning in the ASRT task, future research should examine whether imposing load on visual-spatial working memory disrupts SL in the ASRT task to a similar extent.

In line with Nemeth et al. (2011), we found SL in the ASRT to correlate with sentence processing (comprehension accuracy). Taken together with findings by Misyak and Christiansen (2012) who linked success in learning AGLs with either adjacent or nonadjacent dependencies with accuracy in comprehending complex sentences containing relative clause constructions, our results imply that processing of complex syntactic constructions relies on SL mechanisms that support representations of non-contiguous long-distance dependencies. The fact that the SRT task was not associated with any cognitive or language measure in our study may be due in part to its psychometric properties (Hedge, Powell, & Sumner, 2017; Siegelman & Frost, 2015). Although frequently used in group-level research designs comparing clinical and non-clinical samples (e.g., Lum et al., 2014; Lum, Ullman, & Conti-Ramsden, 2013), the SRT task may not be an ideal assessment for detecting individual differences in SL as virtually all individuals within normative samples are able to achieve sequence-specific learning with minimal effort and error.

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