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# Implicit Statistical Learning and Language Skills in Bilingual Children

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**Purpose:** Implicit statistical learning in 2 nonlinguistic domains (visual and auditory) was used to investigate (a) whether linguistic experience influences the underlying learning mechanism and (b) whether there are modality constraints in predicting implicit statistical learning with age and language skills.

**Method:** Implicit statistical learning was examined in visual and auditory domains. One hundred twelve English native speaking monolinguals and Spanish–English bilinguals age 5–13 years participated in the study. Language skills were measured by standardized language tests.

**Results:** The overall results showed that all children implicitly learned statistical regularities above chance level in both modalities. However, there was no group difference between monolingual and bilingual children on either visual or auditory tasks. Lastly, a different tendency in predicting implicit statistical learning was observed for each group. In the monolingual group, both age and language scores significantly explained auditory statistical learning, whereas age explained visual statistical learning. In the bilingual group, age explained auditory statistical learning, and nothing was significant for visual statistical learning.

**Conclusions:** These findings are discussed in terms of the extent to which implicit statistical learning is influenced by internal and external factors and a consideration of important notions when testing bilingual children's language skills.

**Key Words:** implicit learning, nonlinguistic statistical learning, bilingual children, language learning

Our environment is characterized by the regular and coherent occurrence of sounds, objects, and events. Thus, if we can usefully encode and examine the regularities underlying such structures, our learning can be much more efficient. Individuals perform computational tasks by extracting input correlations among available inputs when facing a visual or auditory system during the learning of new information. Language learning is one of the main outputs of this computational task.

Thus, research on language acquisition and mastery has recently begun to consider this type of ability, which is variously referred to as *implicit learning, statistical learning, artificial grammar learning,* or *procedural learning*. Currently, it is debatable whether or not these phrases are tapping the same underlying learning mechanism (Perruchet & Pacton, 2006). However, in this article, we consider that all of these terms refer to a broad underlying phenomena, that is, to the ability to incidentally learn (i.e., to learn without being explicitly instructed) new information in which patterns or rules are embedded. *Implicit statistical learning* is the key terminology that will be used throughout this article.

It has been suggested that infants as young as 8 months know how to extract statistical probabilities among complex inputs, whether they are linguistic or nonlinguistic (Conway & Christiansen, 2005; Gomez & Gerken, 1999; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996). Such findings support two ideas, one being that this ability has a key function when infants break down a complex language stream and start to learn language, and the second being that this statistical learning exists in many different modalities, including auditory, and visual; auditory may be the most suited for temporal processing compared with other modalities (Saffran, 2003).

Implicit statistical learning is considered to be a strong innate ability that individuals possess (Perruchet & Pacton, 2006). However, it is also well documented that the ability to learn regularities among sequential information interacts with our life experience. Within this framework,

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recent findings have suggested that early life experience, such as being exposed to two different languages, may enhance bilingual infants' implicit statistical learning (Kovács & Mehler, 2009). By contrast, early auditory deprivation may have a negative effect on implicit statistical learning (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). For example, Conway et al. (2011) examined children with cochlear implants (CIs) who had experienced a period of auditory input deprivation. These children showed poor performance on visual sequence learning compared with typically developing peers. In addition, the ability to learn sequence visual information was significantly correlated with language performance in children with CIs. The authors concluded that nonlinguistic statistical learning is highly linked to language ability and that early auditory experience influences a more general learning mechanism that is critical for language development.

## *Statistical Learning and Language Skills*

Findings have consistently shown that implicit statistical learning is closely linked to language learning, including language processing (Altmann, 2002; Conway & Christiansen, 2005; Conway & Pisoni, 2008; Kirkham, Slemmer, Richardson, & Johnson, 2007; Kuhl, 2004; Pothos, 2007; Reber, 1967; Saffran, 2003; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997; Turk-Browne, Jungé, & Scholl, 2005; Ullman, 2004; Yim & Windsor, 2010), word learning (Graf Estes, Evans, Alibali, & Saffran, 2007; Mirman, Magnuson, Graf Estes, & Dixon, 2008), orthographic and phonotactic patterns (Chambers, Onishi, & Fisher, 2003; Pacton, Perruchet, Fayol, & Cleeremans, 2001), and syntax acquisition (Gomez & Gerken, 2000; Ullman, 2004). In addition, several studies have supported the importance of implicit statistical learning in language learning by providing evidence of the poor performance of children who have language and/or reading difficulties (Evans, Saffran, & Robe-Torres, 2009; Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Plante, Gomez, & Gerken, 2002; Tomblin, Mainela-Arnold, & Zhang, 2007; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003).

Recent findings indicate that the same neural mechanism serves for both syntactic processing of language and statistical learning of sequential patterns (Abla, Katahira, & Okanoya, 2008; Benasich et al., 2006; Christiansen, Conway, & Onnis, 2007). Christiansen et al. (2007) used event-related potential to investigate brain activity while adults performed a statistical learning task and a natural language reading task. In both tasks, ungrammatical information existed that resulted in a P600 effect in event-related potential. These results suggest that the same neural mechanisms are recruited in implicit statistical learning and the processing of complex, syntactic language information.

A direct link between language skills and implicit statistical learning has also been found in several other studies (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Evans et al., 2009; Yim & Windsor, 2010). Evans et al. (2009) used speech sounds and tones to examine whether children with and without specific language impairment (SLI) could track statistical probabilities among complex input and how this ability was related to their vocabulary knowledge. The children heard a 21-min nonsense speech stream, similar to that used in Saffran et al. (1997), and were asked to pay attention and answer questions later. After this training session, children were tested for their knowledge of word boundaries (e.g., children had to decide between words and nonwords based on previous exposure). The results showed that the typically developing group performed above chance (58%), whereas the group with SLI was at chance level (52%). Using a parallel paradigm with a 42-min tone sequence, results showed that as with the linguistic stimuli, the group of typically developing children, but not the group with SLI, were able to track statistical probabilities at a level above chance. The authors concluded that children with SLI have deficits in domain-general implicit learning because they showed poor performance with both speech and tone inputs. In addition, a significant correlation between receptive and expressive vocabularies and statistical learning accuracy in the speech stream was observed only in the typically developing children. There was no significant relationship for the group with SLI. One limitation of this study was, however, that the relation between nonlinguistic statistical learning and the children's vocabulary was not examined.

In the Conway et al. (2010) study, the direct relations between implicit statistical learning and language abilities was examined. Language abilities were measured based on word predictability in degraded listening conditions. Subjects were asked to write down the last word of a sentence under two conditions in which the target word was placed in either a semantically predictable or nonpredictable sentence. Their hypothesis was that under the degraded listening condition, participants should have used their long-term knowledge that had implicitly become accumulated for many years through linguistic exposure. The implicit statistical learning task was measured by how well participants remembered the rule-based visual sequences over non–rule-based sequences. Thus, participants were to immediately reproduce the pattern by touching the monitor. The results showed that adults were better on a language task in which the target word was placed in a high predictability sentence. The correlation results between implicit statistical learning and language scores were statistically significantly positive. Their findings support the view that implicit statistical learning is more closely related to language skills that have been accumulated over a long period.

In a similar way, Yim and Windsor (2010) investigated whether the statistical learning of nonlinguistic stimuli can predict language skills above and beyond contributing factors to language performance such as age, nonverbal IQ, and memory. Both children and adults were tested in this study, and their implicit statistical learning was assessed in two domains: auditory and visual. All of the stimuli were not namable, and subjects were exposed to complex sequences during training followed by a test session. To emphasize different aspects of language skills, language performance was measured in four different ways: (a) the ability to rapidly name common colors, shapes, and objects (rapid naming); (b) the ability to repeat nonwords accurately (nonword repetition); (c) the ability to accurately judge the grammaticality of a sentence; and (d) overall language performance as measured by a standardized test (Clinical Evaluation Language Fundamentals [CELF]; Semel, Wiig, & Secord, 2003). The results showed no difference between children and adults, and more important, nonlinguistic statistical learning ability significantly predicted language performance. However, there were important different tendencies in terms of the contribution of language skills between memory and nonlinguistic statistical learning. Implicit statistical learning significantly predicted language ability that emphasized complex semantic and grammatical knowledge learned over time (grammaticality judgment and CELF score) above and beyond age, nonverbal IQ, and memory skills. However, it was memory that significantly predicted language skills, which emphasize access and retrieval of less complex linguistic information (rapid naming and nonword repetition). These results were consistent with those of a previous study (Conway et al., 2010), in which implicit statistical learning was demonstrated to be highly related with long-term knowledge of language.

Literature on implicit statistical learning has examined mainly monolingual individuals whose real-world language learning consisted of only one language and, therefore, one statistical regularity. However, it is unknown (aside from the findings later discussed on simultaneous bilingual infants in Kovács & Mehler, 2009) if individuals who are systematically exposed to two structural regularities throughout their life proceed to a different performance level, allowing them to take advantage of the dual language context of their underlying learning mechanism.

Multiple language proficiency has become an increasingly valuable skill, and it may thus be useful to understand how individuals can learn two distinct sets of grammatical rules simultaneously. In real-world language learning, this can be accomplished with minimal confusion between the two linguistic structures, but the circumstances under which this can be possible in implicit statistical learning tasks performed in the laboratory is unclear (Perruchet & Pacton, 2006). Performing such a task successfully would require extracting two distinct structural regularities from a stimulus stream with sufficient specificity that they are not conflated; in other words, the learning must occur with a high degree of stimulus specificity. The stimulus specificity of implicit statistical learning is a topic of much debate when testing whether acquired knowledge consists of modality-dependent versus abstract representations (Altmann, Dienes, & Goode, 1995; Brooks & Vokey, 1991; Chang & Knowlton, 2004; Christiansen & Curtin, 1999; Conway & Christiansen, 2005, 2006; Manza & Reber, 1997; Mathews et al., 1989; Peña, Bonatti, Nespor, & Mehler, 2002; Perruchet, Tyler, Galland, & Peereman, 2004; Reber, 1989; Shanks, Johnstone, & Staggs, 1997; Tunney & Altmann, 2001). Several researchers (e.g., Conway & Christiansen, 2005, 2009; Saffran, 2003) have investigated modality constraints affecting implicit statistical learning across domains. To date, it has been found that when stimuli are presented simultaneously, visual implicit statistical learning is better than that of auditory, yet when the stimuli are presented sequentially, auditory statistical learning is better (Conway & Christiansen, 2005). Given these findings, it is proposed that speech may be more closely related to auditory statistical learning because the linguistic inputs are presented sequentially.

## *Implicit Learning of Two Statistical Regularities*

From a young age, bilinguals are exposed to two distinct linguistic systems, each of which has its own set of statistical information. Children implicitly monitor the linguistic input they receive for statistical probabilities, which guides them to make future choices about what is an acceptable construction in their language. One example of the monitoring of statistical information is found in word boundaries. For a bilingual child, syllable pairs that occur as highly probable word boundaries in the L1 may be less probable, or even entirely conflicting, in the L2. For example, in English, the syllable pair of /ti-be/, as in *pretty baby,* is unlikely to occur within a word, but it may very well be an acceptable within-word syllable transition in the child's L2. Given this potentially incongruent statistical information that is a consequence of learning two languages, one must consider whether bilingual children are capable of differentially monitoring the statistical probabilities of two distinct languages.

Recent evidence has suggested that under certain conditions, adult monolinguals are able to track statistics from two different languages. Weiss, Gerfen, and Mitchel (2009) passively exposed adult monolingual English speakers to two distinct artificial languages whose statistical word-boundary probabilities varied. When the voice of presentation for each language differed, monolinguals were able to accurately track separate statistical probabilities for each language. This is somewhat analogous to the classic *one parent–one language* system of bilingual language learning, wherein each parent speaks a different language to their child. When the two artificial languages were spoken by the same speaker, however, monolinguals were no longer able to track the statistics. It seems, then, that for children, perhaps only a one parent-one language system would result in the accurate monitoring of separate language statistics. However, children who are exposed to two languages are not commonly exposed in such a systematic way. It is more likely that both languages are used interchangeably regardless of context, resulting in a weakening of any pragmatic or supersegmental cue for statistical grouping. In order to maintain accurate, distinct statistical information, it may be that the statistical learning mechanism in bilingual children develops more strongly than in monolingual children.

Conway and Christiansen (2006) demonstrated that individuals may learn two artificial grammars simultaneously without confusing them if each grammar is presented in a different modality or perceptual dimension (e.g., one is instantiated as sequences of visual shapes, and the other as sequences of auditory tones). Participants in this study were exposed to one grammar that was presented in the auditory modality and another that was presented in the visual modality. After the exposure trial, subjects were tested using a dual crossover design, which allowed assessment of the simultaneous learning systems that occur independently of one another. The overall results showed that participants were able to learn two artificial grammars in two different modalities. Their conclusion was that our underlying learning systems operate independently of one another yet can allow us to learn two different sets of grammar simultaneously.

Kovács and Mehler (2009) presented intriguing results on bilingual infant flexibility in tracking multiple speech structures. Preverbal 12-month-old bilingual infants were tested and compared with their monolingual peers. Infants listened to trisyllabic speech stimuli (e.g., AAB structure or ABA structure). An eye-tracking method was used to examine whether the bilingual infants were better at simultaneously learning multiple structures than were monolinguals. Findings showed that bilingual infants were able to learn two structures within the same time frame, whereas monolingual infants could learn only one structure. The authors concluded that bilingual infants are more flexible at learning two structures simultaneously, which may relate to their ability to avoid interference between the two structures.

These previous studies (Conway & Christiansen, 2006; Kovács & Mehler, 2009; Weiss et al., 2009) all suggested that individuals can simultaneously learn two languages in real life.

## *Influential Factors for Statistical Learning in Bilinguals*

Many different factors can drive implicit statistical learning, and especially when considering the differences between participants in the current study, experience, attention, and age are the three key factors that need to be highlighted.

Bilingual children experience different number of languages in diverse situations with various functional needs. An important role of experience in mediating the statistical learning mechanism has been reported (Saffran et al., 1997). This study investigated pattern learning in children age 6–7 years old as well as in undergraduate students. Participants were asked to carefully listen to continuous speech sounds in order to answer questions afterwards. While participants were in the training session, they were told to color pictures. After the training session, participants had to differentiate words from nonwords on the basis of the speech stream they had heard. As in their previous study (Saffran et al., 1996), words were formed from the exact same sound combinations that were represented in the speech stream (e.g., *babupu*). Nonwords were different combinations of sounds that were present in the speech stream but that did not appear consecutively (e.g., *batipa*). In the second experiment of the same study, another set of participants (again children age 6–7 years and undergraduate students) completed the same training session. However, these participants were exposed to the same training stimuli once more on the following day. Results showed that participants performed significantly better with greater exposure.

Similar results were found in a study by Lany and Gomez (2008), in which 12-month-old infants who were passively exposed to artificial languages were able to learn the probabilities of adjacent dependencies, and this experience enhanced their ability to learn nonadjacent dependencies as well, which is a skill that normally does not develop until 15 months. This suggests that early experience in tracking statistical information can result in developmental enhancements and the generalization of statistical learning ability to novel conditions. One could argue that because bilingual children must track two sets of statistics from a young age, they have more experience in tracking statistical information, and this may help them to develop a stronger statistical learning mechanism due to experience.

The second key factor is attention, which may positively influence bilinguals' implicit statistical learning. Attentional resources may also indirectly contribute to the enhancement of statistical learning abilities in bilingual children. Bilinguals have been shown to possess enhanced attentional abilities, such as inhibitory control (Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010; Martin-Rhee & Bialystok, 2008). The development of a more fine-tuned attentional system in bilinguals is often considered to be due to the experience of continued inhibition of the unused language. Attention is important for statistical learning tasks, as they require the ability to passively attend to relevant features of the stimuli (Turk-Browne et al., 2005), and depleted attentional resources can disrupt statistical learning (Toro, Sinnett, & Soto-Faraco, 2005).

One last important factor is age, which is relevant in both monolingual and bilingual children. It is of interest to many researchers whether implicit statistical learning is age invariant or not (Don, Schellenberg, Reber, DiGirolamo, & Wang, 2003; Meulemans, Van der Linden, & Perruchet, 1998; Reber & Kotovsky, 1997; Saffran et al., 1997; Thomas et al., 2004; Vinter & Perruchet, 2000). Some have argued that implicit learning is not influenced by age, whereas others have suggested that age is an important factor in explaining implicit statistical learning. Thus, in the current study, age was entered as one of the variables for predicting implicit statistical learning.

The question remains as to whether children who are raised with two languages develop more robust statistical learning mechanisms due to receiving dual-language input. The depth and amount of experience bilingual children have with tracking statistical probabilities for multiple languages, coupled with the effects of their prior experience of generalization of statistical dependencies, may affect their statistical learning abilities. Furthermore, the enhanced attentional resources of bilingual children in the face of a statistical learning mechanism that depends on attentional ability also suggests that bilingualism may affect statistical learning. Taken together, these studies provide reason to believe that bilingual children may have an enhanced statistical learning mechanism.

As mentioned above, previous studies (Conway et al., 2010; Evans et al., 2009; Yim & Windsor, 2010) have found a direct correlation between language skills (e.g., long-term knowledge accrued through exposure to language) and implicit statistical learning. The current study considers whether these results can be replicated and expanded to bilingual children, a group not tested in previous studies.

Bilingual children's language knowledge is distributed across languages (Conboy & Thal, 2006; Kan & Kohnert, 2005; Kohnert, 2010; Kohnert, Bates, & Hernandez, 1999; Pearson & Fernández, 1994; Pearson, Fernández, & Oller, 1993; Umbel, Pearson, Fernández, & Oller, 1992). Thus, to assess bilinguals' language skills, both languages should be measured. One of the main practical issues in assessing bilinguals' language skills relates to whether standardized tests are accurate and unbiased measures (Kohnert & Madina, 2009). To date, findings have supported the view that standardized measurements are biased toward previous world knowledge and are thus influenced by prior language experience (Campbell, Dollaghan, Needleman, & Janosky, 1997). However, this is a debate more relevant to work identifying practical language impairment in bilingual populations. For the current study, we used a standardized test that measures overall language skills (CELF; Semel et al., 2003; Wiig, Semel, & Secord, 2006). There are three rationales for using this standardized test. First, based on previous findings, language skills, especially with regard to linguistic knowledge accumulated over the long term, are more closely related to implicit statistical learning. Thus, it may make more sense to use a standardized test in context. Second, in previous studies (Conway et al., 2010; Yim & Windsor, 2010), CELF scores were significantly correlated with nonlinguistic statistical learning. In this study, we examined whether language skills significantly predict implicit statistical learning and investigate whether these findings will be verified for both monolinguals and bilinguals. Last, in order to measure both languages, specifically English and Spanish, it is necessary to use a similar tasks across the two languages that measures overall language performance. The CELF—English (CELF–E; Semel et al., 2003) and CELF—Spanish (CELF–S; Wiig et al., 2006) versions can be used for this purpose.

In summary, although a limited number of studies have extended implicit statistical learning paradigms to bilingual children, this is—to the best of our knowledge—the first study to investigate implicit statistical learning in bilingual children compared with monolingual children. This study examined how language experience can influence the underlying learning mechanism involved by assessing bilingual children's performance compared with that of monolinguals. In addition, the direct relation between language skills and implicit statistical learning was explored. Implicit statistical learning was investigated in both visual and auditory domains using nonlinguistic stimuli. First, we hypothesized that bilinguals' life experience with linguistic systematizing will influence their implicit statistical learning. However, there may not be a difference between the two groups because the implicit statistical learning in this study does not require any suppression of interfering rules in order to activate the target behavior. In addition, bilingual children in the most relatable previous study (Kovács & Mehler, 2009) were infants and simultaneous bilinguals, which differs from the current study. Thus, our results may differ from the findings of this earlier work. Second, both age and language skills were entered as predictors for explaining implicit statistical learning. If age is invariant in explaining implicit statistical learning, then there would be no significant variance when predicting implicit statistical learning with age. However, if age is a critical factor in implicit statistical learning, then age would be found as a significant predictor. Second, we hypothesized that there may be a different pattern across groups in explaining implicit statistical learning due to their prior linguistic experience difference. Last, modality constraints may appear in predicting visual versus auditory statistical learning with language skills based on previous findings that the auditory modality is better suited when inputs are sequentially presented (Saffran, 2003; Sherrick & Cholewiak, 1986). Thus, this modality constraint supports the idea of a stronger correlation between the auditory modality and language skills. However, other previous studies (Conway et al., 2010; Yim & Windsor, 2010) found a close relationship between visual statistical learning and language skills. Thus, we thought it possible to find similar results.

# Method

## Participants

Research fliers were posted around the Northwestern University campus area to recruit participants, and parents voluntarily contacted the research lab. Thus, both monolingual and bilingual children who were interested in the study came to the lab and were tested on experimental tasks over two sessions, which lasted for 3 hr in total. If the child was first assessed in the English version of the language test, then the Spanish version was used in the following session. Experimental tasks were also counterbalanced for auditory and visual tasks. Consequently, half of the participants performed visual statistical learning first, and the other half participated in the auditory statistical learning first. Parental reports were given to confirm children's normal language development. Children with known medical conditions likely to impede the development of auditory and spoken language were excluded (e.g., diagnoses of pervasive developmental delay). As a result, all children were reported as within the normal range in their cognitive and linguistic development. In addition, all children passed a hearing screening (pure tones presented at 25 dB at 1, 2, and 4 KHz). The monolingual children had spoken English as their native language since birth and had not been exposed to languages other than English. Bilingual children had spoken Spanish from birth at home and were exposed to English at school from the age of 3 years onward. Thus, all of our bilingual children were sequential bilinguals who used Spanish at home and English at school (Kohnert, 2010).

A total of 112 children (63 monolinguals and 49 bilinguals) participated in the study. Age was comparable across groups: the mean age for monolingual children was 102 months ($SD$ = 28), ranging from 5;1 to 13;2 (years; months). Bilingual children had a mean age of 98 months ($SD$ = 29) ranging from 5;0 to 13;8. The Leiter International Performance Scale—Revised (Leiter–R; Roid & Miller, 2002) was used to measure nonverbal IQ. There was no difference between the two groups (monolingual: $M$ = 110, $SD$ = 13; bilingual: $M$ = 104, $SD$ = 14). However, CELF–E test (Semel et al., 2003) scores were significantly lower for bilingual subjects: monolingual, $M$ = 112, $SD$ = 14; bilingual, $M$ = 96, $SD$ = 18; $t(97) = 4.8$, $p < .001$. The mean CELF–S test (Wiig et al., 2006) score was 96 ($SD$ = 16). Table 1 summarizes the descriptive statistics of the two groups.

## Stimuli

*Visual materials*. A total of 33 simple, non-namable shapes from three different categories were initially used. These included nine shapes adapted from Fiser and Aslin (2002), 10 shapes from a study by Gauthier, James, Curby, and Tarr (2003); eight black-and-white multi-angle shapes from a mental rotation task (Windsor, Kohnert, Loxtercamp, & Kan, 2008), and six Japanese hiragana. All shapes were the same size, 6.85° × 6.85° (visual angle degree), and were shown in black on a white background. To identify these final 33 shapes, pilot testing was carried out with 40 undergraduate students who viewed a larger set of 63 shapes from the same categories. These participants were asked to name the shapes if they were able to do so. Each shape was presented for 6 s, and there was a 3-s interval between shapes. The 33 shapes that were named by fewer than four participants were initially selected as the experimental stimuli. This procedure enabled the principle investigator to control linguistic mediation and strictly select nonlinguistic stimuli for the project. Among these 33 shapes, nine that were not named by any of the students were used for visual statistical learning. Figure 1 shows the final nine shapes used for the visual statistical learning test.

**Table 1.** Means (*SD*s) for monolingual and bilingual children on age, nonverbal IQ, and standardized language tests.

| Group | Age (mos) | Nonverbal IQ—LEITER | Standardized language | |
|---|---|---|---|---|
| | | | CELF–E | CELF–S |
| Monolinguals | 102 (28) | 110 (13) | 112 (14) | |
| Bilinguals | 98 (29) | 104 (14) | 96 (18) | 96 (16) |

*Note.* Nonverbal IQ scores are represented in standard score; language scores are represented with raw scores. LEITER = Leiter International Performance Scale—Revised; CELF–E = Clinical Evaluation of Language Fundamentals—English; CELF–S = Clinical Evaluation of Language Fundamentals—Spanish.

**Figure 1.** The nine non-namable visual shapes used in the visual statistical learning task. A total of 33 simple, non-nameable shapes from three different categories were initially used. All shapes were the same size, 6.85° × 6.85° (visual angle degree), and were shown in black on a white background. A pilot testing was carried out with 40 undergraduate students who were asked to name the shapes if they were able to do so. Each shape was presented for 6 s, and there was a 3-s interval between shapes. Among these 33 shapes, nine that were not named by any of the students were used for visual statistical learning. This procedure enabled the principal investigator to control linguistic mediation and strictly select nonlinguistic stimuli for the project. These are the final nine shapes used for the visual statistical learning test.

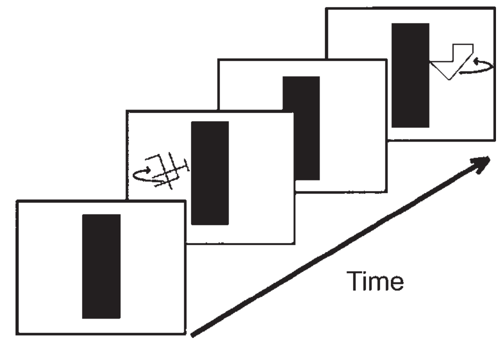
*Auditory materials*. It was important to control for the possibility of linguistic mediation. Novel auditory stimuli that contained no phonetic content were used. Nine pure-tone sounds were generated by Cool Edit Pro (Syntrillium, 1998). These tones were chosen because they were not namable and could not be matched to musical notes, which can be linguistically labeled. Two adults listened to 12 pure tones, and if one or both of the listeners could match the sound to a musical note, then the stimuli were eliminated. As a result, three tones were excluded, and nine were left. Each tone was 330 ms in duration, with frequencies of 330 Hz, 349 Hz, 370 Hz, 392 Hz, 440 Hz, 466 Hz, 494 Hz, 523 Hz, and 554 Hz. All sound files were digitized at 22.05 kHz, with 16-bit quantization. In order to make sure the sounds were perceptually distinct, two untrained listeners were presented with sound pairs and identified whether the two sounds were same or different. All nine sounds were reported to be different from one another.

## Procedure

*Visual statistical learning*. In the training session, participants looked at a series of visual stimuli. A continuously looped 4.5-min movie of a sequence of shapes was generated on an IBM laptop computer with MATLAB, using the Psychophysical Toolbox (Brainard, 1997; Pelli, 1997). A 7.8° (degree of visual angle) wide by 18.0° long, static, black vertical bar was positioned in the middle of the 14-in. monitor. A single shape moved continuously in a horizontal manner from behind the vertical black bar to the left edge of the screen, and then back toward the bar. The shape then moved along the midline of the screen. This was followed by a second, different shape that appeared on the other side of the bar. It took 1.3 s (see Yim & Windsor, 2010, for the reason for using 1.3 s) for a shape to change to another shape. An example of this shape movement is shown in Figure 2. The sequence of shapes followed a semirandom order. Each shape appeared an equal number of times during the shape sequence. The three base triplets can be referred to as A-B-C, D-E-F, and G-H-I (see Figure 1). If A-B-C is a base triplet, then whenever A appeared on the screen, B came next, followed by C. After C, the first shape from one of the three other triplets (chosen at random) appeared next. This rule repeated throughout the 4.5-min continuous stream of shapes.

Participants were advised of how this would appear on screen and were asked to press a button once they thought a shape was fully visible. They were told that they would see their final score and speed at the end of the training, which was described to them as a game. They were given an opportunity to ask questions, instructed not to speak during the procedure, and told that questions would be asked of them afterward. After this, participants were shown two sets of three shapes and were asked to press a button to indicate the triplet set that looked familiar, on the basis of what they had seen in the training session. In past research, 24 test pair sets were made, in which one of the pairs was a base triplet and one was an impossible triplet (i.e., a triplet that did not occur in the training movie). Each test pair appeared in the same way as in the movie; a shape came out from the vertical black bar in the middle, traveled to the left edge of the screen, and then moved back toward the bar. Then the shape changed to a different form when it reappeared on the other side of the bar. The dependent variable was the

**Figure 2.** Graphical representation of the visual sequence in the visual statistical learning task. Each shape came out from the black bar in the middle of the computer screen. The shape was shown for 1.3 s and disappeared. Then the next shape came out from the bar for the same amount of time. The sequence of shapes followed a semirandom order. Each shape appeared an equal number of times during the shape sequence. The three base triplets can be referred to as A-B-C, D-E-F, and G-H-I. If A-B-C is a base triplet, then whenever A appeared on the screen, B came next, followed by C. After C, the first shape from one of the three other triplets (chosen at random) appeared next. This 4.5-min sequence was played during the training session and then was used similarly in the test session.



percentage accuracy in identifying the 24 base triplets. This task was designed to measure participants' ability to implicitly learn a pattern among streams of shapes.

*Auditory statistical learning*. Nine pure-tone sounds were generated by Praat software. Each tone was 330 ms in duration. Three base triplets were used to make approximately 3.37 min of continuously streaming sounds in a semirandom order, following the same rule as for the visual stimuli. Training and the test sessions followed the same procedure as that for the visual pattern learning task. The dependent variable was the percentage accuracy in identifying the 24 base triplets. This task was designed to measure participants' ability to implicitly learn a pattern among streams of tones.

### Test Preparation

We wanted to ensure that certain test triplets were not judged as more familiar than others. Therefore, we arranged the test so that a monolingual control group that did not participate in the main study watched the visual statistical testing triplets and listened to auditory testing triplets without being exposed to the training session. Five children were asked to press the button that looked or sounded more familiar. The overall performance on visual was 49.4%, which was not significantly different from 50% ($p$ = .53) and on auditory was 48.4%, which, again, was not significantly different from 50% ($p$ = .18) without being exposed to the training session. On the basis of these results, we assumed that there was no artifact in the design of the stimuli that would drive children's performance in a certain direction.

## Results

To address the concern of a potential practice effect across modalities, we calculated accuracy separately for visual and auditory statistical learning, depending on the order of presentation involved. Monolingual participants who took part in the visual statistical learning first had equivalent accuracy on that task compared with those who took part in the auditory statistical learning first ($M$: 55.7% vs. 56.3%), $F(2, 41) = 0.010$, $p = .92$. There also was no order disadvantage for those who had taken part in this task without having first completed the visual statistical learning ($M$: 59.9% vs. 57.3%), $F(1, 52) = 0.225$, $p = .64$. In a similar way, the bilingual participants who took part in the visual statistical learning first had equivalent accuracy to those who first took part in auditory statistical learning ($M$: 56.2% vs. 53.1%), $F(1, 29) = 0.304$, $p = .59$. There also was no order disadvantage when this was reversed ($M$: 56.1% vs. 58.0%), $F(1, 44) = 0.212$, $p = .65$.

A $t$ test was carried out to examine whether children could learn statistical rules above the chance level of 50%. Children did show evidence of implicit statistical learning in the visual and auditory domains. In the test session, they successfully chose the sequence that had occurred in the statistical learning phase more than 50% of the time. On the visual statistical learning task, monolingual children scored 56% ($SD$ = 18.9%), which was statistically different from 50%, $t(42) = 2.1$, $p = .04$, whereas bilingual children had a mean of 56.8% ($SD$ = 16%), which was again statistically different from 50%, $t(33) = 2.4$, $p = .02$. On the auditory statistical learning task, monolingual children had a mean of 58.1% ($SD$ = 13.4%), which was statistically different from 50%, $t(53) = 4.5$, $p < .001$. Bilingual children had a mean of 56.9% ($SD$ = 13.8%), which was statistically different from 50%, $t(48) = 3.4$, $p < .001$. Overall, all participants were able to implicitly learn statistical regularities when they were exposed to visual and auditory streams of stimuli.

Our first research question was to examine whether bilingual children would outperform monolingual children on implicit statistical learning. A separate univariate analysis of variance was used to compare group differences in the two domains. Table 2 shows the mean and $SD$ of both groups for the visual and auditory statistical learning tasks. On the visual task, there was no statistical difference between groups, $F(1, 75) = 0.037$, $p = .85$, with monolingual children having a mean of 56% ($SD$ = 18.9%) and bilingual children a mean of 56.8% ($SD$ = 16.0%). In addition, there was no difference by group for the auditory statistical learning task, $F(1, 101) = 0.239$, $p = .63$. Here, monolinguals had a mean of 58.2% ($SD$ = 13.4%), and bilinguals had a mean of 56.9 ($SD$ = 13.8%). Thus, there was no group difference in implicit statistical learning in both domains.

The second research question was determining how much of the variance in children's implicit statistical learning could be explained by age and language skills. Thus, stepwise multiple regression analysis was conducted for the two separate groups on the two different tasks. First, their age and CELF–E scores were entered into the regression model for monolinguals. The full regression model accounted for 22% of the variance in auditory statistical learning. Age was a significant predictor

**Table 2.** Mean ($SD$) percent accuracy of monolingual and bilingual children on the visual and auditory statistical learning tasks.

| Group | Visual statistical learning (%) | Auditory statistical learning (%) |
|---|---|---|
| Monolinguals | 56.0 (18.9) | 58.2 (13.4) |
| Bilinguals | 56.8 (16.0) | 56.9 (13.8) |

*Note.* There were no statistically significant differences between the two groups on either visual or auditory statistical learning.

of monolinguals' auditory statistical learning, $\beta = .36$, $t = 2.7$, $p = .008$, accounting for 13.1% of the variance in auditory statistical learning. The CELF–E was another significant predictor of monolinguals' auditory statistical learning, $\beta = .29$, $t = 2.3$, $p = .002$, accounting for 9% of variance. For the visual statistical learning, only age was statistically significant, accounting for 20% of the variance, $\beta = .45$, $t = 3.1$, $p = .004$.

For the bilingual group, not only age and CELF–E scores but also CELF–S scores were entered into the regression model. The full regression model accounted for 13.1% of the variance in auditory statistical learning. Age was the only predictor that statistically significantly explained the variance, $\beta = .36$, $t = 2.3$, $p = .02$. However, CELF–E was a significant predictor for bilinguals' visual statistical learning, $\beta = -.39$, $t = -2.3$, $p = .02$, accounting for 15.2% of the variance.

Considering this negative correlation between predicting visual statistical learning and CELF–E, we examined whether there were any outliers within bilingual children. First, three data points were observed as a source for driving the negative correlation when a scatter plot was created between visual statistical learning and CELF–E scores. Second, a box plot, histogram, and stem-and-leaf plot were used to identify outliers, using SPSS Version 19.0 for Windows. The results revealed that the same three children observed from the scatter plot were found to be outliers. These children had relatively low CELF–E scores compared with their age-group peers. Specifically, Subject 67 was 10;6 years of age and scored 67, whereas peer scores ranged from 83 to 133; Subject 68 was 9;9 and scored 50, with peer scores from 87 to 121; and finally, Subject 85 was 13;9 and scored 79, but peer scores ranged from 96 to 109. Thus, when these three outliers were excluded, the stepwise regression model was reanalyzed. However, neither age nor CELF–E explained the variance for visual statistical learning. The power for this regression analysis was 62%, with observed $R^2$ of .068, $p = .598$, and $n = 31$.

## Discussion

Our experiments comprised a controlled examination of linguistic experience on implicit statistical learning in two domains; that is, in visual and auditory modalities. We also explored whether age and language skills can predict implicit statistical learning in nonlinguistic domains.

The first important finding is that there was no statistically significant difference between monolingual children and bilingual children. We hypothesized that the lifetime exposure to two different sets of linguistic rules might have had an influence on implicit statistical learning. However, we did not find any group difference in either domain. There are four possible reasons for this. First, participants had to learn one single rule rather than two statistical rules simultaneously. This experimental design may have left no room for bilinguals to show an advantage over monolinguals. Second, our assumption of outperformance by bilinguals was based on the hypothesis that attention is closely related to implicit statistical learning. Thus, we proposed that bilinguals, who are known to have better attention, might outperform monolinguals. However, as shown in previous studies (Hernández et al., 2010; Martin-Rhee & Bialystok, 2008), bilingual children are better at certain types of attention that require interference suppression. Thus, as Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002) suggested, bilinguals are specifically better at interference suppression, not response inhibition. It can be argued that during our learning and testing paradigm, children were required to use their full attention and needed to use response inhibition because two-alternative forced choice was the testing method. However, there was no specific study paradigm that directly tapped interference suppression. This may be the reason why we did not observe superior performance by bilinguals in implicit statistical learning. Third, our bilingual group comprised sequential bilingual children who acquired their first language up until the age of 3 years and subsequently learned a second language. Thus, their underlying learning mechanism might have been different from simultaneous bilinguals, which may be the reason why we could not find the bilingual advantage reported in Kovács and Mehler (2009). We hypothesized that bilingual children's different linguistic experience and attention level, as compared with monolingual children's, would accelerate their performance on implicit statistical learning. However, it may be that our sequential bilingual children's experience and attention might not have been as accessible or useful in the task context, leading to unexpected results. Fourth, it can be argued that the implicit statistical learning mechanism is sensitive to the dimension of integrity of the language-processing system but not to the number of languages available to the child for processing. If a child can effectively use input from the environment to learn important information, we consider this child to have an intact processing system (Windsor & Kohnert, 2004). Studies have shown evidence that implicit statistical learning is important in language learning (Evans et al., 2009; Howard et al., 2006; Menghini et al., 2006; Plante et al., 2002; Tomblin et al., 2007; Vicari et al., 2003) and that there may be an interaction between these two constructs when testing children with reading and language difficulties (e.g., children with CI, children with dyslexia, and children with specific language impairment). It is well documented that when there is some breach in the internal learning mechanism, as represented by language performance, implicit statistical learning is in the lower end of normal variation (Evans et al., 2009). However, participants in our study were typically developing children who lay within the middle or even higher end of normal variation. Their systematic exposure to two different linguistic rules did not appear to affect their underlying learning mechanism. Thus, unless individuals have some breach in their underlying learning mechanism, implicit statistical learning performance might not be different based solely on linguistic experience. Future studies could address this issue by testing simultaneous bilinguals compared with sequential bilinguals to examine differences in implicit statistical learning.

The second important finding is that monolinguals and bilinguals showed a different pattern in terms of predicting auditory and visual statistical learning with age and language skills. In the monolingual group, both age and CELF-E scores significantly predicted auditory statistical learning. These findings are in line with those from previous studies (Conway et al., 2010; Evans et al., 2009; Yim & Windsor, 2010) and confirmed two facts. First, age is an important variable in the performance of implicit statistical learning; older children performed better on implicit learning ability in our study than their younger counterparts. However, whether implicit learning is age invariant or not remains an unresolved issue that needs to be thoroughly explored (Meulemans et al., 1998; Saffran et al., 1997; Thomas et al., 2004; Vinter & Perruchet, 2000). Second, as expected, language skills as measured by the CELF–E statistically significantly explained the variance in auditory statistical learning. Studies have consistently found a close relationship between language performance and nonlinguistic statistical learning in the auditory domain (Abla et al., 2008; Gomez & Gerken, 2000; Graf Estes et al., 2007; Kuhl, 2004; Mirman et al., 2008). In addition, given that modality constraints affect implicit statistical learning across domains (Conway & Christiansen, 2009; Saffran, 2003; Sherrick & Cholewiak, 1986), we expected to find a positive relationship between language skills and auditory statistical learning. The auditory modality is known to better be suited for sequential input (Conway & Christiansen, 2009; Sherrick & Cholewiak, 1986), and visual modality appears to have an advantage in the processing of spatial input (Friedes, 1974). Conway and Christiansen (2009) found that participants could extract statistical patterns better when the visual information was given within a spatial format and when auditory information was presented in a temporal fashion. This may explain why we found significance in predicting auditory statistical learning with language skills. That is, language is learned mainly via a sequential input of listening to rapid speech; thus, learning language requires temporal processing. However, different from previous studies (Conway et al., 2010; Yim & Windsor, 2010), language skills in the current study did not explain any variance in visual statistical learning in monolinguals. A significant positive correlation between language skills and visual statistical learning was found in previous studies. The only salient difference between previous studies and the current study is that participants in previous studies were adults. In Conway et al. (2010), the study population comprised college students, and in Yim and Windsor (2010), both children and adults were combined for regression analysis. Given that age is an important factor in implicit statistical learning, there may be a different tendency between adults and children. Adults are assumed to possess well-developed and stable language and cognitive systems, whereas children are still learning and developing their total learning system. Thus, a direct comparison between children and adults in predicting implicit statistical learning with language skills is warranted in future study.

In the bilingual group, auditory statistical learning was predicted only by age, different from the monolingual group results. As outlined above, bilingual language skills are distributed across two languages (Kohnert et al., 1999), and it is difficult to capture a full picture of these skills with standardized tests (Kohnert & Madina, 2009). Thus, researchers recommend developing and using processing-dependent measures (e.g., nonword repetition, rapid naming) that are less influenced by previous world knowledge (Campbell et al., 1997; Dollaghan & Campbell, 1998; Paradis & Crago, 2000). Previous studies have found that an implicit learning task did not correlate with any linguistic task but rather with a language processing task, which required knowledge of the predictability of items in a sequence, such as a sentence perception task with high word predictability (Conway et al., 2010). Thus, future studies should consider measuring language performance not only via standardized tests, but also through tasks that tap processing linguistic information so as to enable accurate evaluation of monolinguals and bilinguals. Next, qualitative analysis for documenting dominance and/or proficiency of each language, or the amount of usage of each language, could have been a better predictor for this group. We expected to find an influence of linguistic experience on statistical learning. Thus, information about how children use their language in real-life situations, which can be obtained from parental and teacher reporting, may be useful.

Finally, there was no significant predictor for visual statistical learning in bilingual children. For this regression analysis, we computed post hoc achieved power, and it was 62%, which was low. Thus, one reason for the nonsignificant finding could be the smaller sample size of bilingual children. Compared with monolingual children ($n$ = 43), there were relatively fewer children due to missing cells ($n$ = 31) for visual statistical learning analysis. However, the sample size might not be the only reason for interpreting these results. In the monolingual group, age was a significant predictor for visual statistical learning. However, this was not true for bilinguals in our study. The hallmark of bilinguals is variability (Kohnert, 2010); the interaction between biological factors and experience in bilingual children is dynamic. Thus, we may not be able to explain their performance solely by the conventional means that may be relevant to monolingual children. As noted earlier, a potentially fruitful method might have been to document duration of exposure to their second language or relative usage of their two languages in real life. These qualitative data might have had greater predictive power than age in bilingual children.

In summary, this study presents empirical evidence that linguistic experience does not implicitly influence the learning of one statistical regularity and that auditory implicit learning strongly correlates with language performance. These results are important because knowledge about the underlying learning mechanism involved in language processing is critical in understanding language development and breakdown, as well as to developing accurate assessments for children, especially those from linguistically diverse backgrounds.

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