Exploring the source of enhanced statistical learning in bilinguals

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Contents

Abstract

Finding how experience influences basic cognitive abilities is a central quest in cognitive science. As all languages exhibit statistical structure, but in language-specific ways, bilinguals must learn and joggle different sets of statistical regularities all the time. The protracted experience of learning and using two languages in life has been claimed to improve executive functions. Here we asked whether individual patterns of bilingual experiences predict another core human ability, the implicit extraction of complex patterns of statistical regularities. In two experiments, we found that degree of bilingualism modulates auditory statistical learning (ASL) but not visual statistical learning (VSL). These results reveal important modality-specific effects of the relationship between bilingual experience and human learning abilities in adulthood.

Introduction

Our environment consists of regular occurrences of complex sounds, visual scenes, and events. Individuals across all ages and linguistic backgrounds become adept at discovering the regularities inherently embedded in the environment. This particular ability to unconsciously identify and acquire the statistical information is referred to as statistical learning (SL). Using an array of tasks and looking at participants coming from different backgrounds, previous studies have shown that SL plays an important role in language acquisition process (Conway & Pisoni, 2008; Fiser & Aslin, 2002; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999).

Individuals' performance in a SL task can depend on both the nature of the task and the ability of the learner (Bartolotti, Marian, Schroeder, & Shook, 2011; Conway & Christiansen, 2005; Emberson, Conway, & Christiansen, 2011; Frost, Armstrong, Siegelman, & Christiansen, 2015; Palmer & Mattys, 2016; Siegelman & Frost, 2015). For instance, in Bartolotti et al. (2011), participants were presented with a Morse code language in two different conditions, the low interference condition (two non-conflicting cues to word boundaries) and the high interference condition (two conflicting cues to word boundaries: transitional probabilities and pauses between words). The results suggest that the bilingual experience can improve SL ability only when the interference is low. When there is high interference, there is no significant difference found between the bilingual and the monolingual.

The modality of the input is also found to have significant influence on SL performance. Conway and Christiansen (2005) examined participants' performance in an artificial grammar learning (AGL) task across three modalities: visual, auditory and tactile. Their results showed that participants successfully learned the statistical regularities across all modalities, however, they learned better when the stimuli were presented in the auditory modality. The different performance of SL in different modalities indicates that SL ability - potentially a domain-general ability - can be subjected to modality- and stimulus-specific constraints.

Even though SL is a universal cognitive ability (Perruchet & Pacton, 2006), there also exist individual differences. According to Siegelman and Frost (2015), these can stem from two main sources of variance: efficiency in encoding representations within a given modality and efficiency in computing the statistical regularities of the stimuli. Performance on SL tasks is relatively stable over time, suggesting that individual differences in SL ability are not random (Arciuli & Simpson, 2012; Siegelman & Frost, 2015). In fact, a growing consensus points to individual differences in SL as the result of both an individual ability and their life experience trajectories.

Recently, researchers have been interested in how life experiences such as growing up in a bilingual environment could affect one's SL ability. Evidence for a putative bilingual advantage in SL has been found across an array of tasks. For instance, Wang and Saffran (2014) found a bilingual advantage in an artificial tone SL task. Escudero, Mulak, Fu, and Singh (2016) more recently found a bilingual advantage in a cross-situational word learning task. To date, there has been considerable attention paid to the investigation of the source and mechanism of the bilingual advantage in SL. It was proposed that the advantage observed could potentially stem from a general improvement in control system (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Rodriguez-Fornells et al., 2005) or a specific improved phonological working memory (Adesope, Lavin, Thompson, & Ungerleider, 2010; Majerus, Poncelet, Van der Linden, & Weekes, 2008) which in turn possibly linked to an improved implicit learning ability (Misyak & Christiansen, 2007) In another word-learning task by Bartolotti et al. (2011), bilingual experience was shown to improve SL in a word segmentation task, but limited to a low-interference condition where there were no conflicting cues to the transitional probabilities between words. In a high-interference condition, only inhibitory control and not bilingual experience improved the performance of the participants.

A recent study by Onnis, Chun, and Lou-Magnuson (2017) took a similar approach to the previous studies, but instead of dichotomizing bilingualism, they treated it as a continuous variable - consistent with the graded nature of bilingualism found in Singapore, the country where the experiment took place. Among Singaporeans, proficiency and dominance vary considerably depending on personal life experiences. Onnis et al. (2017) showed that degree of bilingualism predicted learning scores in a dual-grammar task similar to Conway and Christiansen (2005). One limitation of the study, as mentioned by the authors, was that the design of the study did not allow to assess whether the bilingual advantage is modality-specific or modality-general. This because the artificial grammar was instantiated with multimodal stimuli composed of visual objects coupled with pseudowords. Establishing the locus of transfer (near or far) for any putative experiential effects on cognition is of theoretical importance, and thus, the first aim of the current study is to establish whether a bilingual advantage for SL is modality-specific or modality-general.

In a recent study, Potter, Wang, and Saffran (2017) investigated the possible link between second language learning and SL performance in domain-relevant (tonal language) and domain-general (visual) tasks. They found that a group of participants who had no previous knowledge of a tonal language but learned Mandarin for 6 months improved significantly in a tonal artificial language task as compared to a control no-training group. Concurrently, the two groups showed no difference in improvement on a visual grammar learning task. The authors further argue that exposure to a tonal language alone is unlikely to account for their pattern of results as in a similar tonal artificial language task in Wang and Saffran (2014), native Mandarin speakers, with life-long exposure to a tonal language (Mandarin), were found to perform worse than the non-tonal bilinguals. In fact, this result could suggest that having a prior exposure to a tonal language could be a kind of interference to learning a new tonal (artificial) language. It is thus possible that the advantage observed in the tonal artificial language task stemmed from the process of learning a second language and not from the characteristic of the second language. The result of specific improvement in the domain-specific (tonal) task suggests that bilingual experience may help improve bilinguals' sensitivity to the linguistic regularities within the relevant domain only. However, the "bilingual group" in Potter et al. (2017)'s study included individuals who only learned a second language for a limited time of two semesters. As raised by the authors, it is possible that the domain-general benefit may take longer to develop, leading to no significant improvement of the participants in the visual SL task. To date, there exists no concrete evidence that a bilingual advantage is modality-specific or modality-general.

Another limitation of Onnis et al. (2017)'s study is that it was not possible to establish whether individual differences in artificial language learning could be better explained by other cognitive abilities such as executive functions, rather than the language dominance measure. According to Bartolotti et al. (2011), SL ability, specifically the ability to segment novel words from speech, is influenced by both bilingual experience and cognitive functioning. Therefore, in this study, participants' cognitive functioning are included, in addition to the degree of bilingualism, as another predictors of the participants' performance in our AGL task.

Hypothesis: The bilingual advantage for statistical learning is constrained by modality. The degree of bilingualism will only be associated with the statistical learning ability of the participants in the auditory modality.

To test the hypotheses, a total of 91 participants were recruited for two separate experiments. In both experiments, participants were trained with a dual-grammar task - a SL task that was adapted to resemble the natural language environment of the bilinguals, where they had to learn two statistical regularities (two artificial grammars) simultaneously; as compared to a single-grammar AGL task, the dual-grammar task is believed to provide more room for the bilingual advantage to be observed (Onnis et al., 2017; Yim & Rudoy, 2013). In experiment 1, the stimuli were presented via sets of auditory psdeuo-words. In experiment 2, the same SL task was given to the participants, however, the stimuli were presented via sets of visual pseudo-shapes. Besides the participants' degree of bilingualism (elaborated more in Method), two executive function measures which were non-linguistics inhibitory control and intelligence were also included as the predictors for participants' performance in the SL task.

Experiment 1: Auditory Statistical Learning of Dual Grammars

Participants were presented with sentences of spoken pseudowords, generated from two different artificial grammars (see Figure 1). After a passive exposure phase (training), a dual forced-choice task tested their ability to differentiate between sequences that followed the same set of rules and sequences that did not.

Method

Subjects. Forty-six students (33 females, 13 males) from XXX University's undergraduate program were recruited and they received $12 in cash in return for their participation. All participants were Singaporean English-Mandarin bilinguals.

Apparatus and Materials.

Statistical Learning Task. The stimuli and their underlying generation (Figure 1) were borrowed entirely from Onnis et al. (2017), who in turn adapted the finite-state grammars of Conway and Christiansen (2006). As shown in Table 1, we used 9 grammatical sequences from each grammar for the training and 10 novel grammatical sequences from each grammar for the test. All sequences ranged in length from 3 to 7 symbols. For the participants to show that they had learned the statistical regularities specific to each grammar, in the test phase, they were asked to judge which novel sequences followed the same set of rule as before and which did not.

Sentences from the two grammars (A and B) were presented as auditory pseudoword sequences to the participants. Each letter symbol in Grammar A was randomly paired with a pseudoword from Set 1 (rud, pel, dak vot, and jic) and each letter symbol in Grammar B was randomly paired with a pseudoword from Set 2 (ginot, labou, liva, taret, and kimose). The pseudowords in Set 1 were generated with the English speaking voice Victoria, using the Speech System Manager of Mac OS X. The pseudowords from Set 2 were generated using the French speaking voice Thomas, using the same software. The assignment of pseudowords to each letter of each grammar was random for each different participant to avoid group-wise sequence-specific biases.

Table 1

Statistical Learning Task: the training and test items from Grammar A and Grammar B used in Experiment 1 and 2.

Training Phase		Test Phase	
Grammar A	Grammar B	Grammar A	Grammar B
VVM	XXM	VTVM	XTXM
XMXM	VTRM	VVTM	VRTRM
XXRVM	VVRXM	XMMXM	XTMTRM
VTVTM	XTTXM	VTTVM	VRVRXM
XXRVTM	XMRTRM	VTTTVM	VVRTXM
VTTVTM	VRRTRM	VVTRVM	XMVRXM
XMMMXM	XMRRTRM	VTTTVTM	XMVRTXM
XXRTTVM	VRVRTXM	XXRTVTM	XMVRTXM
VTVTRVM	VRRVRXM	XMXRTVM	VVRTTXM
		XMMXRVM	XMRVRXM

Bilingual Language Profile. To measure the degree of bilingualism in this study, we abandoned the popular but potentially limiting dichotomization approach based on subjective thresholds, whereby participants are divided into two groups: bilingual versus monolingual. As this approach implied an assumption that the relationship between the level of bilingualism and its effect is linear, if this assumption does not hold, by comparing the extremes of the bilingual continuum, a large amount of important information would be missed (Royston, Altman, & Sauerbrei, 2006). Therefore, in this study, we treated bilingualism as a continuous variable to capture the entire bilingual variability of participants. In fact, recent studies have also examined the effect of bilingualism without dichotomizing it (Thomas-Sunesson, Hakuta, & Bialystok, 2016; Yow & Li, 2015). The Bilingual Language Profile (BLP) is a validated questionnaire for assessing bilingual profiles through self-reports (Birdsong, Gertken, &

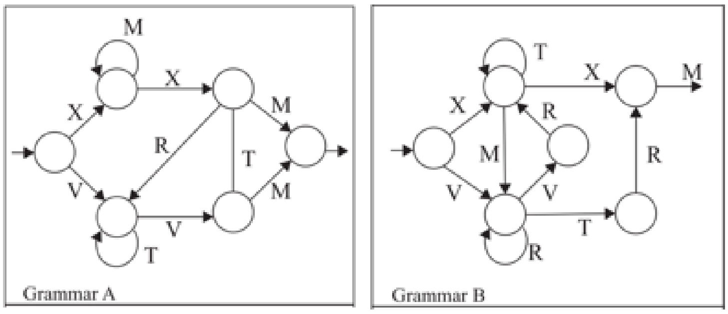

Figure 1. The two artificial grammars used. The letter symbols from Grammar A and Grammar B are placeholders to indicate the underlying sequential structure governing each grammar. Letters from both grammars were mapped onto sets of pseudowords (auditory vocabulary) in Experiment 1, while they were mapped onto abstract shapes in Experiment 2 (visual vocabulary, see Figure 8).

Amengual, 2012). For each language (English and Mandarin/Tamil) participants scored themselves on four subcomponents, Language History, Language Use, Language Proficiency and Language Attitude. Subsequently, their scores were compounded according to the BLP guidelines to yield an English global score and a Mandarin global score. The less dominant language score was subtracted from the other to produce a unique language dominance/balance index for each individual. Values closer to 0 indicate more balanced bilinguals.

Nonlinguistic Inhibitory Control Task. In addition to participants' bilingual experience, we also assessed their executive functions abilities, specifically, their inhibitory control. Because languages can never be entirely 'switched off' (Marian & Spivey, 2003) bilinguals and multilinguals face the daily cognitive task of activating and deactivating each language selectively during comprehension and production. Therefore, it has been hypothesized that bilingual experience could serve to sharpen individuals' executive control compared to monolingual experiences. In a recent study, Yow and Li (2015) have shown that even among the bilingual population, more balanced bilingual individuals experience lower Stroop interference effects. As the cognitive advantage could potentially influence one's SL ability, we have included two executive functioning measurements, namely the Inhibitory Control Task and the

Raven's Progressive Matrices, in addition to the degree of bilingualism, to predict the participants' performance in our AGL task.

Raven's Progressive Matrices. As part of a larger university study we also obtained a measure of fluid intelligence. Raven's Progressive Matrices (RPM) (Raven et al., 1938) is a non-verbal multiple choice test of abstract reasoning. In each question, the participants were asked to identify a picture that completed the given pattern. In total, there were 60 test items, divided into 5 sections (A to E). In each section, the questions became increasingly hard, requiring greater cognitive effort from the participants to answer correctly. The task was stopped whenever a participant made 5 consecutive or non-consecutive response errors, and an index of the participants' fluid intelligence was calculated as the proportion of correct responses out of the maximum score of 60. In this study RPM was used as an indirect filter for participants' engagement in the study, as too low scores can be matched against an aged norm and excluded from analysis.

Procedure. All participants completed the tasks in this order: 1) BLP Questionnaire, 2) Auditory Statistical Learning task, 3) Inhibitory Control Task (Stroop), and 4) RPM task. Before beginning the SL task, participants were informed that they were going to experience sequences of sounds via headphones. In the instructions given to the participants, we emphasized the importance of paying attention to the sound or the images, without explicitly mentioning the presence of the underlying grammar generating the stimuli.

The order and structure of stimuli presentation was as in Onnis et al. (2017). In both modality conditions, each pseudoword in a given sequence was presented for 500ms with 100ms ISI. A longer 1700ms ISI was used between sequences. Figure 2 illustrates the presentation of the sequences. In the training phase, 18 grammatical sequences (9 per grammar) were presented in blocks. Each block was repeated six times and the order of the blocks as well as the order of the sequences in a block were pseudo-random such that the sequences of Grammar A and Grammar B were interleaved, partly mimicking the nature of exposure characteristic of bilingual learning. Thus, in the training phase, participants listened to 18 sequences of stimuli per block for 6 blocks, 54 sequences per grammar and 108 sequences in total (in between blocks participants could take a rest). Figure 3 illustrates the presentation of blocks.

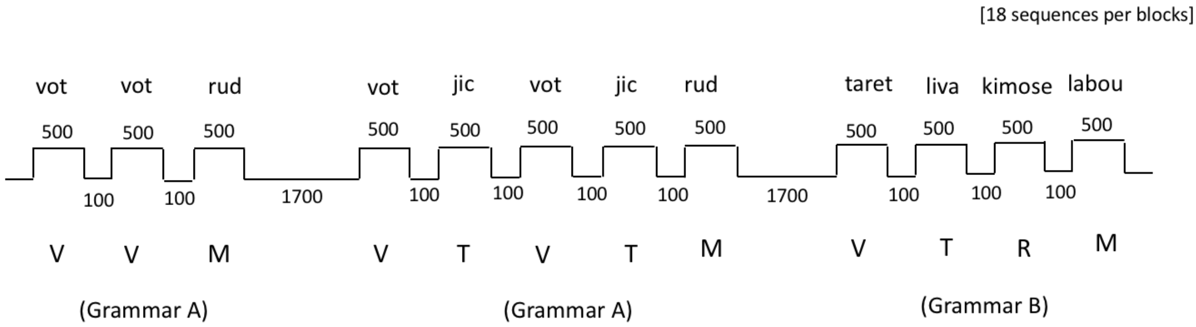

Figure 2. Sample of presentation of sequences and their duration during training

Before the test phase began, participants were informed that the sequences they had heard followed a set of rules that determined the order of the stimuli within each sequence. Their next task was to classify the sequences into two groups: those that conformed to the same set of rules as before (grammatical) and those that were different (ungrammatical). In this test phase, a total of 20 test sequences were used, 10 of them were grammatical with respect to Grammar A and 10 were grammatical with respect to Grammar B. To generate ungrammatical sequences, half of the test sequences from Grammar A were instantiated with the set of vocabulary assigned to Grammar B during training, and half of the test sequences from Grammar B were instantiated with the set of vocabulary assigned to Grammar A during training. This effectively implemented a crossover design Conway and Christiansen (2006) in which half of the grammatical test sequences of one grammar were used as the ungrammatical test sequences for the other grammar.

Participants used the “Y” and “N” keystrokes on a computer keyboard to classify the sequences; “Y” for grammatical and “N” for ungrammatical. A score of 1 was given if the test sequence was instantiated using the same set of vocabulary as with the training sequences from the same grammar, and was judged as grammatical. Similarly, a score of 1 was also given if the test sequences was instantiated with the different set of vocabulary and was judged as ungrammatical.

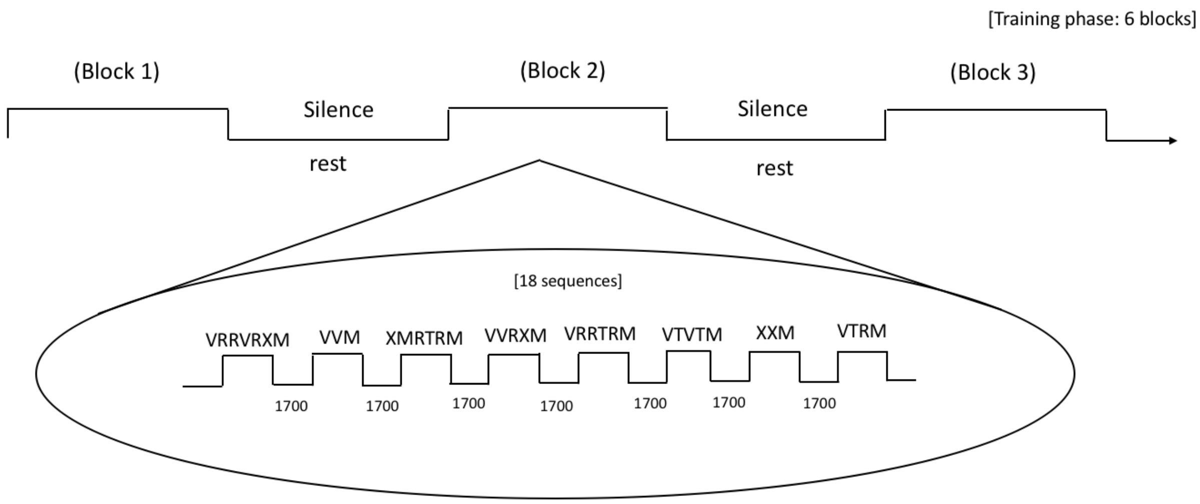

Figure 3. Sample of presentation of blocks during training.

Results

Participants (n=2) whose RPM scores were two standard deviations below the mean were excluded from analyses. This corresponds to values lower than the 5th percentile on a normed population of university students, and were thus considered not sufficiently engaged in the study. We then calculated accuracy scores on the dual grammar task for each participant and each artificial grammar as the proportion of correct endorsements to grammatical test items and correct rejections to ungrammatical test items. As a group, our participants learned both languages significantly above chance (Figure 4): Grammar A (mean = 0.57, sd = 0.15, $t(43) = 2.90$, $p < 0.01$, $d = 0.46$) and Grammar B (mean = 0.61, sd = 0.15, $t(43) = 4.53$, $p < 0.001$, $d = 0.73$).

The measure of Language dominance obtained from the Bilingual Language Profile questionnaire ranged from 7.44 (close to equally bilingual) to 142.60 (more dominant in one language), (mean = 61.95, sd = 36.51), indicating a useful variability in our sample. To assess whether language dominance predicted accuracy scores, we fitted a mixed-effects generalized linear model. Composite accuracy scores were computed for each participant and regressed against Grammaticality of test item (Grammatical, Ungrammatical), Grammar (A, B), Language Dominance, RPM and Stroop performance as fixed effects. The final model indicated two main effects:

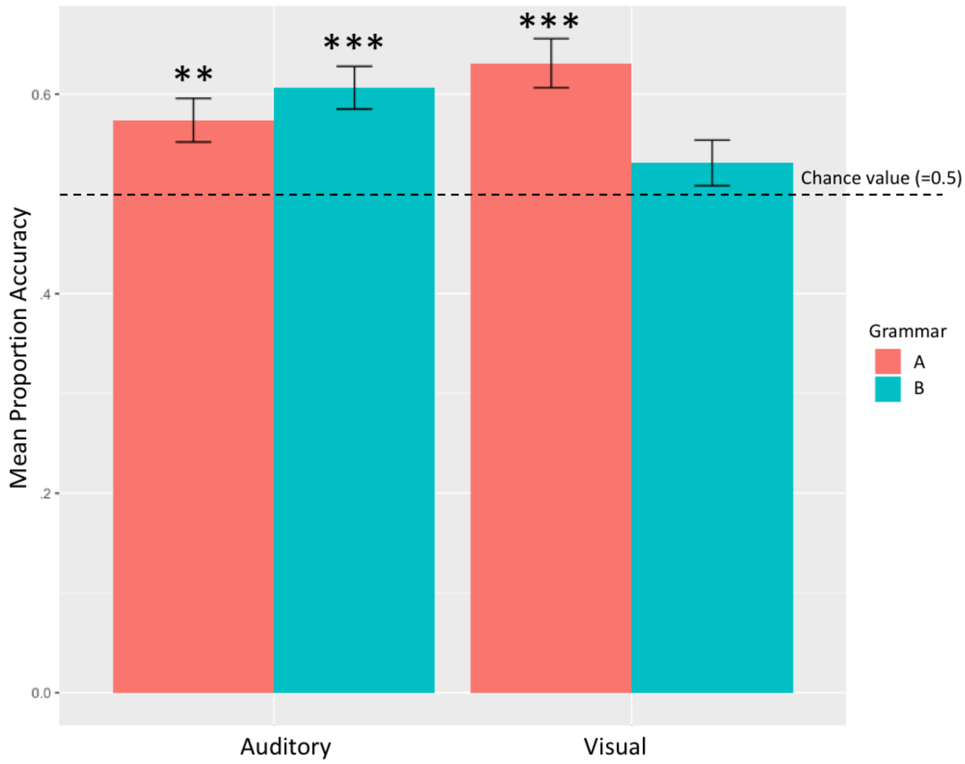

Figure 4. Mean Proportional Accuracy Score for each Grammar (A and B) in each experiment (Auditory and Visual). Two asterisks (**) indicate significance level of $p < 0.01$, three asterisks (***) indicate significance level of $p < 0.001$. Error bars indicate 1 SE.

Grammar and Language Dominance. Grammar ($\beta = 0.08$, $z = 4.10$, $p < .001$) suggests that participants were better at Grammar B. In addition, Language dominance independently predicted accuracy scores (scaled $\beta = -0.01$, $z = -1.976$, $p < 0.05$). Thus, participants with a more balanced bilingual profile performed better than less bilingual individuals (Figure 5). The final model also indicated a Grammar by Language Dominance interaction (scaled $\beta = -0.03$, $z = 2.086$, $p < 0.05$), such that the effect of Dominance was more pronounced for Grammar A. According to the main effect found for Grammar, Grammar A appeared more difficult to learn than Grammar B since participants' accuracy score was higher from Grammar B. The interaction of Grammar by Language Dominance suggests that being a more balanced bilingual may effectively matter for more difficult tasks. Finally, the model indicated a Language by

Grammaticality interaction: participants were better at endorsing grammatical test items than rejecting ungrammatical test items, in particular for Grammar B. No main effect of Stroop Performance was found (scaled $\beta = 0.115$, $z = 1.431$, $p = 0.153$), indicating that Inhibitory Control was not a significant predictor of accuracy score.

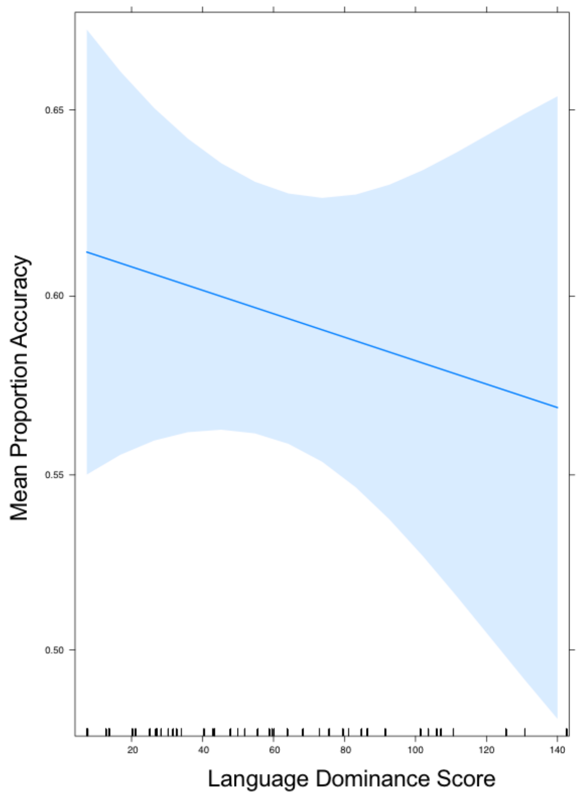

Figure 5. Plotted effects (and confidence intervals) of Language Dominance on the combined mean accuracy scores from both grammars. Lower scores on Language Dominance indicate a more balanced bilingual profile (higher bilingual profile). Higher bilingualism predicts higher accuracy scores on the auditory AGL task.

Experiment 2: Visual Statistical Learning of Dual Grammars

In Experiment 2, the same underlying dual artificial grammar as in Experiment 1 was presented to a new group of participants who had not participated in Experiment 1. However, instead of two sets of pseudowords, the grammars in this experiment were instantiated with two different sets of pseudoshapes, making the task one involving non-linguistic visual SL.

Method

Subjects. Forty-five students (30 females, 15 males) were recruited from the same university, and received $12 as compensation. All participants were Singaporeans with English as one of their languages. Forty-four participants reported Mandarin as their other language and one of them reported Tamil as his other language. An additional two students were tested but excluded from the analysis as they were not brought up in Singapore.

Materials. The same grammars used in Experiment 1 were presented as sequences of visual shapes (Figure 6). The letter symbols in Grammar A were randomly paired and replaced with 5 blue shapes and the letter symbols in Grammar B were randomly paired and replaced with 5 red shapes. The exact same training and test sequences generated from Grammar A and B were also used in this experiment.

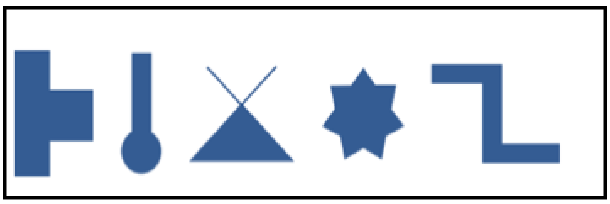


Figure 6. The visual vocabularies that were mapped onto the letters from Grammar A (left) and Grammar B (right) were the same sets of shape that were used in the same AGL task in Onnis et al. (2017).

Procedure. The procedure for Experiment 2 was exactly the same as for Experiment 1, in order to make the results more comparable. All participants completed the tasks in this order: 1) BLP Questionnaire, 2) Visual Statistical Learning task, 3) Inhibitory Control Task (Stroop), and 4) RPM task.

Results

As in Experiment 1, participants (N=4) whose RPM scores were two standard deviations below the mean were excluded from analyses. We calculated accuracy scores on the dual grammar task for each participant and each artificial grammar as the proportion of correct endorsements to grammatical test items and correct rejections to ungrammatical test items. As a group, participants learned Grammar A but not Grammar B significantly above chance (Figure 4): Grammar A (mean = 0.64, sd = 0.17, $t(40) = 5.29$, $p < 0.001$, $d = 0.85$) and Grammar B (mean = 0.52, sd = 0.15 , $t(40) = 0.976$, $p = 0.34$, $d = 0.16$). The Language dominance score obtained from the Bilingual Language Profile questionnaire ranged from 0.019 (close to equally bilingual) to 149.30 (more dominant in one language), (mean = 64.33, sd = 40.35), indicating variability in our sample. Accuracy scores on the Visual SL task were modeled as a binomial distribution and regressed against Grammaticality of test item, Grammar, Language Dominance and Stroop task as fixed effects. We also regressed Participants as random effect, and fitted a maximal model with all predictors and interactions between the fixed factors. We then performed a stepwise model selection by AIC to select the most parsimonious model. The final model indicated two main effects: Grammar and Grammaticality. Grammar (β= -0.52, z = -3.62, $p < .001$) indicate that participants were better at Grammar A. In addition, Grammaticality indicated that participants were better at correctly endorsing grammatical items than rejecting ungrammatical items (β = -0.42, z = -2.93, $p < 0.01$). No main effect of Stroop Performance was found (scaled β = -0.078, z = -1.075, p = 0.282), indicating that Inhibitory Control was not a significant predictor of accuracy score.

Discussion

In a recent study, Potter et al. (2017) had reported that after a short-term (6 months) of second language learning, as compared to a no-training control group, participants with no previous bilingual experience had observed a significant improvement of SL ability in a tonal (auditory) SL task, but not in a visual SL task. However, as the "bilingual group" in Potter et al. (2017)'s study had only been having the bilingual experience for 6 months, the discrepancy between the domain-specific (auditory) and domain-general (visual) conditions could be explained by the differences in time that the respective advantage in each modality needed to manifest; as compared to the domain-specific benefits, the domain-general benefits may take a longer time to develop. There is still a possibility that bilingual experience can lead to both domain-specific and domain-general benefits if given a long enough exposure time.

Moreover, even though no past study besides Potter et al. (2017)'s study had attempted to examine the modality effect of bilingual advantage in SL ability, many previous studies have reported the modality-general benefits (i.e benefits observed in both auditory and visual modalities) of the bilingual experience in other cognitive skills such as inhibitory control (Dijkstra & Van Heuven, 1998; Linck, Schwieter, & Sunderman, 2012) where bilinguals often outperform monolinguals on nonverbal tasks that require resolving conflict from competing alternatives. Therefore, likewise, it is possible that bilingualism could also lead to modality-general benefits in the ability to learn novel statistical structures.

In this study, we hypothesized that the bilingual advantage in SL ability is constrained by modality. To test the hypothesis, in two experiments, we examined the nature of enhanced SL in balanced bilinguals (Onnis et al., 2017). We assessed young adults' SL and investigated whether having comparable language profiles (proficiency, usage, history and attitude) in two languages predicted higher SL scores in the domain-specific modality (auditory) or in both modalities (auditory and visual).

We first found a difference in performance across modalities. Given a challenging task of learning two sets of statistical structures concurrently, each instantiated with stimuli in the same modality, participants exposed to the visual dual-grammar were only able to learn the structure of one grammar. Conversely, participants exposed to the auditory dual grammar, given the exact same underlying structure, were able to simultaneously learn both statistical regularities above chance. This result is consistent with past studies reporting an auditory advantage in SL (Conway & Christiansen, 2005; Frost et al., 2015). This could reflect modality-specific differences that exist among the SL subsystems. One of the proposed explanations for the auditory advantage stems from the differences in the sensitivity of the modality for different types of information. While auditory stimuli necessarily unfold in time, visual information can be available instantaneously in the visual array. Thus, sensitivity to temporal information in the auditory cortex is enhanced as compared to the visual cortex (Chen & Vroomen, 2013; Recanzone, 2009). Alternatively, the difference in performance across two experiments could be explained by the difference in their difficulty. The accuracy scores of participants as a group (Figure 4) showed that learning was not as successful in the visual condition, suggesting that the visual dual-grammar task might pose as a more challenging task than the auditory dual-grammar task to learners. It is possible that on a harder task (visual), even participants with more balanced bilingual profile also had to struggle to learn, and thus making it harder to observe a difference in performance between the more balanced and the relatively less balanced bilinguals. In other words, the visual SL in this study may simply be too difficult for the bilingual advantage to be observed.

The second finding from our experiments is the presence of possible modality constraints on the bilingual advantage in SL, which extend the original study of Onnis et al. (2017). This finding can be read in light of parallel findings by Emmorey, Luk, Pyers, and Bialystok (2008), who found a bilingual advantage in cognitive control limited to unimodal bilinguals (bilinguals in two spoken languages), and not in bimodal bilinguals (who speak and sign). Their results point to the cognitive enhancement stemming from a a modality constraint that forces language selection, and not from a general effect of bilingualism (the representation of two languages). Likewise, it is likely that auditory SL was enhanced in our unimodal bilinguals because of the modality-specific competition emerging from having to track different auditory statistics in each spoken language. If this was so, an intriguing possibility to be tested in the future is that bimodal bilinguals may *not* exhibit enhanced SL abilities in neither modalities, because each modality is not subjected to extra learning work.

A third finding of our study concerns the relation between bilingualism, SL, and cognitive functions, which was left unanswered by Onnis et al. (2017). It is possible that higher SL abilities observed in the study stemmed from general bilingual advantage in executive function, such as better inhibition control (Yow & Li, 2015), rather than the heightened SL abilities per se. In the current study, superior auditory SL was predicted by bilingualism, but not inhibitory control. This finding is supported by the findings reported in Bartolotti et al. (2011)'s study where bilingual experience was found to positively related to word learning ability while inhibitory control did not have any influence on learning in the low interference condition (where an additional pause cue reinforced the statistical cues in the word segmentation task). Together with previous findings, the reported results in this study suggested that there may be a genuine heightened ability in certain aspects of SL among bilinguals, independent of executive control, and that the pool of cognitive functions that benefit from bilingualism extends beyond executive functions. It is however important to note that both the reported results in this study and in Bartolotti et al. (2011)'s do not imply that inhibitory control has no influence on SL. In fact, Bartolotti et al. (2011) suggested that inhibitory control and bilingualism affect different aspects of learning; while the bilingual experience helped to heighten the bilinguals' sensitivity towards statistic cues, the enhanced inhibitory control helped the bilinguals to better suppress conflicting language knowledge cues and focus attention on relevant cues of the novel language. Evidently, in the high interference condition in Bartolotti et al. (2011)'s study where in order to successfully learn the statistical structure, participants had to suppress conflicting cues, inhibitory control was found to be a significant predictor of the superior performance of the bilinguals over the monolinguals.

Conclusion and Limitations

Our findings have extended the current understanding regarding bilingualism and SL in several ways. Firstly, by including simultaneous or early sequential bilinguals, we found parallel results with Potter et al. (2017) where the bilingual advantage was only observed in the modality-specific (tonal) SL task and not in the modality-general (visual) SL task, providing a more concrete evidence for the presence of modality constraints in bilingual advantage in SL. However, future studies could strengthen our claim by employing a visual SL task with comparable difficulty with the auditory SL task to eliminate the possibility that the task difficulty might have prevent the observation of a bilingual advantage in the visual condition.

In addition, SL is a general term that encompasses many different form of learning and literature has shown that different forms of SL task involves different combinations of cognitive processes. For instance, Hsu and Bishop (2010) had suggested that word segmentation, artificial grammar learning and novel sequence learning are all different types of SL. Although all of them rely on statistic cues, they recruited different learning mechanisms. As our study only looked at a type of SL, artificial grammar learning specifically, future work is needed to not only examine the modality effects of bilingual advantage in other types of SL tasks, but also validate our hypotheses and results of modality constrained bilingual advantage in SL.

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