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What Predicts Successful Literacy Acquisition in a Second Language?

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Abstract
In the study reported here, we examined whether success (or failure) in assimilating the structure of a second language can be predicted by general statistical-learning abilities that are nonlinguistic in nature. We employed a visual-statistical-learning (VSL) task, monitoring our participants' implicit learning of the transitional probabilities of visual shapes. A pretest revealed that performance in the VSL task was not correlated with abilities related to a general *g* factor or working memory. We found that, on average, native speakers of English who more accurately picked up the implicit statistical structure embedded in the continuous stream of shapes better assimilated the Semitic structure of Hebrew words. Languages and their writing systems are characterized by idiosyncratic correlations of form and meaning, and our findings suggest that these correlations are picked up in the process of literacy acquisition, as they are picked up in any other type of learning, for the purpose of making sense of the environment.

Keywords
foreign-language learning, individual differences, bilingualism, statistical learning

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Most modern societies today include as an integral part of their educational curriculum the learning of a second or foreign language, whether because they are multilingual societies or simply because globalization emphasizes the need for a lingua franca. Beginning with Carroll's seminal work (e.g., Carroll & Sapon, 1959), studies tracking the process of second-language acquisition have suggested that individuals substantially differ in their capacity to learn another language (e.g., Lundberg, 2002; Sparks, Patton, Ganschow, & Humbach, 2009). Whereas some people assimilate a new linguistic system with relative ease, for others this task involves significant difficulty. What determines this variability? What predicts successful and fast acquisition of an additional language?

The question of the source of individual differences is seldom straightforward (see Dewaele, 2009). Many factors can be offered to explain success or failure in any given task, and pinpointing a single mental capacity to account for the population variance in performance is difficult in most cases. For example, research on spoken-language and literacy acquisition in a second language has suggested that success is moderated by a variety of individual differences in factors such as the context of language exposure, phonological abilities, working memory, executive functions, motivation, and personality traits (e.g., Bialystok, Craik, & Luk, 2008; DeKeyser, 2000; Dewaele, 2009; Kroll & Linck, 2007). In the present context, however, we were concerned with adjudicating between two qualitatively different theoretical approaches to second-language acquisition in young adults: The first approach considers it to be a domain-specific capacity belonging to the modular faculty of language, whereas the second considers it to reflect a general and nonlinguistic cognitive capacity for statistical learning.

The view that second-language acquisition is a subset of the language faculty of cognitive architecture assumes that second-language learning is mediated by the same

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linguistic capacities as first-language learning, and by similar neurocircuitry. Indeed, it has been shown that first-language linguistic capacities, such as phonological awareness, syntactic abilities, orthographic knowledge, and vocabulary, generally predict success in second-language acquisition (e.g., Ganschow, Sparks, & Javorsky, 1998). Similarly, the level of literacy achieved in one's native language has been shown to determine, to a large extent, the ability to acquire literacy in a foreign language (e.g., Koda, 2007). Moreover, second-language neurocircuitry has been shown to converge with first-language neurocircuitry as second-language proficiency increases (e.g., Abutalebi, Cappa, & Perani, 2001). According to this approach, mastering literacy in a second language draws on specific capacities that are specific to language, and therefore, linguistic measures are the best predictors of success in this task.

The theoretical approach underlying the claim that second-language learning mainly reflects a general capacity for statistical learning considers language learning to be primarily a process of picking up and implicitly assimilating the statistical properties of a linguistic environment. In this view, language is regarded as yet another example of a well-structured environment, and learning it draws on the general cognitive ability to perceive and identify systematic structures and correlations. Thus, words in each language, whether morphologically simple or complex, are characterized by statistical correlations and transitional probabilities that constrain and determine their internal structure, and by correlations between their sublinguistic components and semantic features (see Frost, 2012a, 2012b, for a discussion). Mastering a lexicon, therefore, involves the implicit learning of these correlations. More specifically for literacy acquisition, each language presents to the reader a writing system that is characterized by a set of correlations that determine the possible co-occurrences of letter sequences, which eventually result in establishing orthographic representations. Moreover, each writing system is characterized by a different level of consistency (i.e., high or low correlations) in the mapping of graphemes to phonemes, and these consistent mappings eventually result in mapping orthographic representations to phonological ones. Morphological structure is also reflected by systematic correlations, in which repeated letter clusters consistently convey features of semantic meaning (e.g., Plaut & Gonnerman, 2000).

This approach suggests that each language implicates a differential tuning to statistical structure, given its idiosyncratic linguistic characteristics. In this view, native speakers who are proficient readers implicitly develop differential sensitivities to the statistical properties of their own language, and while learning to read in a second language, speakers (and readers) acquire a new lexical system, mainly by picking up and assimilating a new set of statistical regularities. Hence, the fundamental cognitive faculty of implicit correlation learning, which underlies any form of learning, plays a primary role in second-language literacy acquisition. Note that two main factors may impede this process. The first factor is the degree of similarity or dissimilarity between the statistical properties of the first and the second language (e.g., Bialystok, McBride-Chang, & Luk, 2005). Second, as with any cognitive ability, there are individual differences in the sensitivity to the correlations in the environment. The question at hand is, therefore, whether individual differences in statistical learning predict individual differences in second-language literacy acquisition. This was the focus of the present research.

To address this question, we examined the process of assimilating the writing system of Hebrew by native English speakers. Hebrew and English were chosen for this study as a first- and second-language pair because they are contrasting languages characterized by qualitatively different statistical properties. These differences concern the structure of base words, which relate to how morphological complexity is determined, and, consequently, the characteristics of the writing systems. English—an Indo-European language with a concatenated morphology—imposes few constraints on the internal structure of base words, and in general, the predictive value of a given phoneme regarding the identity of the subsequent one is relatively low. For example, word onsets can consist of any consonant or any vowel, and because the permissible syllables are numerous, in principle, phonemes could be located in any position within the spoken word with more or less equal probability. Prefixes and suffixes are then linearly appended to the base word and are characterized by high distributional properties (Frost, 2012a).

In Hebrew, a Semitic language, words—whether spoken or printed—are structured very differently. Semitic words are normally composed by intertwining a triconsonantal root morpheme, which carries the core meaning of the word, with word-pattern morphemes—abstract phonological structures consisting of vowels or of vowels and consonants, in which there are "open slots" for the root's consonants to fit into. Semitic words, therefore, have a recognizable, predictable, and well-defined internal structure. Word patterns can begin with a very restricted number of consonants, and these determine a set of transitional probabilities regarding the order and identity of subsequent consonants and vowels. Because the language is root based, and the roots convey the core meaning of words, these need to be easily extracted and recognized by the speaker. The only clue regarding their location within the world is a well-defined phonological word structure, which on the one hand constrains dramatically the permissible phonological word forms in the language, but on the other hand, allows the root consonants to stand out. Given the bimorphemic structure of Hebrew words, the writing system of Hebrew consists of letters that mostly represent consonants (thereby root information), whereas most of the vowels can optionally be superimposed on the consonants as diacritical marks ("points"). These points, however, are omitted from most adult reading material (Bentin & Frost, 1987; Frost, Katz, & Bentin, 1987). Because the structure of spoken words is highly constrained by the permissible Semitic word patterns, readers can converge on the correct vowel configuration quite effortlessly (Frost, 1995, 2006).

In the last decade, the reading of Hebrew has been extensively investigated by Frost and his colleagues in a variety of experimental paradigms (Deutsch, Frost, & Forster, 1998; Deutsch, Frost, Peleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005; Feldman, Frost, & Pnini, 1995; Frost, Forster, & Deutsch, 1997; Frost, Deutsch, & Forster, 2000; Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson, 2000; Frost, Kugler, Deutsch, & Forster, 2005; Velan & Frost, 2007, 2011). One consistent finding in all of these studies is that root primes facilitate both lexical decision and naming of target words that are derived from these roots. Moreover, proficient Hebrew readers have been shown to be tuned to the statistical properties that characterize the Semitic structure of words, so that the extraction of the embedded root consonants is fast and automatic (e.g., Deutsch et al., 2003; Frost et al., 1997), and the retrieval of vowel information is governed by the knowledge of word patterns (Frost, 2006). In other words, the sensitivity of Hebrew readers to the skewed frequency distribution of phonemes and letters in their language determines their processing of printed information; consequently, the typical marker of reading Hebrew—sensitivity to the location of root consonants—emerges (Frost, 2012a; Velan, Deutsch, & Frost, 2013).

In the present study, we tracked the process of assimilating the linguistic properties of Hebrew in native speakers of English during their first year of learning Hebrew as a second language. We focused on reading as an output measure because most research on processing morphological information in Hebrew has been carried out in the visual modality, and the markers of learning Hebrew have been mostly documented in the domain of visual word recognition. More important, as Hebrew print contains mainly consonantal information, whereas vowels, for the most part, are not represented in print, reading Hebrew fluently cannot be carried out by simply applying grapheme-phoneme conversion rules but requires a deep understanding of the language (Frost, 2006). Reading proficiency in Hebrew was assessed, therefore, in three tasks. The first monitored speed of decoding pointed nonwords and reflected the assimilation of the characteristics of the Hebrew writing system. The second monitored accuracy in naming unpointed words, which reflects the implicit learning of Hebrew phonological word patterns, that is, the transitional probabilities of permissible phoneme sequences in Hebrew. The third—cross-modal morphological priming—directly tapped the main marker of reading in Hebrew: The assimilation of the morphological root-based composition of words. Because our sample of English speakers, not surprisingly, presented a varied distribution of relative success in learning Hebrew, our aim was to examine whether this success (or nonsuccess) in assimilating the writing system and the Semitic structure of words could be predicted by general statistical-learning abilities that are nonlinguistic in nature.

We therefore employed a visual-statistical-learning (VSL) task in which 24 relatively complex visual shapes (taken from Turk-Browne, Jungé, & Scholl, 2005; see also Glicksohn & Cohen, 2011; Kim, Seitz, Feenstra, & Shams, 2009) were presented one at a time in a consecutive stream that lasted about 10 min. The 24 shapes were organized in eight triplets, the members of which were always presented in the same sequence in the 10-min stream, with sets of triplets appearing in random order. The transitional probabilities among shapes within triplets were 1. Participants were not told that the stream was constructed of triplets. However, following the familiarization phase, participants were presented with 32 two-alternative forced-choice (2AFC) trials, in each of which they saw two sets of triplets: (a) a sequence of three shapes that appeared in the stream in the original order (transitional probabilities = 1) and (b) foils made of a sequence of three shapes that were taken from the stream but did not appear in that order (transitional probabilities = 0). Participants' success rate in distinguishing the base triplets from the foils reflected their implicit learning of the transitional probabilities of the visual shapes within the stream. The visual shapes used for the experiment and examples of the transitional probabilities of triplets are presented in Figure 1.

We then correlated relative success in the VSL task with relative success in the Hebrew reading tasks. We hypothesized that if a general statistical-learning ability underlies learning to read in a new language that is characterized by a novel set of statistical regularities, then relative success in learning the transitional probabilities of random visual shapes would predict the speed and success of learning to read a new language. The theoretical implications of this possibility cannot be overestimated. Confirmation of this possibility would suggest that a general nonlinguistic faculty of statistical learning accounts, at least to some extent, for success in second-language acquisition when the first and second languages differ in their basic statistical properties. Such an outcome would also imply that a simple and short test involving visual shapes could predict the speed of

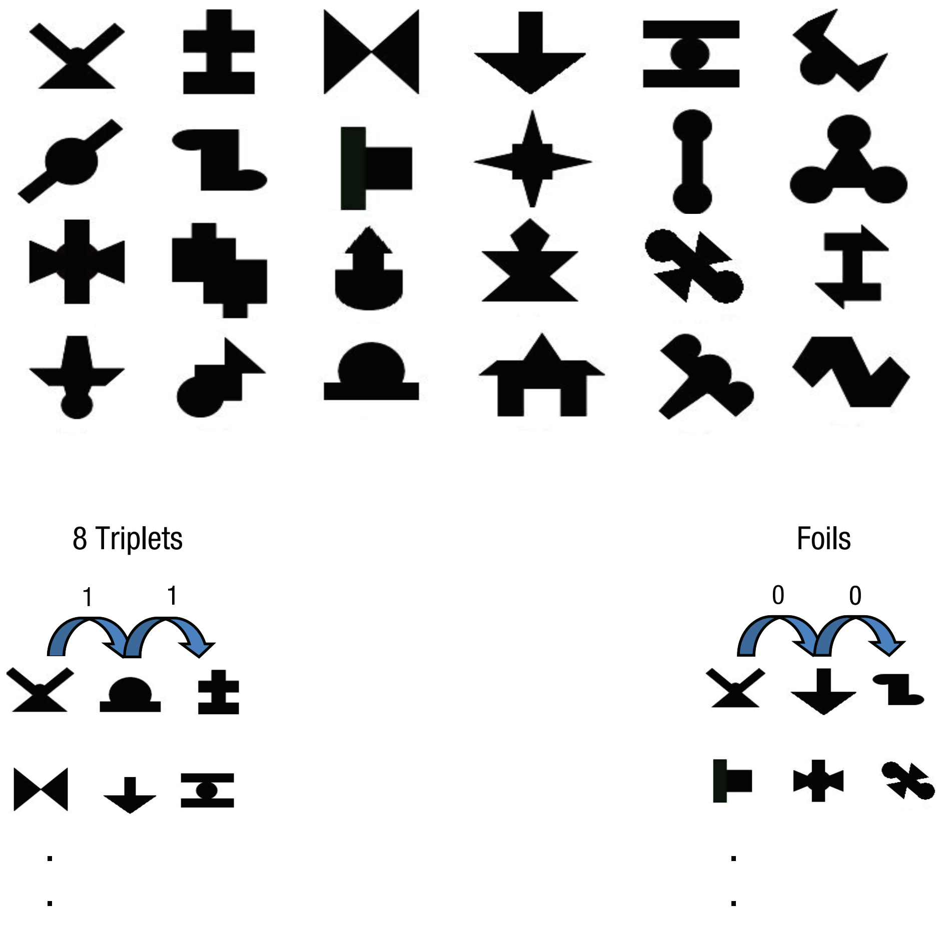

Fig. 1. The 24 visual shapes employed in the visual-statistical-learning task and examples of triplets and foils. The 24 shapes were organized into eight triplets, the members of which always appeared in the same sequence, and all shapes were then presented one at a time in a 10-min stream. On each trial in a subsequent recognition-memory test, participants saw two sets of triplets and indicated which one had appeared in the stream (transitional probability between each shape = 1) and which was a foil (transitional probability between each shape = 0).

assimilating a new linguistic environment, even before the first foreign word has been learned.

Method

Participants

The participants were 27 American students (13 males, 14 females) at the Hebrew University Overseas School who were admitted to the Hebrew Learning Program. The program consists of 6 levels of Hebrew proficiency; participants were taken from Levels 3 to 5 to ensure that they had the necessary vocabulary required for participating in the experiments yet that they were not entirely proficient. Their mean age was 26 years.

Design and procedure

Each participant was tested twice (during the first and the second semester) with experimental tasks that monitored his or her learning of Hebrew, and tested once with the VSL task. This allowed us to track his or her individual learning curve.

VSL task

As described in detail in the introduction, this task monitors participants' ability to detect the implicit transitional probabilities embedded in a continuous stream of visual shapes. Participants' scores ranged from 0 to 32, based on the number of correct identifications of triplets in the 32

2AFC trials. Our choice of the VSL task was based on the following pretest.

Preliminary validation procedure

As with any correlation design, one general concern when interpreting a correlation between levels of performance in two tasks is that a third, perhaps trivial, capacity underlies both. The task of ruling out all possible alternative cognitive capacities is obviously infinite. However, in the present study, we first aimed at mapping the relation between performance in the VSL task and performance in tasks that are traditionally taken as reliable indices of nonverbal reasoning abilities related to a general *g* factor, verbal working memory, and naming speed. We therefore chose (a) the Block Design (BD) task from the Wechsler Adult Intelligence Scale–Revised battery (Wechsler, 1981), a test of spatial-reasoning ability that, much like Raven's Advanced Progressive Matrices, is relatively insensitive to verbal memory limitations; (b) Raven's Advanced Progressive Matrices (Raven, 1978); (c) the verbal working memory (WM) test developed by the Israel National Institute for Testing and Evaluation (NITE); (d) rapid automatic naming (RAN) with digits, letters, and objects (developed by NITE), which is a reliable predictor of general speeded output, probably because of its sensitivity to the rate of serial encoding in working memory; and (e) the Digit Span task from the Wechsler Adult Intelligence Scale–Revised.

To ensure that performance in the VSL task was not confounded with these general cognitive abilities, we tested two independent samples. In Sample 1, 76 participants from the Hebrew University were tested in a 1-hr session with the VSL, BD, WM, and RAN tasks. In Sample 2, 56 participants from the Hebrew University were tested in a 2-hr session with the VSL, Raven Advanced Progressive Matrices, digit-span, WM, and RAN tasks, all in random order. The correlation matrices obtained in the two samples are presented in Table 1.[1]

Learning Hebrew as a second language

We used three tasks to assess Hebrew reading proficiency: speed of decoding of pointed nonwords, naming of unpointed words, and cross-modal morphological priming.

To assess fast decoding of pointed nonwords, we borrowed a test from the diagnostic computer-based test battery developed by NITE in 2007 to standardize the diagnosis of learning disabilities of Hebrew speakers. The main advantage of this test is that it produces standard scores based on norms of the Hebrew-speaking population, and, therefore, it provided a frame of reference for our participants. We tested our participants twice, once at the beginning of the year and a second time at the end of the year, so that we could compute a learning score for each participant that measured his or her improvement in reading Hebrew between the first and the second sessions, in terms of standard deviations.

To assess naming of unpointed words, we presented participants with 60 unpointed Hebrew words in a naming task. Although their instructions were to read the words aloud as fast as possible, our measure of interest was the number of words that were named accurately by assigning the correct vowel configuration. This was taken as evidence of the assimilation of the word-pattern morphemes of Hebrew. As in the decoding of nonwords, our measure of learning considered the improvement in performance between the first and the second testing sessions.

We used the cross-modal morphological-priming paradigm to directly assess the learning of Semitic word structure. As in Frost, Deutsch, Gilboa, et al. (2000), participants were presented with spoken word primes via earphones while printed targets appeared on a computer screen, and they were asked to make a lexical decision about whether the target was a word or a nonword. Primes and targets were related morphologically (i.e., derived from

Table 1. Correlations Between Performance on the Visual-Statistical-Learning (VSL) Task and General Cognitive Abilities in the Two Independent Samples

	Sample 1 (n = 76)					Sample 2 (n = 56)	
			Rapid automatic naming				
Correlation with VSL	Block Design	Verbal working memory	Digits	Objects	Letters	Raven's APM	Digit Span
r	.19	.15	.18	.27	.02	.2	.24
p	.1	.2	.12	.02	.86	.14	.07

Note: The Block Design and Digit Span tasks were taken from the Wechsler Adult Intelligence Scale–Revised battery (Wechsler, 1981), and the verbal working memory and rapid-automatic-naming tests were developed by the Israel National Institute for Testing and Evaluation. Raven's APM = Raven's Advanced Progressive Matrices (Raven, 1978).

the same root), semantically, or phonologically, and unrelated control words served as a baseline for computing the priming effect. The semantic and phonological related-word trials were used in this study as fillers to make the manipulation less salient. Our measure of interest was morphological root priming. For Hebrew advanced or beginning readers, this paradigm has been shown to result in strong effects of morphological relatedness relative to simple phonological or semantic overlap between primes and targets (Frost, Deutsch, Gilboa, et al., 2000; Frost, Narkiss, Velan, & Deutsch, 2010).[2]

Results

Pointed nonword decoding

The output of the computerized test assessing pointed nonword decoding is a standard score calculated relative to Hebrew-speaker norms. Thus, we computed a learning score for each participant that reflected the difference between his or her performance in the first session and his or her performance in the second session. This reflected the amount of his or her learning during the academic year. Overall mean scores at Session 1 and Session 2 were quite similar (−2.23 for Session 1 and −2.36 for Session 2), which suggests that some participants indeed improved between testing sessions, but some did not or even scored worse in Session 2 than in Session 1. We then correlated this learning score with the score each participant obtained in the VSL task. As can be seen in Figure 2, performance in the VSL task predicted the learning scores, such that participants who succeeded in the VSL task showed large improvement in pointed Hebrew nonword decoding (r = .57, p < .002). The correlation between the scores obtained in Session 1 and Session 2 was .85.

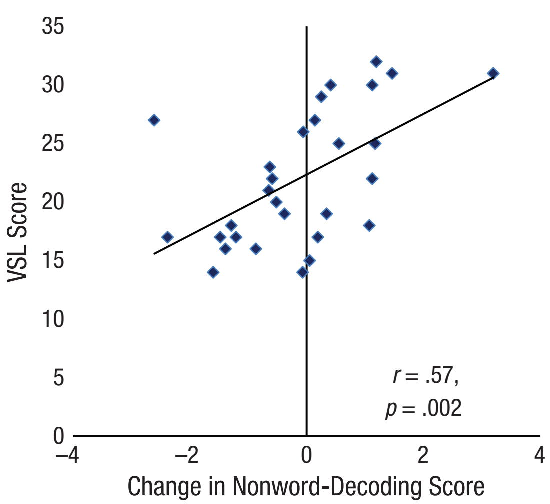

Fig. 2. Scatter plot (with best-fitting regression line) showing scores on the visual-statistical-learning (VSL) task as a function of the change in standard scores on the pointed-nonword-decoding task from Session 1 to Session 2.

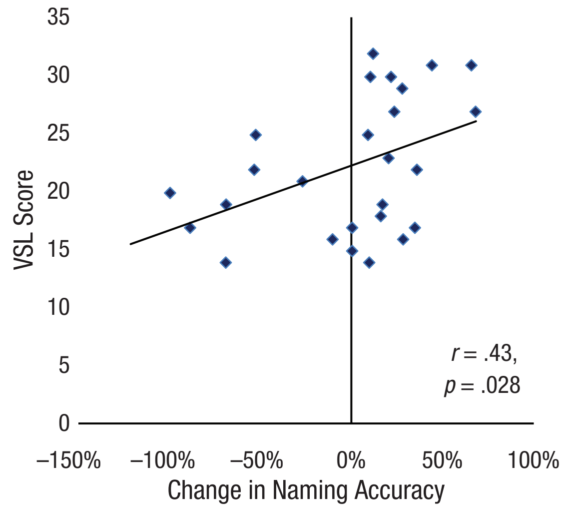

Fig. 3. Scatter plot (with best-fitting regression line) showing scores on the visual-statistical-learning (VSL) task as a function of changes in the percentage of unpointed words that were accurately named from Session 1 to Session 2.

Unpointed naming accuracy

For each participant, we monitored the number of correct and incorrect assignment of the right vowel configuration to the 60 unpointed words in Session 1 and in Session 2. We then defined the amount of learning between sessions in terms of decreased percentage of errors in Session 2 relative to Session 1. Again, some participants had fewer errors in Session 2 than in Session 1, which demonstrates an assimilation of the word patterns of Hebrew, whereas some participants' scores did not improve or even deteriorated (Fig. 3). As with pointed nonword decoding, the correlation between VSL scores and learning scores was robust and significant (r = .43, p < .028). The correlation between the scores obtained in Session 1 and Session 2 was .63.

Morphological-priming effects

Overall response latencies were faster in Session 2 relative to Session 1 because of increased proficiency, and therefore, the morphological-priming effects were proportionally reduced. Given this classical pattern of scaling, an improvement score in priming could not be unequivocally calculated. We therefore calculated morphological-priming effects for Session 1 and Session 2 separately (Fig. 4). The measures in the two sessions consisted, therefore, of independent validation of our predictions. Similar to the findings with pointed nonword

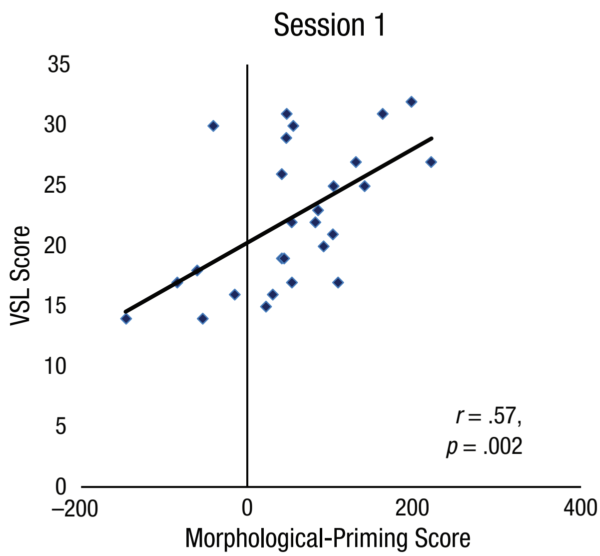

Fig. 4. Scatter plots (with best-fitting regression lines) showing scores on the visual-statistical-learning (VSL) task as a function of morphological-priming scores. Results are shown separately for Session 1 and Session 2.

decoding and naming of unpointed words, results showed that scores in the VSL task were highly correlated with the amount of priming, such that higher VSL scores predicted larger root morphological-priming effects (r = .57, p < .002, for Session 1; r = .44, p < .021, for Session 2).

As the cross-modal-priming experiment also included a semantic-relatedness condition as a filler, we examined the correlation between the VSL task and semantic-priming effects. The correlations were low and nonsignificant (r = .15, p < .45, for Session 1; r = .26, p < .19, for Session 2; see Fig. 5). Thus, the VSL task does not seem to be correlated simply with better performance or with any priming effect but seems to be a predictor of the reading markers related to the structural properties of Hebrew as a Semitic language.

Discussion

In this study, we examined whether differential ability to detect the implicit transitional probabilities of visual shapes in a continuous stream predicts differential ability in literacy acquisition in a second language when the first and second language present contrasting linguistic environments in terms of statistical properties. We therefore tracked the learning process of Hebrew, a Semitic language, in native speakers of English, an Indo-European

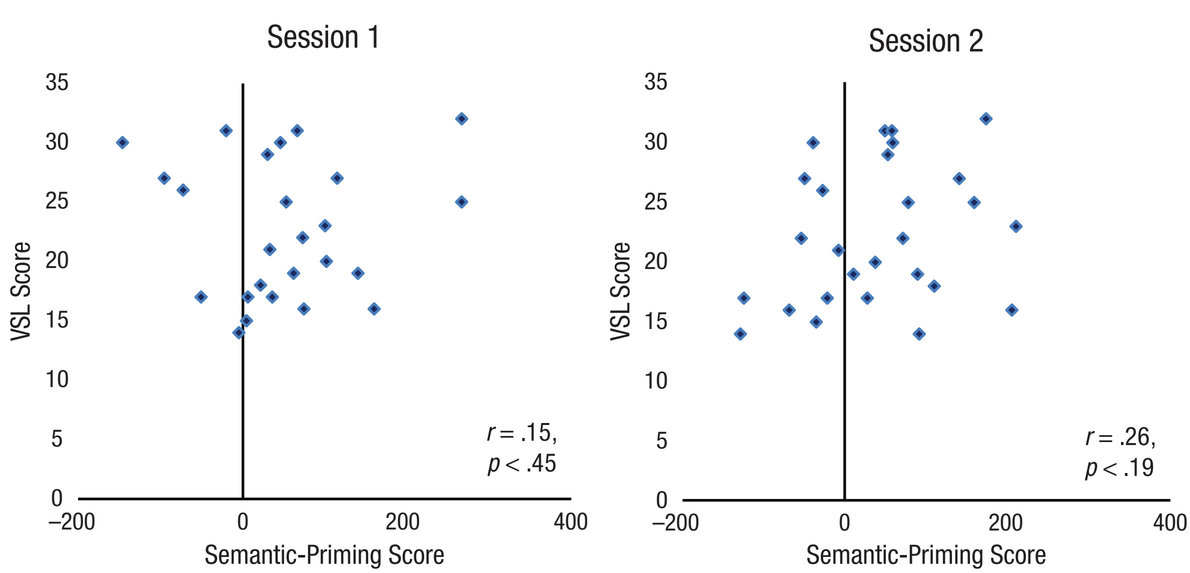

Fig. 5. Scatter plots showing scores on the visual-statistical-learning (VSL) task as a function of semantic-priming scores. Results are shown separately for Session 1 and Session 2.

language. Our results seem unequivocal. Participants who scored well in the VSL task, that is, picked up the implicit statistical structure embedded in the continuous stream of visual shapes, on average, scored well on the tasks that monitored the assimilation of the Semitic structure of Hebrew words. We should note that this correlation was exclusive to morphological priming, the typical finding with Hebrew readers, and was not found for semantic priming, which suggests that this correlation is related to learning the structural Semitic properties of the language.

Admittedly, the present pioneering study is based on a sample of Hebrew learners that was not large ($N = 27$), and a possible concern when relatively small samples are employed in correlational designs is that one or two deviant observations could drive the correlation. The scatter plots in Figures 1 through 4 clearly demonstrate that this was not the case. The distribution of observations in the three tasks systematically showed that the higher the VSL scores of our participants, the higher their scores for learning Hebrew.[3] Moreover, as performance in the VSL task was not correlated with general performance factors, such as scores on the BD, WM, or RAN tasks, our findings suggest a genuine link between statistical learning of visual shapes and learning to read in a second language. Converging preliminary data reported recently with learners of Chinese as a second language (Wu et al., 2012) suggest that our findings are not specific to learning Hebrew as a second language. Similar to the present results, the findings of Wu et al. (2012) showed that the level of Chinese literacy of readers of alphabetic orthographies could be accurately predicted by their performance in the VSL task. This outcome suggests that our findings extend to other languages and writing systems.

Admittedly, coming from abroad to study Hebrew, our participants were likely to be motivated to learn Hebrew, and this may have had some impact on their rate of learning. Also, our design did not allow us to statistically compare the power of the VSL task in predicting a second-language learning outcome relative to other general cognitive abilities. Nevertheless, the observed systematic and significant correlation between the VSL task and second-language literacy acquisition has considerable theoretical implications. It suggests that a common faculty underlies performance in a task that taps the implicit learning of transitional probabilities of a stream of visual shapes and a series of measures that tap the acquisition of the deep linguistic structures characteristic of a given language. This finding points to the possibility that a unified and universal principle of statistical learning can quantitatively explain a wide range of cognitive processes across domains, whether they are linguistic or nonlinguistic (Frost, 2012a, 2012b). Note that similar claims have been advocated by Ahissar and her colleagues, who demonstrated that a general cognitive factor, mainly sensitivity to the statistics of simple auditory stimuli, is related to language aptitude (e.g., Ahissar, Lubin, Putter-Katz, & Banai, 2006).

We entertain, then, the suggestion that cognitive systems are tuned to seek correlations in the environment and that the implicit assimilation of event co-occurrences is the basis for many different types of learning. The linguistic environment is no exception to this basic principle. Languages and their writing systems are characterized by idiosyncratic correlations of form and meaning, and these are picked up in the process of literacy acquisition, as they are picked up in any other type of learning, for the purpose of making sense of the environment.

Author Contributions

R. Frost developed the study concept with his laboratory students N. Siegelman, A. Narkiss, and L. Afek, who were in charge of the data collection and data analyses. R. Frost wrote the article, and all authors approved the final version of the article for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Notes

1. We examined the correlation of performance in the VSL task with the various cognitive abilities in a pretest using independent samples of students because we were constrained by the length of testing in the experimental tasks performed by our American students.
2. Stimuli, details of presentation, and raw scores are displayed at the following site: http://psychology.huji.ac.il/.upload/staff/42/L2%20Literacy%20Stimuli%20and%20RawScores.pdf
3. Note that the observed correlations between VSL and reading scores were partly driven by a seeming "decrease" of reading scores over time for some learners. This, however, probably reflects a simple regression to the mean of some slow learners, who obtained a score in Session 1 that was slightly better than their actual performance, rather than a true decline in performance.

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