Executive Function Predicts Artificial Language Learning in Children and Adults

By

Leah Lynn Kapa

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Chairperson John Colombo

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Susan J. Kemper

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Alison Gabriele

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Andrea Follmer Greenhoot

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Meagan M. Patterson

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The Dissertation Committee for Leah Lynn Kapa

certifies that this is the approved version of the following dissertation:

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Chairperson John Colombo

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ABSTRACT

Prior research has established an executive function advantage among bilinguals as compared to monolingual peers. These non-linguistic cognitive advantages are largely assumed to result from the experience of managing two linguistic systems. However, the possibility remains that the relationship between bilingualism and executive function is bidirectional such that experience with two languages improves executive functioning, but also, individuals with better executive function skills are improved language learners. The goal of the current studies was to test whether executive function abilities predict novel artificial language learning outcomes among children and adults. An artificial language was used to simulate the processes involved in natural language learning within a controlled laboratory setting. In Study 1, monolingual preschool children's executive function was assessed using the Dimensional Change Card Sort task, a visual Simon task, and the Attention Network Test (ANT). Their performance on these tasks was used to predict their success in acquiring expressive and receptive knowledge of a small artificial language system. Study 2 examined how college-age adults' executive function performance (Wisconsin Card Sort, Simon task, ANT) predicted artificial language learning outcomes. After controlling for working memory and English receptive vocabulary, executive function scores positively predicted children's receptive vocabulary performance and adults' ability to produce labels and sentences in the artificial language system. These findings provide initial evidence suggesting that executive function processes may be employed during the early stages of language learning and support the possibility of a bidirectional relationship between executive function and language acquisition.

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BACKGROUND

Learning and speaking two languages introduces challenges to the cognitive system that are not present for individuals who speak a single language. Research suggests that non-linguistic cognitive control skills are advantaged or improved in bilingual individuals compared to monolinguals. This difference is often assumed to result from experience and practice with managing the demands of speaking or using two languages, which theoretically leads to increased practice in cognitive control (see Bialystok & Craik, 2010, for review), in turn resulting in cognitive advantages. However, the issue of the directionality of the relationship between cognitive control and bilingualism remains unaddressed.

Evidence of bilingual cognitive advantages comes from research including participants who are highly proficient in both of their languages (i.e., balanced bilinguals). Second language proficiency is typically established based on the length of time that an individual has spoken or studied an L2 and/or skill in the L2 based on participant report or language testing. The balance between a bilingual's two languages is established using the relative proficiency between the L1 and L2 and/or the frequency of use of each language. Research including bilingual participants who have limited proficiency in one of their two languages (Bialystok, 1988; Carlson & Meltzoff, 2008) or who have unbalanced proficiency in their two languages (Bialystok, Craik, & Ruocco, 2006) suggests that these bilinguals do not share advantages in cognitive control that have been reported among proficient and balanced bilinguals. Although researchers have established that cognitive advantages of bilingualism are moderated by L2 proficiency and language balance, these variables are somewhat difficult to define because they are often relative within a study sample. Therefore, no absolute criteria for the level of proficiency or language balance that is necessary for producing executive function advantages have been established.

A viable alternative or complementary explanation for these findings is that individuals with superior cognitive control skills may be more efficient in the process of acquiring a second language (L2) because they are equipped with the cognitive skills necessary for managing two language systems (e.g., inhibitory control and cognitive flexibility). This increased language-learning efficiency may in turn result in these individuals achieving higher levels of L2 proficiency. In other words, the reported bilingual advantages in cognitive control may reflect, to some extent, the fact that individuals with enhanced cognitive control abilities are more likely to become the highly proficient and balanced bilinguals who are included as participants in research demonstrating bilingual cognitive advantages.

The goal of the current studies is to test the hypothesis that some of the presumed effects of bilingual experience on cognitive function may be attributable to the possibility that individuals' cognitive skills affect their ability to learn a second language (L2). In order to test this within a controlled, laboratory setting, children and adult participants were tested on a battery of cognitive measures and learned a highly simplified, artificial language (instead of a natural L2). The relationship between participants' cognitive abilities and their language learning outcomes was then modeled using multiple regression analyses. This research stems from fields of bilingualism, executive function, artificial language research, and language acquisition. The research will be introduced by first considering the reported effects of bilingualism on cognitive skills, then focusing on the relationship between non-linguistic cognition and language in first language acquisition, followed by a review of the construct of executive function, and finally, a consideration of the use of artificial languages in language acquisition research.

It should be noted that although the goal of the current research is to test the possibility that individuals' executive function skills may be predictive of their ability to acquire an L2, which is essentially the opposite direction that has been suggested previously (Bialystok & Craik, 2010), it is assumed that the relationship between cognitive control and L2 is bidirectional. In other words, executive function abilities may indeed predict L2 acquisition, but likewise, successful acquisition of an L2 is related to improvements in executive function skills. Presupposing that high levels of executive functioning are necessary for successful L2 acquisition is untenable given that the majority of the world's population is bilingual, and in many countries bilingualism is normative. Instead, the current hypothesis is that individuals with better executive functioning will also demonstrate improved language-learning abilities compared to individuals with poorer executive function skills. This hypothesis does not assume that high levels of executive functioning are necessary for successfully acquiring a second language, but instead is based on the possibility that executive functioning skills may make this process more efficient.

Bilingualism and Cognitive Functioning

A growing body of evidence supports a relationship between bilingualism and cognitive functioning, such that individuals who are proficient in speaking more than one language demonstrate enhanced cognitive functioning compared to their monolingual peers. Cognitive advantages of bilinguals over monolinguals have been demonstrated in preschool-age children (Bialystok, 1999; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008; Yoshida, Tran, Benitez, & Kuwabara, 2011), young adults (Costa, Hernàndez, Costa-Faidell, & Sebastiàn-Gallès, 2009; Costa, Hernàndez, Sebastiàn-Gallès, 2008; Prior & MacWhinney, 2010), and older adults (Bialystok, Craik, & Freedman, 2007; Bialystok, Craik, Klein, & Viswanathan, 2004). There is also a small literature describing the same effects in bilingual-exposed infants (Kovàcs & Mehler, 2009a, 2009b) and bilingual toddlers (Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011). Previous research has found that bilinguals outperform monolinguals on a variety of different cognitive tasks, but evidence has converged on a common set of cognitive skills showing advantages among bilinguals: improved inhibitory control, attentional monitoring, and attentional switching. Evidence of a bilingual advantage on each of these skills is considered in turn.

Inhibitory control

Inhibitory control is the ability to ignore some information or to suppress a prepotent response in order to focus attention on other (presumably relevant) information for completing a cognitive task. Tasks designed to measure inhibitory control generally do so by providing some form of conflicting information that a participant must ignore in order to respond successfully. Several such tasks have been used to compare inhibitory control between monolinguals and bilinguals. For example, in an influential study, Bialystok (1999) tested monolingual and bilingual preschool children on the Dimensional Change Card Sort (DCCS; Zelazo, Frye & Rapus, 1996) and found that bilinguals significantly outperformed monolinguals.

The DCCS is a card sorting task that requires children to first sort a set of cards by one dimension (e.g., shape) during a pre-switch phase, and then re-sort the same cards using a different dimension (e.g., color) during a post-switch sorting phase. Sorting tasks tax inhibitory control because participants must inhibit a response learned and reinforced during the pre-switch phase (e.g., sort based on shape) in order to successfully employ the post-switch sorting rule (e.g., sort based on color). Bialystok (1999) reported that bilingual preschool children made significantly fewer post-switch sorting errors than monolingual children did, suggesting that bilingual children were better than monolinguals at using inhibitory control to avoid using the pre-switch sorting dimension. Superior performance on the DCCS has also been used to support a bilingual advantage in attentional switching; this is discussed below. Subsequent studies have replicated an advantage of bilingual children over monolinguals on the DCCS (Bialystok & Martin, 2004; Carlson & Meltzoff, 2008). Carlson and Meltzoff (2008) reported that on a battery of nine cognitive inhibition tasks, including the DCCS, bilingual preschool-age children outperformed both monolinguals and children with six months of L2 immersion school experience. Although Carlson and Meltzoff (2008) report an advantage for bilingual preschoolers on measures of cognitive inhibition, there was no such advantage for behavioral inhibition tasks (e.g., delay of gratification).

Further evidence of a bilingual inhibitory control advantage comes from Martin-Rhee and Bialystok's (2008) finding that bilingual preschoolers and school-age children outperformed monolingual peers on the Simon task. In this computerized version of the Simon task, participants saw a colored target presented on the left or right side of a computer screen, and received instruction to respond to the color of a visual target using spatial key presses (e.g., if target is red, press left key). On congruent trials, the target and the correct response key aligned spatially (e.g., target on left side of screen and left key press), whereas on incongruent trials, the target appeared in the opposite spatial position from the correct key. Thus, on incongruent trials inhibitory control is necessary in order to avoid erroneously responding to the target's spatial location, whereas no inhibition is necessary on congruent trials. The reaction time (RT) or accuracy difference between congruent and incongruent trials is the Simon effect. Smaller Simon effect scores indicate less interference from incongruent information, or in other words, better inhibitory control. Martin-Rhee and Bialystok (2008) reported that bilingual children demonstrated a significantly smaller Simon effect compared to monolingual children.

Evidence of a bilingual advantage in inhibitory control has been extended beyond childhood to include bilingual adults (Bialystok, Craik, & Ruocco, 2006; Bialystok, Craik, & Ryan, 2006; Bialystok, et al., 2004; Costa et al., 2008). Using the Attention Network Test (ANT; Fan, McCandliss, Sommer, & Posner, 2002), Costa et al. (2008) reported that bilingual adults scored significantly lower (i.e., better) than monolinguals on the executive network, which is a measure of inhibitory control. The ANT is a modified flanker task in which participants respond to the direction of a central arrow that is presented in isolation (→), with congruent flankers (→→→→→), or with incongruent flankers (→→←→→). The executive network is assessed by subtracting RT on congruent trials, which do not require inhibition, from RT on incongruent trials, which require inhibition of incongruent flankers. The resulting “executive network score” indexes the response speed cost of ignoring the incongruent flankers. Thus, a lower executive network score represents improved inhibitory control. Additional support for improved inhibitory control among adult bilinguals comes from a comparison on the Simon task (described previously), in which bilingual young adults and older adults demonstrated a smaller Simon effect (i.e., better inhibitory control) compared to monolinguals (Bialystok et al., 2004).

Attentional monitoring

A second cognitive skill that is reportedly advantaged among bilinguals is attentional monitoring, or the ability to detect stimuli changes that may necessitate changes in response strategy. Tasks that assess attentional monitoring are those in which multiple trial types are randomly intermixed, thus forcing participants to respond differentially to different trial types. An example of such a task is the ANT. Within each trial block of the standard ANT, participants receive equal numbers of neutral, congruent, and incongruent flanker trials randomly intermixed. Therefore, during testing, participants must be prepared to respond to any of these possible flanker types. Within the ANT, improved attentional monitoring manifests as faster RT on all flanker trial types because this reflects an ability to detect and respond efficiently to changing response demands. Costa et al. (2009) reported that bilingual adults responded significantly faster than monolinguals to all trial types on the standard version of the ANT, which suggests a bilingual advantage in attentional monitoring.

In order to examine this attentional monitoring advantage further, Costa et al. (2009) systematically manipulated the attentional monitoring demands of the ANT by changing the percentage of trials of each flanker type. Trial blocks that predominately contained trials of one flanker type were low monitoring because switches between flanker types were rare. Conversely, blocks that contained similar numbers of each flanker type created high monitoring conditions, as this led to frequent changes in flanker type between trials. Bilingual adults demonstrated RT advantages on only the high-monitoring blocks, lending support to the notion that bilinguals possess improved attentional monitoring skills – as opposed to generally faster response speed – compared to monolinguals. In accord with the conclusions of Costa et al. (2009), Costa et al. (2008) also reported overall improved RT for bilinguals on the standard (i.e., high monitoring) version of the ANT.

Similar to adult bilinguals' RT advantages on the ANT, Martin-Rhee & Bialystok (2008) found that on trial blocks containing both congruent and incongruent trials on the Simon task, bilingual children responded significantly faster than monolingual children did. However, when trial blocks contained a single trial type (i.e., either congruent or incongruent trials), no RT differences emerged between bilingual and monolingual children. In other words, bilingual children were not simply faster responders, but were advantaged when attentional monitoring was required. Bialystok et al. (2004) observed this same pattern of RT results among adult bilinguals who responded faster than monolinguals on both congruent and incongruent trials within intermixed trial blocks on the Simon task.

Additional evidence of an attentional monitoring advantage among bilinguals comes from Bialystok's (2010) report that bilingual children were significantly faster than monolinguals at completing intermixed blocks of congruent and incongruent global-local trials. In the global-local task, participants were shown larger, global figures (e.g., letter S) that were composed of smaller figures that were either congruent (e.g., letter S) or incongruent (e.g., letter X) with the global figure. As with other conflict tasks, participants' responses in the global-local task are typically slower on incongruent trials than on congruent trials. However, Bialystok (2010) reported that bilingual children responded to both congruent and incongruent trials faster than monolingual children did, suggesting an advantage beyond inhibitory control. Indeed, this RT advantage supports an advantage for bilingual children in attentional monitoring because it emerged when congruent and incongruent trials were intermixed trial blocks, which resulted in high attentional monitoring demands.

Attentional shifting

Attentional shifting is a cognitive control component that is required to switch attention between stimuli. For example, in the ANT, trials preceded by a trial of a different flanker type (e.g., a congruent trial following an incongruent trial) are considered to be switch trials, and would presumably tax a participant's ability to shift attention. Costa et al. (2008) reported that both bilinguals and monolinguals exhibit slowed RT on switch trials compared to non-switch trials (i.e., trials preceded by the same flanker type), presumably due to the increased attentional shifting demands of switch trials. However, the magnitude of the RT difference between switch and non-switch trials was smaller among bilingual adults, which suggests that bilinguals were more efficient in attentional shifting compared to their monolingual counterparts.

Prior and MacWhinney (2010) provided additional support of an attentional shifting advantage among bilingual adults using a task-switching paradigm. In this task, monolingual and bilingual adults viewed colored shapes on a computer screen and a cue alerted them to respond to either the color or shape of the stimulus. Participants completed single-task blocks in which a single dimension (i.e., color or shape) was cued in all trials. Participants also completed a mixed-task block that cued both color and shape responding and comprised both switch (e.g., a color trial following a shape trial) and non-switch (e.g., a color trial following a color trial) trials. Unlike the single-task blocks, the mixed-task block required participants to employ attentional shifting in response to the changing classification dimensions on switch trials. Monolinguals and bilinguals performed equally on single-task blocks and non-switch trials within the mixed-task block, but bilingual adults were significantly faster than monolinguals in responding to switch trials in the mixed-task block. Taken together, these results suggest that bilinguals and monolinguals performed equivalently when the task did not require attentional shifting, but on a switching task that demanded attentional shifting, bilingual adults outperformed monolinguals.

A bilingual advantage in attentional shifting has also been established among bilingual children using the trail-making task. Bialystok (2010) reported that bilingual children were significantly faster than monolingual children in completing Trails B. Trails B is a task in which children draw a line to sequentially connect a series of letters and numbers randomly arranged on a page by switching between letters and numbers (e.g., A-1-B-2). In order to succeed on this task, participants must consistently shift attention between the two dimensions (letter and number) as they connect the series. Bilingual children’s faster performance on Trails B suggests that these children were more efficient in shifting their attention between the two dimensions compared to monolingual children. Additionally, as previously noted, the DCCS, which has been used to compare bilingual and monolingual children's inhibitory control (Bialystok, 1999; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008) also indexes attentional shifting. In post-switch sorting on the DCCS, children must shift attention away from the first sorting dimension in order to respond based on the new sorting dimension. Thus, bilingual children's enhanced performance on DCCS post-switch sorting provides additional support for a bilingual advantage in attentional shifting.

Finally, even pre-verbal infants who receive exposure to two languages (i.e., infants who are becoming bilingual) seem to have better attentional shifting skills compared to infants who hear a single language. Kovacs and Mehler (2009a) compared bilingual- and monolingual-exposed infants' ability to shift attention in response to an auditory or visual cue. In the pre-switch phase of the task, seven-month-old infants learned a pairing between an auditory or visual stimulus and the location of a visual reinforcer on a screen (i.e., left or right). In the post-switch phase of the task, infants were presented with the same auditory or visual stimulus, but the reinforcer appeared on the opposite side of the screen. Kovacs and Mehler (2009a) found that monolingual- and bilingual-exposed infants were equally successful in learning the pairing between the stimulus and the location of the reinforcer during pre-switch trials. When the target stimulus appeared, infants from both groups made anticipatory looks toward the location of the reinforcer before it appeared. However, during post-switch trials, only the bilingual-exposed infants successfully switched their responding and began making anticipatory looks toward the novel reinforcer location. Monolingual infants continued looking toward the side cued during pre-switch trials. Thus, even infants who are merely exposed to two languages demonstrate improved performance over monolingual-exposed infants in a task that requires shifting attention in response to changing stimuli.

Source of bilingual cognitive advantages

Generally, researchers hypothesize that the cognitive advantages of bilingualism are the result of bilinguals continually practicing cognitive control processes while controlling two language systems. For example, during lexical access, bilinguals must maintain separation between their two languages (see Bialystok, 2007, for review) in order to correctly access the target language and avoid accessing the non-target language. Both behavioral (Marian & Spivey, 2003a; 2003b; Poulisse, 2000; Schwartz & Kroll, 2006) and neuroimaging evidence (Abutalebi et al., 2007; Christoffels, Firk, & Schiller, 2007; Hoshino & Thierry, 2011; Jeong et al., 2007; Marian, Spivey, & Hirsch, 2003; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008) suggests that when speaking or listening to one of their languages, bilinguals' second languages are simultaneously activated. Bilinguals likely use inhibitory control (Green, 1998) to prevent lexical access in the non-target language. Thus, bilinguals are practicing inhibitory control whenever they hear or speak either one of their languages. Furthermore, the ability to hold two labels in mind for a single object may tax bilinguals' cognitive flexibility skills.

Another communication challenge of bilingualism that is not shared by monolinguals is the need to choose the appropriate language for each interlocutor. Bilinguals must use attentional monitoring to determine which language they should use based on the language used by their interlocutors (Costa et al., 2009; Crinion et al., 2006; Soveri, Rodriguez-Fornells, & Laine, 2011). Finally, bilinguals must rely on attentional shifting when it is necessary to switch between their two languages (Abutalebi & Green, 2008; Costa & Santesteban, 2004; Jackson, Swainson, Cunnington, & Jackson, 2001; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Mueter & Allport, 1999; Thomas & Allport, 2000) due to either code switching or changing between communication partners. Bilinguals' additional experience with cognitive control processes during language use is assumed to result in general, non-linguistic improvements in inhibitory control, attentional monitoring, and attentional shifting, which then leads to the documented advantages over monolinguals.

Although necessarily speculative at this point, it is theoretically possible that these additional cognitive demands of bilingualism may be less challenging to individuals who are already equipped with strong executive function skills. That is, individuals with good inhibitory control abilities may find the task of ignoring competing lexical items between two languages easier compared to those individuals with poorer inhibitory control. For example, an individual may be more successful at learning to produce a novel label for an object if she can use her inhibitory control skills to better suppress the prepotent response, which would be to label the object using her native language. Likewise, individuals with better cognitive flexibility may have enhanced ability to consider simultaneously two possible labels for a single action or object, which would potentially facilitate the process of acquiring new labels. Finally, individuals with improved attentional shifting skills may naturally be more adept at dealing with the challenges incurred when switching between two languages. While not intended to address specific issues of how executive function processes are used in the acquisition of a new language, the current studies focus on the more basic question of whether or not executive functioning may be involved in artificial language learning.

Relationship between Cognition and Language in First Language Acquisition

Although there is increasing attention focused on the relationship between cognitive functioning and language among bilinguals and second language learners, questions regarding the relationship between language and cognitive development have long been central in the domain of first/child language acquisition. In support of the notion that cognitive development affects language outcomes, researchers have provided evidence to suggest that early-developing cognitive skills are related to children's later language and literacy development. Additionally, researchers have found that children with impaired language development may also demonstrate deficits in their higher-order cognitive systems when measured using non-linguistic tasks. Support for the role of language in influencing cognitive development comes from research suggesting that both adults and children may use self-directed speech to complete difficult cognitive tasks and from cross-linguistic evidence that individuals' non-linguistic cognitive concepts may be influenced by their language system.

Cognition drives language development

One source of evidence that non-linguistic cognitive skills underlie first language development comes from research considering how early-developing cognitive skills that are measured in infancy relate to later language outcomes. Rose, Feldman, and Jankowski (2009) conducted a longitudinal study in which children's early memory/attention abilities were assessed at 12 months using a visual task in which infants were familiarized with pictures and then presented with a familiar and novel picture. In this task looking preference for the novel picture is indicative of the child having encoded and remembered the familiarization images, leading to a preference for the novel object. Participants' language abilities were assessed via parent report at 12 months and then children were given a language comprehension test at 36 months. The authors reported that children's language abilities both at 12 months and 36 months of age were significantly predicted by their performance on the memory/attention tasks at 12 months. This suggests that infants' memory/attention abilities are related to both concurrent and future language abilities.

The aforementioned research suggests that infants' very early memory abilities are related to their emergent and later language abilities (Rose et al., 2009), but this relationship between memory and language seems to continue beyond infancy. A number of researchers have identified working memory, particularly phonological working memory (i.e., the temporary storage and manipulation of phonological information), as a possible predictor of first language abilities among both children and adults (see Baddeley, 2003 for review). For example, Gathercole and Adams (1993) reported that among very young children at 2 and 3 years of age, there is a positive correlation between children's performance on phonological working memory measures (word and non-word repetition tasks) and their vocabulary size. However, the authors note that the directionality of this relationship cannot be discerned because improved phonological working memory skills may be contributing to children's improved word-learning abilities and subsequent higher receptive vocabularies, or conversely, children's improved word knowledge due to larger receptive vocabularies may in turn enhance their abilities to retain and repeat the words and non-words used to assess working memory.

Gathercole, Willis, Emslie, and Baddeley (1992) provide evidence of the directionality of the relationship between verbal working memory and language from longitudinal measures of children's vocabulary, phonological working memory (non-word repetition), non-verbal intelligence, and reading abilities at ages 4, 5, 6, and 8. Based on the outcomes of cross-lagged partial correlations, the authors report that – when controlling for age, nonverbal intelligence, and previous outcome scores – phonological working memory at age 4 significantly correlated with vocabulary at age 5, but age 4 vocabulary does not correlate with phonological working memory at age 5. Conversely, the opposite pattern is found between ages 5 and 6, with phonological vocabulary significantly correlated with later phonological working memory, but not the reverse. Based on these longitudinal data, it seems that the directional relationship between vocabulary knowledge and phonological working memory abilities may change across development in childhood, shifting from phonological working memory driving vocabulary acquisition to vocabulary knowledge affecting phonological working memory skills. However, evidence from adult L2 word-learning suggests that among adult learners, phonological working memory is significantly correlated with the number of L2 words successfully acquired (Atkins & Baddeley, 1998), which again suggests that working memory abilities may drive language acquisition.

Additional evidence of a relationship between language and non-linguistic cognitive skills comes from research conducted with children with impaired language and/or cognitive development. For example, children with specific language impairment (SLI), who are characterized by impairments in both their receptive and expressive language abilities, have also been reported to demonstrate non-linguistic deficits in their general speed of processing (Lahey, Edwards, Munson, 2001; Miller, Kail, Leonard, Tomblin, 2001) as well as in their verbal working memory (Montgomery, 2002; Weismer, Evans, & Hesketh, 1999). Archibald and Gathercole (2006) found that children with SLI performed significantly below age expectations on measures of verbal working memory – serial recall and non-word repetition – and the deficits in non-word repetition remained even after children's language abilities were taken into account. These findings suggest that children with SLI may have lower phonological working memory abilities than would be expected when considering their overall language ability. This has led to speculation that the characteristic language impairments of individuals with SLI may, in part, be driven by underlying deficits in cognitive processing, including slowed processing speed and limited verbal working memory.

Further evidence of cognitive deficits in SLI comes from a combination of behavioral and neuroimaging data. Ellis Weismer, Plante, Jones, and Tomblin (2005) conducted a functional magnetic resonance imaging (fMRI) study comparing working memory in adolescents with SLI and typically developing peers. Based on behavioral outcomes of a listening span task, participants with SLI were significantly less accurate compared to participants with typical language development on measures of encoding (yes/no comprehension questions) and retrieval (final word recall). Furthermore, fMRI scanning revealed hypoactivation among the SLI group compared to the control group during both encoding and recall. These findings suggest that working memory deficits associated with SLI continue into adolescence and further, provide support of underlying neurological differences in working memory processes among individuals with SLI compared to typically developing peers.

Language drives cognitive development

Other research suggests that the relationship between cognition and language may be reversed, such that linguistic abilities lead to the development of cognitive skills, particularly the higher-order cognitive skills of interest in the current research. As discussed previously, cognitive and attention skills in infancy are related to later language outcomes, suggesting that children may rely on these cognitive skills during the process of language acquisition. However, there is also evidence that the development of language abilities, especially self-directed speech, may lead to developmental gains on non-linguistic cognitive tasks. For example, during executive function tasks that require switching attention between various stimuli or attributes (e.g., the DCCS), researchers have found that children are more successful when they are instructed to name the relevant stimulus/attribute before providing a response. For example, when completing the DCCS, children who are instructed to label the relevant sorting dimension (e.g., ‘this is a blue card), are more successful in post-switch sorting compared to children who are not encouraged to provide relevant dimension labels (Kirkham, Cruess, & Diamond, 2003; Towse, Redbond, Houston-Price, & Cook, 2000). In other words, children are capable of using language to focus their attention during executive control tasks.

It is interesting to note that although adults rarely produce self-directed speech aloud while completing such tasks, they are likely also relying on internalized self-directed speech to guide performance during cognitively demanding tasks. When researchers disrupt adults' internal speech by instructing them to produce unrelated speech aloud (i.e., articulatory suppression) during executive function measures, adults' performance declines significantly (Dunbar & Sussman, 1995; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004). Taken together, this experimental evidence suggests that young children may not automatically use self-directed speech to guide attention, but instructing them to do so improves executive control; whereas, adults seem to employ internalized self-directed speech as a cognitive strategy, and therefore, disrupting their ability to use language to guide attention leads to declines in performance on executive control tasks.

Further support of language influencing cognition comes from cross-linguistic research demonstrating that individuals' linguistic systems affect their non-linguistic cognitive concepts. A classic version of this notion is the Sapir-Whorf hypothesis, which assumes that individuals who speak different language perceive the world differently as a result of their language systems. Several more recent cross-linguistic studies of spatial cognition provide support for this hypothesis. Languages typically use either an egocentric frame of reference system that is relative to the speaker's location (e.g., 'left' and 'right') or an absolute frame of reference (e.g., 'north' and 'south') to describe nearby spatial relationships. Experimental evidence supports the notion that speakers of egocentric versus absolute frame of reference languages respond differently on non-linguistic object location tasks (Majid, Bowerman, Kita, Haun, & Levinson, 2004). When locating the 'same' object in two arrays after a 180 degree turn, speakers (both adults and children) of egocentric languages use egocentric spatial relationships (e.g., choosing the object to the left of a reference point), whereas speakers of absolute frame languages use absolute spatial relationships (e.g., choosing the object to the north of a reference point).

The role of spatial language in the development of spatial cognition is further demonstrated by research focused on spatial knowledge among deaf children with no exposure to spatial language. Gentner, Özyürek, Gürcanli, and Goldin-Meadow (2013) compared the performance of congenitally deaf Turkish children (with hearing parents and no exposure to sign) to hearing Turkish children on a task that required children to map spatial relationships from one array to another. The researchers verified in a language production task that the deaf children did not have signs for spatial relationships. The deaf children, although matched with hearing children on another cognitive measure, performed significantly worse than hearing children did on the spatial mapping task. The discrepancy in performance by hearing and deaf children led Gentner et al. (2013) to conclude that the deaf children's spatial deficits resulted from their inability to represent spatial relationships linguistically (i.e., their lack of spatial signs). In other words, language was necessary for conceptualizing the spatial relationships involved in the non-linguistic mapping task.

Taken together, this body of research suggests that language and cognition interact during first language development, and the relationship between language and cognition is likely bidirectional. Some cognitive skills appear to affect language acquisition, whereas the development of other cognitive skills is influenced by linguistic experience. Thus, the relationship between language and cognition is not limited to bilingualism and L2 acquisition.

Executive Function

The types of cognitive skills that researchers have found to be advantaged among bilinguals belong to a set of cognitive processes collectively referred to as executive function, which is a group of higher-order cognitive skills that regulate other cognitive processes (Carlson, 2005). Executive function development follows a rise-and-decline pattern across the lifespan such that these skills develop rapidly across the preschool period (Carlson, 2005; Garon et al., 2003) and continue to improve until young adulthood (Davidson et al., 2006; Lehto et al., 2003; Zelazo, Craik, & Booth, 2004) but then decline in older adulthood (Buckner, 2004; Zelazo et al, 2004). Researchers debate the extent to which executive function should be considered a single, unitary construct versus a set of separable, independent skills. In an influential study, Miyake Friedman, Emerson, Witzki, and Howerter (2000) used factor analysis to examine three components of executive function (inhibition, shifting, and updating/monitoring) and found that these components are related, but separable skills in adults. This outcome supports an integrative framework that considers both the independence and unity of executive function components. Researchers have also successfully applied this integrative framework model of executive function to the development of executive function in preschoolers (Garon, Bryson, & Smith, 2008) and school-age children (Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003).

Garon et al. (2008) reported that different executive function skills (working memory, response inhibition, and shifting) develop at differential rates across the preschool period, which supports the hypothesis that executive function comprises dissociable components. However, Garon and colleagues postulate that a single mechanism, specifically underlying attentional skills, accounts for the development of all executive function components. The developmental evidence of separable components combined with a common underlying mechanism supports an integrative view of executive function as a unitary construct that includes dissociable sub-processes. Similarly, Davidson, Amso, Anderson, and Diamond (2006) found that as executive function develops between preschool age and adolescence, component skills develop at different rates, and these skills show both independence and interrelations with one another. Defining executive function within an integrative framework is consistent with reports of advantaged cognitive skills among bilinguals, as some executive function components are advantaged, while others are not. For example, studies have reported that working memory, a component of executive function, is equivalent among bilinguals and monolinguals (Bialystok, 1999; Bialystok, 2009; Feng, Bialystok, & Diamond, 2007; Martin-Rhee & Bialystok, 2008; but see Bialystok, Craik, Klein, & Viswanathan, 2004). Thus, bilingualism appears to confer advantages on some, but not all, components of executive function.

Artificial Language Research

Researchers have used artificial languages to address a wide range of questions about the process of natural language acquisition. Artificial languages are either languages that have been created by researchers or are miniature versions of real languages. These linguistic systems are typically very small, consisting of only a few words and grammatical elements. Using artificial language systems provides clear advantages over studies of natural language acquisition. First, the small size of the languages allows learners to acquire artificial languages in a matter of hours or days, which is much faster than the process of natural language acquisition. Second, using an artificial language allows researchers to manipulate the language to include only the linguistic features of interest. Additionally, using an artificial language provides researchers strict control over amount of language exposure/training that participants receive, which allows researchers to compare learning outcomes across participants following equivalent amounts of language training. Because these languages are created for research, it is impossible that research participants will have any previous experience with the language systems, ensuring that all participants are equally naïve at the beginning of language training.

Artificial language methodology has been used to explore a number of questions about the process of first and second language acquisition in children and adults. The acquisition of syntax has been studied using artificial languages to explore whether some word orders (e.g., subject verb object) are easier to learn than other orders (Byrne & Davidson, 1985; Johnson, Blakely, & Olness, 1990). Researchers have also used artificial languages to test whether adults (Folia, Udden, de Vries, Forkstam, & Petersson, 2010; Forkstam, Elwer, Ingvar, & Petersson, 2008; Petersson, Forkstam, & Ingvar, 2004) and children (Saffran, 2001; 2002) can extract phrase boundary information from listening to artificial languages. Following language exposure, both adults and children are capable of recognizing strings that are within a phrase versus those that cross phrase boundaries. In addition to tests of language comprehension, artificial languages have been used to assess children and adults' ability to produce grammatical utterances following artificial language training (Abbot-Smith & Tomasello, 2009; Goldstein, 1983; Hudson Kam & Newport, 2005; Wonnacott, Newport, & Tanenhaus, 2008).

Researchers have also employed artificial languages to study the acquisition of morphology. Braine, Brody, Brooks, and Sudhalter (1990) manipulated the characteristics of an artificial language in order to determine how frequency, phonological properties, and correction/feedback affected children's acquisition of affixes. Similarly, artificial languages have been used to test Slobin's (1973) assumption that children are more successful in learning suffixes than prefixes (Kuczaj, 1979; Daneman & Case, 1973; MacWhinney, 1983). These researchers found that children were indeed better at learning artificial languages that contained suffixes than languages with prefixes. Interestingly, MacWhinney (1983) found that the advantage in suffix learning did not extend to adults who, unlike children, were equally capable of learning prefixes and suffixes.

Despite the advantages of using artificial languages in research on the processes involved in natural language acquisition, the methodology does have some limitations. The central limitation of using artificial language methodology to address questions of natural language acquisition is the fact that artificial languages may not actually be language (Ingram & Pye, 1993). That is, these systems constructed by researchers may not be similar enough to natural languages to inform questions about language acquisition. A second and related limitation of artificial language methodology is the highly reduced language system that participants are acquiring. The limited size and complexity of the language systems used in laboratory training studies is potentially problematic because participants may learn these artificial systems using different processes or strategies than those that underlie natural language acquisition. However, neuroimaging evidence suggests that participants trained on artificial/miniature languages display the same neural responses during processing as those elicited while individuals process natural languages (Forsktam, Hagoort, Fernandez, Ingvar, & Petersson, 2006; Friederici, Steinhaur, & Pfeifer, 2002; Petersson et al., 2004).

Additional limitations in research using artificial language methodology arise from the training used to teach such languages to participants (Ingram & Pye, 1993), which is often unlike the process of natural language acquisition. In some artificial language research, participants simply listen to language streams with no referential meaning (Saffran, 2001), whereas in others, participants receive explicit negative feedback (Braine et al., 1990), which is largely absent in natural language acquisition. Because participants’ language exposure during artificial language learning is unlike most natural language learning experiences, the applicability of findings derived from such training studies to natural language acquisition is unclear. With these limitations in mind, artificial language methodology is still a useful first step in exploring the process of language acquisition within a controlled laboratory setting.

Although many researchers consider the acquisition of artificial languages to be analogous with first language acquisition, McLaughlin (1980) argued that artificial language learning is a proxy for L2 acquisition because children and adults come to the task of learning an artificial language after having already acquired a first language. Thus, McLaughlin (1980) notes that like L2 learners, participants presumably draw on their knowledge of their own language while learning a new, artificial language. McLaughlin's view of artificial language learning as analogous to L2 learning is adopted in the currently proposed research.

Current Studies

The goal of the current studies is to examine whether individuals' executive function skills – specifically those skills that are advantaged among bilinguals (e.g., attentional monitoring, inhibition, and shifting) – predict their ability to acquire an artificial language. Previous research focusing on cognitive skills among bilinguals assumes that enhanced cognitive abilities result from bilingual experience (Bialystok, 2007; Bialystok, Craik, & Luk, 2012); however, it may also be the case that individuals with strong executive function skills are advantaged language learners (Festman, Rodriguez-Fornells, & Munte, 2010). Theories of bilingual lexical access and language processing posit a need for increased executive function skills in order to manage two languages; therefore, it logically follows that monolinguals who possess these executive function skills may be better equipped to deal with the complexity of two languages. If this were true, individuals with advanced executive function skills would be better or more efficient L2 learners than individuals with poorer executive functioning. This possibility receives support from recent research in which bilinguals, who have improved executive function and demonstrate advantages over monolinguals on artificial language-learning tasks.

Evidence from bilingual research

Support for the possibility that better executive function skills result in improved language learning comes from the results of Yoshida et al. (2011), showing that bilingual preschool children who outperformed monolingual children on a test of executive function (ANT) were also better than monolinguals at learning artificial adjectives. In the artificial adjective task, children were presented with known objects (e.g., ducks) that were covered with a novel surface feature (e.g., sponge) and heard the object described using a novel adjective (e.g., ‘This is a *blickish* duck.’). Children were then presented with two new objects, one of which shared the surface feature with the training object, and one of which did not, and asked to pick an object using the novel adjective (e.g., ‘Can you get me the duck that is *blickish*?’). The monolingual children performed at chance when selecting between the two test objects, whereas the bilingual children were significantly better than chance at choosing the test object that matched the training object.

Based on these findings, Yoshida et al. (2011) concluded that bilinguals’ improved adjective learning abilities were a result of their advantaged executive function skills. Specifically, the researchers concluded that bilingual three-year-olds were able to inhibit the assumption that novel labels are nouns, which allowed them to learn new adjectives. Conversely, monolingual children were not able to overcome their noun bias, which resulted in an inability to interpret the novel labels as adjectives. Correlational analyses provide further evidence that bilingual children’s adjective learning was related to their cognitive control abilities. Both accuracy and RT performance on the ANT significantly correlated with adjective-learning performance for bilingual children, but these tasks were uncorrelated among monolingual participants, which the researchers suggested might have been due to floor effects in both tasks for monolinguals. These findings support the possibility that enhanced executive function abilities facilitate language learning in bilingual children, but the relationship between executive function and language learning in monolingual children remains unclear.

The results of Kovacs and Mehler (2009b) provide additional evidence that bilingual children, in this case pre-verbal infants, are advantaged artificial language-learners compared to monolinguals. Specifically, bilingual 12-month-olds were capable of learning two speech regularities (e.g., AAB and ABA) when they heard both patterns presented in a randomized order, whereas monolingual infants learned only one of the two patterns (e.g., AAB). During a familiarization phase, a toy appeared on one side of a screen after auditory presentations of one syllable pattern (e.g., AAB) and on the opposite side of a screen following the other syllable pattern (e.g., ABA). In the testing phase, infants again heard stimuli conforming to the two possible syllable patterns, but they were no longer followed by visual toy presentations. Infant's eye movements were tracked during testing. Bilingual-exposed infants looked to the correct side of the screen (i.e., the side on which the toy appeared during familiarization) following both AAB and ABA stimuli. Monolingual-exposed children only looked to the correct side following AAB stimulus presentations. These results suggest that monolinguals were only able to focus attention on one of the two language patterns, whereas bilinguals were capable of simultaneously learning both patterns. Kovacs and Mehler (2009b) interpreted these findings in light of executive function advantages of bilingualism, such that the experience of dealing with language input from two language systems leads to improved cognitive control, which in turn results in better language learning in situations where multiple speech structures are present.

In order to determine whether the language learning advantages that have been reported among bilinguals with high levels of executive functioning (Kovacs & Mehler, 2009b; Yoshida et al., 2011) extend to monolinguals, the studies examined artificial language learning among monolingual children and adults. Following McLaughlin's (1980) assertion that artificial language learning is analogous to L2 learning, these studies used artificial language learning as a metric of individuals' second language-learning capacity. Using an artificial language paradigm instead of naturalistic L2 learning allowed us to ensure that all participants received equal language training, which eliminated the possibility that language learning outcomes varied as a factor of language input or previous experience. In addition, the use of a simple, artificial language allowed us to teach the same language system to both preschool children and adults using the same training methods, permitting us to draw language-learning comparisons across these two age groups.

Hypotheses

Based on the assumption that individuals with better executive function skills will be advantaged in language acquisition, it is hypothesized that among both children and adults, executive function performance will significantly predict language-learning outcomes such that individuals with better executive function scores will also have higher scores on tests of artificial language learning. The specific hypotheses that extend to both Study 1 and Study 2 are below.

Hypothesis 1: Verbal ability (L1) and working memory will positively predict children's and adults' outcomes on artificial language learning tasks such that higher verbal and working memory scores will be related with higher scores on receptive and expressive artificial language tasks.

Hypothesis 2: Executive function abilities (inhibition, shifting, and monitoring) will account for a significant amount of variance in children's and adults' artificial language-learning outcomes, both receptive and expressive, after controlling for the effects of verbal ability and working memory. Again, the relationship between executive function abilities and artificial language learning is hypothesized to be positive. It is assumed that executive function performance will be most predictive of expressive artificial language tasks, as more control will be required when producing the new artificial language.

Although it is predicted that both children and adults will follow the same pattern, comparing analyses between Study 1 and Study 2 may reveal that executive function differentially predicts artificial language-learning outcomes at different developmental points (i.e., preschool versus adulthood). Furthermore, executive function is expected to predict both expressive and receptive artificial language performance, but it is hypothesized that executive function abilities will be more predictive of performance on artificial language production tasks than on receptive tasks as L2 production requires more controlled processing than L2 comprehension (Kroll & Tokowicz, 2001). No specific predictions are made regarding which executive function components (e.g., inhibition, shifting, monitoring) will best predict performance on artificial language outcomes.

STUDY 1

Study 1 investigated the relationship between executive function and language learning in preschool-age children. The preschool period is a time during which executive function skills undergo rapid development (Carlson, 2005), which makes this age group interesting for an examination of the relationship between executive function and language acquisition, as we are likely to find a wide range of both executive function and artificial language-learning abilities among children in this age range.

Method

Participants

The participant group comprised 42 children (19 female) between the ages of 4;0 and 5;11 (mean age 4;8). All children were reported by parents to speak a single language (English) fluently at the time of testing. Ten children were reported to regularly hear a non-English language, but these children received less than one hour of non-English language exposure each day and were unable to speak the language fluently. Parent report also confirmed that participants had normal or corrected-to-normal vision and hearing (see Appendix A). Participants were recruited by distributing study information to area daycares and preschools, through flyers posted in the community, and by contacting families maintained in the Early Cognition Laboratory participant database.

Artificial language description

The artificial language that children learned is a modified version of the artificial language created by Hudson Kam and Newport (2005) in their study of the regularization of determiner use following inconsistent input. Four additional nouns were added to the artificial language based on the work of Wonnacott et al. (2008). Additionally, the determiner used by Hudson Kam and Newport (2005) was eliminated from the artificial language for the purposes of this study, and only transitive verbs were used. The resulting simplified artificial language system comprises 12 nouns (i.e., objects) and 4 motion verbs. Each of the 12 nouns are animate, real-world objects (animals or humans) and can be both an agent (i.e., actor) and a theme (i.e., recipient of action) within the language's argument structure. Each of the 4 verbs describes the motion of an agent (noun 1) in relation to the stationary theme (noun 2). The combination of nouns and verbs results in 528 possible sentences in the artificial language. The word order of the artificial language is verb-noun1-noun2. This artificial language is very simplified compared to natural languages, as it lacks syntax (other than linear word order), prosody, and morphology and adheres to the phonotactic regularities of English. Within the language, subjects and objects are only differentiated through word order. The following are example sentences in the language along with glosses of their meanings.

1. */blɪt nɜrk fumpogʌ/*

   move under frog bird

   "The frog moves under the bird"

2. */flɪm fumpogʌ nɜrk/*

   move around bird frog

   "The bird moves around the frog"

Table 1 includes a complete list of the lexical items and their meanings in the artificial language. It is important to note that because this artificial language system is extremely simple, the process of acquiring the system does not parallel the more complex task of natural language learning, but the artificial language does include some early-acquired linguistic properties of natural languages including lexical learning (both nouns and verbs) and basic word order.

Measures

Receptive vocabulary.

English receptive vocabulary was measured using the Peabody Picture Vocabulary Test—Fourth Edition (PPVT-4; Dunn & Dunn, 2007) Form A, which is a standardized vocabulary measure. During each trial of the PPVT-4, participants viewed a test plate depicting four images and heard a target word read by the experimenter. The participant then selected which of the four images corresponded to the target word. Test items became increasingly difficult as testing progressed. Testing administration began by establishing a basal score, which is the lowest set of 12 items on which the participant commits one or no errors. Testing continued until participants reached their ceiling set, which is the highest set of 12 items on which a participant commits eight or more errors. Raw scores were calculated by subtracting the number or total errors committed between the basal and ceiling sets from the highest item number in the ceiling set. These raw scores were then converted to age-normed scaled scores using charts of standardized scores provided in the testing manual.

Executive function.

Children's executive function abilities were measured using three tasks that tap into the components of executive function described previously. In addition to assessing attentional monitoring, inhibitory control, and attentional shifting, a fourth measure, digit span, was included to measure working memory capacity. Working memory is considered a component of executive function (Miyake et al., 2000), but most researchers do not report working memory advantages among bilingual individuals (Bialystok, 1999; Bialystok, 2009; Feng, Bialystok, & Diamond, 2007; Martin-Rhee & Bialystok, 2008). Therefore, as a working memory measure, digit span was included in analyses as a possible predictor of artificial language learning, but was not expected to explain all of the variability in language learning. Instead, it was hypothesized that other executive function components (e.g., attentional monitoring, shifting, and inhibition) that are advantaged among bilinguals would predict artificial language learning over and above working memory alone.

Digit span.

Working memory was measured using forward and backward digit span tasks. In the forward digit span task, the experimenter read increasingly long lists of numbers to children, and children repeated the list in the same order. The backward digit span is identical to the forward digit span task except participants repeated the list of numbers backwards. In both span tasks list length began at two digits and increased by one digit until children made errors on two lists of a given span. Children received one point for each correctly repeated list and a score of zero for each incorrect repetition. Points were summed across lists within the backward and forward task, resulting in two span scores for each participant, which were then summed to create a total digit span score.

Dimensional Change Card Sorting.

Children's inhibitory control and attentional shifting were tested using the DCCS (Zelazo, Frye & Rapus, 1996). Children first completed the standard version of the DCCS. Participants received a set of 12 test cards with images that varied on the dimensions of color and shape (e.g., red rabbits and blue cars). Two sorting bins were placed in front of the participant, each labeled with a target card (e.g., blue rabbit and red car). In the pre-switch phase of the task, children were instructed to sort the test cards with the target cards using one of the two dimensions (e.g., color) by placing cards face down in boxes. Half of the participants were assigned color as the first sorting dimension and half were assigned shape. No significant differences were found in task performance (i.e., the number of correctly sorted cards) based on the order of dimension presentation $t(40) = -.24$, $p = .82$.

After children sorted six cards, the experimenter informed them that the game changed. In this post-switch phase, children were instructed to sort the remaining six cards using the opposite dimension (e.g., shape). Again, children sorted the cards by placing them face down in the boxes. The experimenter reminded children of the sorting dimension before each trial (e.g., ‘Remember in the shape game, all the bunnies go here and all the cars go here. Here is a car. Where does it go?’). In order to succeed on the post-switch phase, children must shift their attention to the new relevant dimension while simultaneously inhibiting attention to the previous sorting dimension. Each participant received a pre-switch score based on the number of cards correctly sorted during pre-switch sorting (0-6) and a post-switch score reflecting the number of correctly sorted cards following the sorting dimension change (0-6).

Only those children who passed post-switch sorting (i.e., correctly sorted five out of six post-switch cards) in the standard DCCS were given the advanced version of the DCCS (Carlson, 2005; Zelazo, 2006). The advanced version of the task is similar to the standard version and maintains the same target cards, but half of the 12 test cards have a black rectangular border surrounding the image. Children were told to sort the cards with a border by one dimension (e.g., color), and to sort the cards without borders using the other dimension (e.g., shape). The border cards were randomly intermixed within the deck of test cards, so children were unaware of when a sorting switch would occur. Again, children were reminded of the rules of the game as the experimenter gave them each card (e.g., ‘Remember, if there is a border play the color game and if there is no border play the shape game. Here’s a card without a border. Where does it go?’). Children’s advanced DCCS scores were the number of test cards correctly sorted (0-12). Children received an overall DCCS score by summing the scores of the pre- and post-switch phases of the standard DCCS and their score on the advanced DCCS (for those children who completed it). Using this method, the possible range of scores on the DCCS is 0 to 24. Each version of the DCCS required approximately five minutes to administer.

Simon Task.

The Simon task is a computerized measure that assesses inhibitory control, attentional shifting, and attentional monitoring. E-Prime software (Schneider, Eschmann & Zuccolotto, 2002) was used to present stimuli and record participants' reaction time and response accuracy. In this task, participants viewed colored target squares presented on a computer screen and used a key-press to respond to the color of the visual target. If the target was blue, participants were instructed to press a target key located on the left of the keyboard (*z*), which was marked with a blue sticker. When the visual target was red, participants were instructed to press a target key located on the right side of the keyboard (*?*) that was marked with a red sticker. Visual targets were presented either on the left or right sides of the screen, resulting in congruent trials (i.e., target key spatially aligned with the visual target) or incongruent trials (i.e., target key not spatially aligned with visual target). Visual targets remained on the screen for 5000ms or until children made a response. Both reaction time and accuracy were recorded for each response. Children began the task by completing practice trials, which continued until they made eight consecutive correct responses or until forty trials had elapsed. Following practice, children moved on to the test phase, which was identical to practice but contained 28 total trials, with 14 congruent and 14 incongruent trials presented in a random order.

Simon task performance was assessed by recording overall reaction time and accuracy, which indexes attentional monitoring due to the intermixed nature of trials. Additionally, a Simon effect score was calculated for each child by comparing reaction time and accuracy on congruent trials to incongruent trials. A reaction time Simon effect was calculated by subtracting children's average reaction time to congruent trials from their average incongruent trial reaction time, with larger differences in reaction time indicating a larger reaction time cost to responding to incongruent trials (i.e., less efficient inhibition). A Simon effect based on accuracy was calculated by subtracting the proportion of correct responses on incongruent trials from the proportion of correct responses on congruent trials, and again a larger accuracy-based Simon effect indicates greater performance disruption due to incongruent information. The Simon effect assesses children's inhibitory control, as inhibition is necessary in incongruent trials in order to avoid responding based on the cue's location instead of color, but inhibition of spatial responding is not necessary on congruent trials. A larger Simon effect (i.e., slower reaction time or lower accuracy on incongruent trials) indexes poorer inhibitory control skills.

Attention Network Test.

The final measure of executive function was the ANT (Fan et al., 2002), which indexes inhibition and attentional monitoring. The ANT (described above) is a computerized test that is a modified version of a flanker task, which includes varied cues presented before each flanker trial. Children completed the version of the ANT modified for children (Rueda et al., 2004), which was administered using E-Prime software (Schneider et al., 2002). In this version of the ANT, children used a mouse button press to respond to the directional orientation (i.e., left or right) of a target fish. The target fish was presented in one of three trial types. In neutral trials, the target was presented in isolation (→). In congruent flanker trials, the target fish was flanked by two fish on each side that were oriented in the same direction as the target (→→→→→). Incongruent trials included a target fish that was flanked by two fish on each side that were oriented in the opposite direction of the target (←←→←←). Each trial began with visual fixation on a center cross on a computer screen for a random duration between 400ms and 1600ms followed by a visual cue (*) presented for 150ms. Cues were varied such that children either received no cue before the target presentation (no cue condition), a central cue replacing the fixation cross (center cue condition), two asterisks presented above and below the fixation point (double cue condition), or a single asterisk appearing above or below the fixation point (spatial cue condition).

Following cue presentation and an additional 450ms of central fixation, the target fish appeared either in isolation (neutral condition) or with flankers (congruent and incongruent conditions) 1^{o} above or below the central fixation cross and remained on the screen until the child provided a key press response or until 3400ms elapsed (Rueda et al., 2004). Note that the standard child ANT (Rueda et al., 2004) allows a maximum response time of 1700ms and includes 3 trial blocks of 48 trials each. Due to the relatively young age of participants in the current study the maximum reaction time was increased to 3400ms. Children responded to the direction of the target fish using the left and right mouse buttons corresponding to the target's direction (e.g., left button press for left-oriented fish). Arrows corresponding to the direction of the mouse button (e.g., left-oriented arrow on the left button) were affixed to the mouse. After each response, children received auditory feedback from the program to indicate if their response was correct ('woohoo') or incorrect (buzzer). Reaction times and accuracy were recorded for each trial. Trials in which children did not respond within 3400ms were scored as errors.

Children were first introduced to the task by the experimenter showing them a card with the target fish and explaining that the fish was hungry and they could feed him by pressing the correct mouse button. Children were then shown cards depicting examples of neutral, congruent, and incongruent trials and asked to touch arrows to indicate which direction the target fish was pointing. After children demonstrated a general understanding of the task, they moved to computerized practice trials. Children completed 24 practice trials during which they received feedback from the experimenter and were encouraged to respond to each trial as quickly and accurately as possible. Following the 24 practice trials, children completed 48 test trials. The standard version of the task (Rueda et al., 2004) includes three trial blocks of 48 test trials (144 total trials), but only the first trial block was administered in the current study due to time constraints.

Participants' performance on the executive network (i.e., inhibition) assessed by the ANT was calculated using both reaction time and accuracy. The executive network indexes inhibitory control by measuring the effect of ignoring conflicting information (e.g., incongruent flankers). A reaction time-based executive network score was calculated by subtracting median reaction time on congruent flanker trials from median reaction time on incongruent flanker trials. Larger reaction-time based executive network scores indicate less efficient inhibition and a greater reaction time cost associated with ignoring incongruent flankers. Accuracy-based executive network scores were calculated by subtracting participants' accuracy (i.e., proportion correct responses) on incongruent flanker trials from accuracy on congruent trials. Larger accuracy-based executive network scores indicate reduced accuracy on incongruent trials that require inhibition as compared to congruent trials that require no inhibition. Because the ANT contains three different flanker types (neutral, congruent, and incongruent) that require different response strategies (i.e., inhibition versus no inhibition) and are randomly intermixed throughout trial blocks, the median reaction time across all trial types indexes attentional monitoring ability, or the ability to efficiently switch between these strategies.

Artificial language.

Children's success in learning the small artificial language system was measured using six tests of receptive and expressive artificial language knowledge that were created for this study. A receptive vocabulary task was used to assess children's receptive knowledge of artificial language nouns. In this task, which is similar to the PPVT-4, children viewed a page of four images arranged in a grid, and chose the image that best represented the artificial language word read to them by the experimenter. There were 12 items in the receptive vocabulary task, one for each of the nouns in the artificial language. Each page contained an image of the correct target noun along with three incorrect foils. Two of the foils were images of other nouns that were represented within the artificial language and the third foil was an animation of a noun (animal) that is not represented in the language. Each noun served as the target on one trial and a foil on two other trials. Children's performance was calculated based on their percentage of correct responses, which was compared to chance performance (25%).

Participants completed a receptive sentence task to assess their ability to comprehend sentences in the artificial language. In this task, children heard a sentence in the artificial language and then viewed two animated videos, one of which correctly depicted the sentence (target) and one that did not correspond with the sentence (foil). Foil animations included the following errors: incorrect verb with correct subject and object, incorrect subject with correct verb and object, incorrect object with correct subject and verb, and reversal of subject and object order with the correct verb. Refer to Table 2 for examples of each foil error type. Children heard the target sentence presented prior to seeing the two animated videos and heard it presented simultaneously with each animation, for three total exposures. Participants then indicated which of the two animations best matched the sentence that they heard either verbally or by pointing. Children completed 24 trials on the receptive sentence task. All sentences used in this task are possible in the artificial language, but the test sentences and their corresponding animations are not included in language training. Additionally, the foil animations are not included in language training. Thus, all of the visual and auditory components of the receptive sentence task were novel at the time of testing. Scoring was based on the percentage of correct responses children provided, which was compared to chance performance (50%).

Participants' expressive vocabulary knowledge was measured using two picture-naming tasks. The vocabulary memory probe was completed at the beginning of Session 2 in order to measure the nouns that participants retained from Session 1, and the expressive vocabulary task was completed after language training during Session 2 (see description of procedure below). In each of these tasks, participants viewed images of nouns within the artificial language presented as single images on a page. The experimenter instructed children to name each item using the artificial language and each response was scored online as correct (all phonemes produced correctly or one phoneme error), incorrect (more than one phoneme error), and no response. Participants' responses were also digitally recorded for offline scoring. Trials on which children committed more than a single phoneme error in a lexical item as compared to their pronunciation during training were scored as incorrect. Vocabulary memory probe and expressive vocabulary task sessions were scored by the experimenter online and then re-scored offline using audio recordings. Phonological errors include phoneme deletion (e.g., /tob*a*t/ for target /tomb*a*t/), insertion (e.g., /tom*o*b*a*t/), and substitution (e.g., /to*n*b*a*t/). Systematic articulation errors were not considered incorrect responses, as these were captured in recordings of children repeating the lexical items during training. Children completed 12 trials on both the vocabulary memory probe and the expressive vocabulary task corresponding to the 12 nouns in the artificial language. Their task scores were the percentage of correct responses.

Children's ability to produce sentences in the artificial language was measured in an expressive sentence task in which they narrated 12 short animated videos (like those included in training) using the artificial language. Children were instructed to produce as much of the sentence as they could remember. Responses were scored online by the experimenter and re-scored offline from digital recordings. The same criteria applied to the expressive vocabulary task were used for scoring correct versus incorrect productions in the expressive sentence task. Each item was scored for verb accuracy, subject accuracy, and object accuracy. Those responses that contain two or more correctly produced words were also scored for word order accuracy. No animation videos used in the expressive sentence task were included in the 300 training items. Therefore, children produced sentences that they had never previously heard in the artificial language. Expressive sentence scores were based on the total number of errors committed out of the number of errors possible. Refer to Appendix B for task scoring procedures.

The final artificial language test was a grammaticality judgment task. Children listened as a puppet – which they were told was also trying to learn the artificial language – produced both correct and incorrect sentences. Children's task was to rate whether the puppet's productions were 'good' or 'not so good.' Correct productions followed the word order of the artificial language (i.e., verb-subject-object), whereas incorrect productions violated this word order (e.g., subject-verb-object, verb-verb-object, verb-subject-verb, etc.). Children completed 24 grammaticality judgment trials, and the experimenter recorded their responses. The correct sentences in the grammaticality judgment task were not included in the videos used to train children on the artificial language. Grammaticality judgment scores were calculated using an *A'* statistic, which is based on the proportion of false alarms (i.e., incorrectly accepting ungrammatical sentences) compared to the proportion of hits (i.e., correctly accepting grammatical sentences).

Although the main focus of Study 1 is to identify which cognitive skills best predict children's performance on each of the artificial language measures, a secondary set of item-level analyses were conducted in order to identify aspects of the artificial language/tasks that were relatively difficult or easy for children to acquire. These analyses are presented in Appendix C.

Procedure

Children completed two one-and-a-half-hour experimental sessions within three days of each other. Participation extended across two days in order to prevent testing fatigue, and because evidence suggests that both implicit and explicit learning processes (Fischer, Drosopoulos, Tsen, & Born, 2006; Pigneux, Laureys, Delbeuck, & Maquet, 2001; Stickgold, 2005) undergo consolidation during sleep, leading to improved learning outcomes. Indeed, researchers have found that infants and adults perform better on language learning tasks when they sleep between sessions (Fenn, Nusbaum, & Margoliash, 2008; Gais, Lucas, & Born, 2006; Gomez, Bootzin, & Nadel, 2006). In Session 1, participants' parents/guardians provided written consent, and participants provided oral assent to participate in the study. Parents/guardians answered basic demographic questions (see Appendix A), confirmed that their child's hearing and vision were normal or corrected-to-normal, and reported any languages that the child spoke fluently or heard regularly. Only children who spoke a single language fluently and who do not receive extensive exposure to a second language (i.e., no more than one hour of L2 exposure on a typical day) were included as participants.

Following child assent, children's ability to label each artificial language object in English was tested using a picture-naming task. In this task, participants were asked to name photographs of the 12 objects used in the artificial language (e.g., boy, giraffe, bee). Participants' responses were recorded. Next, children were introduced to an alien puppet that they were told speaks a language called Sillyspeak. The experimenter explained to participants that they were going to learn some of the alien's language through books and cartoons. Artificial language exposure began with an introduction to the nouns, which follows Hudson Kam and Newport's (2010) procedure for teaching an artificial language to children and adults. Additionally, Goldstein (1983) found that teaching children lexical items (nouns) prior to introducing them to word combinations improved syntactic learning outcomes among preschool-age children. The experimenter presented the child with a book containing 12 images representing the 12 nouns in the artificial language with one image on each page. The experimenter produced the artificial language label for each item and the children immediately repeated the label. This procedure was repeated four times for a total of four exposures to each noun.

Following noun training, children watched a series of short cartoon video segments (each six seconds) that included a visual animation component along with an auditory description of the action and nouns in the artificial language. Each video segment comprised a verb, noun 1, and noun 2. For example, an animation might demonstrate a frog jumping on top of a rhinoceros while simultaneously playing the audio '*Luks nɜrk nagrʌ.*' A single female speaker produced the audio recordings. Children watched the training videos for a total of 30 minutes in Session 1; taking breaks every 10 minutes or as needed. In 30 minutes, children viewed 300 short animated videos, each depicting a unique sentence in the artificial language. During the 30 minutes of training, children heard each verb 75 times, each noun used as noun-1 25 times, and each noun used as noun-2 25 times.

After artificial language training was completed, children completed the PPVT-4, forward and backward digit span measures, the DCCS, the Simon task, and the one trial block of the ANT. Language training procedures preceded testing in order to avoid any influence of fatigue associated with executive function testing on artificial language learning.

Session 2 occurred between 1 and 3 days after Session 1 and began by resuming artificial language training. The session started with a memory probe to assess which artificial language nouns the children recalled from Session 1. Children were presented the pictures of the 12 nouns in the same order used during training in Session 1 and were asked to name each picture using the artificial language. Children were praised for correct answers and were asked to repeat the correct artificial language label for those items on which they responded incorrectly or provided no response. After asking children to name each of the 12 nouns in the vocabulary memory probe procedure, the experimenter presented the 12 nouns again and asked that children repeat their artificial language names. Participants' responses were audio recorded during the vocabulary memory probe for future scoring and their repetitions of the noun labels were also recorded. These recordings of repetitions were then used as baseline correct responses for scoring expressive language tasks in order to take any systematic articulation errors into consideration on task scoring.

Following noun training, children watched the same series of 300 video segments that they watched in Session 1 presented in a different order. Again, children watched the videos for a total of 30 minutes. After artificial language training was completed, participants completed artificial language testing in the following order: expressive vocabulary test, receptive vocabulary test, expressive sentence test, receptive sentence test, and grammaticality judgment task.

Results

Preliminary Analyses

Prior to conducting regression analyses, descriptive statistics were calculated for participant characteristics (age and parent education), artificial language outcome measures, and executive function performance. These descriptive statistics are presented in Tables 3. Children's artificial language outcomes were averaged for each task and compared to chance performance. Performance on the vocabulary memory probe [$t(41) = 5.89$, $p < .001$], expressive vocabulary task [$t(41) = 9.58$, $p < .001$], and expressive sentence task [$t(41) = 10.28$, $p < .001$] were all significantly greater than 0. Likewise, children exceeded chance performance (.50) on the grammaticality judgment task [$t(41) = 2.96$, $p < .01$] but performed equal to chance on the receptive sentence task [$t(41) = 1.50$, $p = .14$]. Finally, average performance on the receptive vocabulary task exceeded chance performance (.25) [$t(41) = 17.44$, $p < .001$]. Refer to Appendix C for additional item-level analyses of children's performance on these artificial language tasks.

Correlational analyses were conducted in order to ensure that participants' artificial language outcomes were not affected by variables that are not of interest for the current study. Artificial language outcomes were not significantly correlated with participants' parents' education or the number of days between Session 1 and Session 2. Age was significantly correlated with receptive vocabulary task performance ($r = .46$, $p = .002$), but not with any other outcome variable. However, including age in the regression model predicting receptive vocabulary does not change the pattern of results.

Additional correlations were obtained in order to measure relationships among artificial language outcome variables (Table 4) and cognitive measures (Table 5). The vocabulary memory probe, expressive vocabulary, receptive vocabulary, and expressive sentence tasks are all significantly positively correlated with one another. There was also a significant correlation between vocabulary memory probe performance and grammaticality judgment task scores and a marginally significant positive correlation between the expressive vocabulary task and the receptive sentence and grammaticality judgment tasks. The low correlations between the receptive sentence and grammaticality judgment tasks and the other artificial language outcomes may be due to the children's relatively poor performance on these two tasks. A somewhat surprising finding is that the majority of the cognitive/executive function measures are unrelated with the exception of a few moderate correlations (see Table 5).

Regression Analyses

Hierarchical regressions were used to determine the amount of variance in each artificial language outcome that is predicted by the executive function measures (DCCS, Simon, ANT) beyond that of English verbal ability (PPVT-4) and working memory (digit span). Changes in R^2 statistics were used to identify whether the final regression model, which contained verbal ability, working memory, and executive function measures as predictors, significantly increased the amount of explained variance as compared to the control model that only contained verbal ability and working memory. Furthermore, partial correlations were used to identify the amount of variance in each outcome explained by individual predictors. Six regression analyses were conducted in order to assess the predictors with each of the dependent variables: artificial language vocabulary memory probe, expressive vocabulary, receptive vocabulary, expressive sentence task, receptive sentence task, and grammaticality judgment task.

In order to identify the best predictors to include in regression analyses from the number of independent variables that resulted from multiple scores derived from the executive function tasks, these scores were correlated with the outcome measures of interest (Table 6). Independent variable scores that significantly correlated with any of the dependent variables were then selected to include as executive function predictors in each regression model (Tabachnik & Fidell, 2007). This procedure resulted in the inclusion of PPVT-4, digit span total, DCCS (summed across pre-switch, post-switch, and advanced tasks), ANT median reaction time, ANT overall accuracy, and ANT accuracy-based executive network score as predictors. Prior to conducting regression analyses, Mahalanobis distances were calculated for the independent variables. No significant multivariate outliers were identified in the data as no participant's

Mahalanobis distance was significant based on the χ^2 distribution (*p*s > .001). Additionally, residual scatter plots were used to confirm that the data were relatively normally distributed and linear, and that residual distribution was homoscedastic. Two participants did not complete the ANT – one due to participant refusal and one due to experimenter error – and therefore, they were excluded from regression analyses.

Vocabulary Memory Probe

Neither the control nor final regression models (Table 7) significantly predicted children's performance on the vocabulary memory probe, which was used to assess the number of nouns in the artificial language that children retained between Session 1 and Session 2. Thus, the variance in the number of words that children retained between testing sessions was not predicted by any of the variables included in the model.

Expressive Vocabulary Task

Children's performance on the expressive vocabulary task was significantly predicted by the control model (R^2 = .15, p < .05) and was marginally significantly predicted by the final model (R^2 = .27, p < .10). However the R^2 change between the two models was not significant, which indicates that the more parsimonious control model best predicts outcomes. See Table 8 for models. Within the control model, children's expressive vocabulary performance is significantly, positively predicted by their performance on the digit span measure such that higher digit span scores predict higher expressive vocabulary task scores.

Receptive Vocabulary Task

Variance in the artificial language receptive vocabulary task was significantly predicted by the control model (R^2 = .16, p < .05) and the final model (R^2 = .55, p < .001) and the change in the R^2 value is significant between the two models (Table 9). These results indicate that including the executive function measures in the final model significantly increases the amount of predicted variance in the receptive vocabulary task beyond the control model. Within the final model, children's receptive vocabulary task performance is significantly positively related to their DCCS performance and significantly negatively related to median ANT reaction time. In other words, better performance on the DCCS and a faster response time on the ANT predict higher scores on the artificial language receptive vocabulary task.

Expressive Sentence Task

The control and final models did not significantly predict children's performance on the expressive sentence task as neither model resulted in a significant R^2 value (ps > .05). See Table 10 for regression models.

Receptive Sentence Task

Performance on the receptive sentence task was significantly predicted by the control model ($R^2 = .22$, $p < .05$) and was marginally significantly predicted by the final model ($R^2 = .30$, $p <.10$). The R^2 change between the two models was not significant, and therefore, the control model including PPVT and digit span is the best predictor of performance (Table 11). Within the control model, PPVT performance was negatively related to receptive sentence performance ($p < .10$) and digit span was positively predictive of outcome performance ($p < .01$).

Grammaticality Judgment Task

The control model was marginally significant ($R^2 = .14$) in predicting children's performance on the artificial language grammaticality judgment task, whereas the final model did not account for a significant amount of variance. Within the control model, digit span was a marginally significant predictor ($p < .10$) of grammaticality judgment task performance. Refer to Table 12 for the details of the regression models.

Study 1 Discussion

In general, children were successful in learning a simple artificial language system across two study sessions. Participants performed above chance on tasks requiring them to produce the artificial language nouns (vocabulary memory probe and expressive vocabulary task) and a task that involving production of three-word sentences in the artificial language (expressive sentence task). Within the expressive sentence task, children were successful in producing the nouns, but there was no instance of a child successfully producing a verb in the artificial language. Additionally, children's performance exceeded chance levels on a receptive vocabulary task including the artificial language nouns and in a grammaticality judgment task that tested their knowledge of the artificial language word order. However, children's performance was at chance on the receptive sentence task, which suggests that they did not fully acquire receptive knowledge of the language. Additional item-level analyses of children's performance on these artificial language measures can be found in Appendix C.

As predicted (Hypothesis 1), children's receptive L1 knowledge (PPVT-4) and their working memory abilities (digit span) were significantly predictive of their success in acquiring the small, artificial language system. The control regression model including only these two predictors accounted for a significant amount of variance in children's performance on the artificial language receptive vocabulary task (16%) expressive vocabulary task (15%), the receptive sentence task (22%), and the grammaticality judgment task (14%). Again following the predictions, within these models, digit span was positively related with their artificial language performance, such that better working memory abilities predicted better artificial language outcomes on these tasks. However, counter to Hypothesis 1, verbal ability was only significant in the control model predicting children's performance on the artificial language receptive sentence task, and this relationship was negative. In other words, lower L1 receptive vocabulary scores predicted better receptive sentence task performance. Although it did not reach significance in all regression models, the relationship between PPVT and all artificial language outcomes except grammaticality judgment was negative.

Also, differing from hypothesized results, verbal ability and working memory did not significantly predict children's performance on all artificial language outcomes as the control model comprising these two predictors did not account for significant amounts of variance in children's performance on the vocabulary memory probe or the expressive sentence task. However, due to the limited sample size in the current study, we cannot conclude that these variables are unrelated with language outcomes because the relationship may indeed exist, but the magnitude of the relationship may be too small to be detected within the current sample.

The results of Study 1 provide some support for Hypothesis 2 because, as predicted, children's executive function scores accounted for a significant amount of variance in their performance on the artificial language receptive vocabulary test beyond the variance accounted for by their English verbal ability and working memory. However, Hypothesis 2 is not fully supported because it predicted that adding executive function task performance to regression models would improve models for all artificial language outcomes, but this prediction was only borne out on the artificial language receptive vocabulary task. Furthermore, Hypothesis 2 assumed that the variability in production tasks, especially, would be explained by executive function, but to the contrary, only children's receptive vocabulary task performance could be predicted using their executive function performance. Again, however, the lack of relationship between predictors and expressive task performance must be interpreted with caution because the study may be underpowered (i.e., too few participants) to detect these relationships.

Finally, although no specific hypotheses were put forth regarding executive function components would best predict children's performance on artificial language learning outcome measures, the results from Study 1 provide some evidence that children's attentional shifting and their attentional monitoring are related to artificial language learning. In the final regression model predicting children's performance on the artificial language receptive vocabulary task, significant individual predictors included children's total DCCS score, which was positively related to artificial language performance and their median reaction time on the ANT, which was negatively associated with artificial language receptive vocabulary. Thus, higher DCCS scores and faster (i.e., better) reaction time on the ANT predicted better performance in identifying the correct visual targets in response to artificial language labels.

Recall that the DCCS requires children to engage in attentional shifting in order to switch between the pre- and post-switch soring rule and involves attentional shifting in that children must be capable of moving their attention between two stimulus properties (e.g., color and shape) to succeed. Perhaps children who were more successful at this task were also more successful on the receptive vocabulary task because they were better able to consider two labels for each object (i.e., the English and artificial language labels). Children's overall reaction time on the ANT, as indexed here by the median reaction time, indexes their attentional monitoring abilities as it captures their efficiency in responding to changing trials with varying demands. It is unclear based on the design of the current study whether children's attentional monitoring abilities were necessary during receptive vocabulary task performance or if children used these monitoring skills during artificial language training, resulting in better artificial language learning, which in turn led to improved task performance.

STUDY 2

Study 2 is an extension of Study 1, which tested the relationship between executive function abilities and success in acquiring receptive and expressive knowledge of an artificial language among monolingual adults. Including adult participants will allow us to assess the relationship between artificial language learning and executive function across development by comparing outcomes between child participants in Study 1 and adults in Study 2.

Method

The participant group comprised adults who were enrolled in introductory psychology courses at the University of Kansas. Eighty-seven adults participated in the study but nine were excluded from analyses. One adult was excluded because English was not her native language, one participant was excluded due to experimenter error, and seven participants were excluded because they did not complete the second study session. The remaining 78 adults self-reported speaking a single language (English) fluently at the time of testing. The majority of adult participants (97.4%) had received some academic exposure to an L2 at the time of testing, 21.5% of participants had been exposed to two non-native languages, and two participants had received exposure to three non-native languages. Participants' duration and type of previous L2 exposure was collected in a questionnaire (Appendix A). All participants self-reported having normal or corrected-to-normal vision and hearing. Participants were recruited through the SONA system maintained by the Department of Psychology at the University of Kansas, and participants received course research credits in exchange for research participation. Prior to study participation written consent was obtained from each participant.

Artificial Language

Adult participants were trained on the same artificial language that was used with children and described in Study 1.

Measures

Receptive vocabulary

English receptive vocabulary was measured using Form B of the PPVT-4 (Dunn & Dunn, 2007), which is described in Study 1.

Executive function

As was the case in Study 1, the executive function tasks included in Study 2 were selected in order to measure multiple components of executive function including working memory, inhibitory control, attentional shifting, and attentional monitoring. Because working memory is not among the executive function components that have been reported to be advantaged among bilingual young adults, the measure of working memory, digit span, is considered separately from tests measuring the other components of executive function within analyses.

Digit Span.

Participants' working memory was tested using the same forward and backward digit span tasks described in Study 1.

Attention Network Test.

Adults were administered the adult version of the ANT (Fan et al., 2002), which contains arrow stimuli instead of fish. Participants completed 24 practice trials followed by two 96-item test blocks and their accuracy and reaction time was measured on each trial with a maximum of 1700ms response time. Reaction time and accuracy were measured on each trial and reaction time-based executive network scores were calculated by subtracting average RT on congruent flanker trials to average RT on incongruent flankers. Average RT (ms) and proportion of correct responses was calculated across the two trial blocks for each participant.

Simon Task.

Participants in Study 2 completed the same version of the Simon task used with children in Study 1, but with a response time limit of 1000ms. Approximately half of participants (n = 40) completed a version of the Simon task presented using INQUISIT 4.0.0 software (Millisecond Software, 2012) and half (n = 38) completed a version of the Simon task that was administered using E-Prime (Schneider et al., 2002). Comparisons of Simon task performance between participants who completed the Inquisit version versus those who completed the E-Prime administered version revealed no significant differences in response time [$t(76) = -1.23$, $p > .05$] accuracy [$t(76) = 1.17$, $p > .05$] or Simon effect [$t(76) = 1.96$, $p > .05$] based on which software was used. Adults' Simon effect scores were calculated by subtracting mean RT on congruent trials from mean RT on incongruent trials. Average RT and accuracy across all trial types was also calculated for each participant.

Wisconsin Card Sorting Test.

Adult participants also completed the computerized version of the Wisconsin Card Sorting Test Computer Version 4 (Berg, 1948; Heaton et al., 1993). Like the ANT and Simon task, the WCST measures multiple components of executive function including inhibitory control (i.e., avoiding perseveration), flexibility (i.e., considering multiple rule possibilities) and shifting (i.e., switching between sorting dimensions). In the WCST, participants sort a set of test cards to match four target cards. Cards can be matched on any of three dimensions: color (red, blue, yellow, green), shape (star, circle, cross, triangle), or number of shapes (one, two, three, four). Participants are naïve to the correct sorting dimension and instead must use trial-and-error along with right/wrong feedback from the computer to determine the sorting rule. After participants have correctly sorted 10 consecutive cards using a given sorting dimension, the sorting rule changes, and participants must again use trial-and-error to determine the new sorting rule. Testing continues until participants correctly sort 10 consecutive cards in six categories (color, number, or shape, each used twice) or sort 128 cards.

The WCST yields both raw and standardized scores of the total number of cards sorted in the task (0-128), the number and percentage of cards correctly sorted, the number and percentage of incorrectly sorted cards (errors), the number and percentage of perseverative responses, the number and percentage of perseverative errors, the number and percentage of nonperseverative errors, the number and percentage of conceptual level responses, the number of trials administered before completing the first sorting rule (10 consecutive correct sorts), the number of rules completed (0-6), failure to maintain set, and learning to learn (Strauss, Sherman, & Spreen, 2006).Perseverative errors are sorting errors that occur when a participants continues to use the previously correct sorting dimension after a rule-change. Errors due to perseveration index failure to use inhibitory control and attentional shifting in order to ignore the previous sorting dimension and switch attention to the new sorting rule. Nonperseverative errors are any errors that are not due to participants using the previously correct rule.

Artificial language

Adult participants completed the same artificial language assessments described in Study 1. The vocabulary memory probe, expressive and receptive vocabulary measures were identical to those used in Study 1. The expressive sentence task contained 24 trials instead of 12 and both the receptive sentence and grammaticality judgment tasks contained 48 items instead of 24. Like children in Study 1, adults produced English sentences to describe half of the videos that they had previously described using the artificial language in the expressive sentence task.

Procedure

Participants completed two hour-long experimental sessions that occurred between one and three days apart. In Session 1, participants provided written consent for participation. After consent was obtained, participants were asked to provide demographic information (e.g., date of birth), the status of their hearing and vision, and previous second language instruction (Appendix A). Next, participants began artificial language training.

Artificial language exposure began with an introduction to the nouns. The experimenter presented the participant with a book containing 12 images representing the 12 nouns in the artificial language with one image on each page. The experimenter named each item in the artificial language, and the participant immediately repeated the lexical item while looking at the picture. Adults repeated each artificial language noun one time during training. After noun training, participants watched a series of short cartoon videos (each six seconds) that included a visual animation component along with an auditory description of the action and nouns in the artificial language. These videos were the same training videos used with children in Study 1. Participants watched videos for a total of 15 minutes during Session 1. In 15 minutes, participants viewed 150 short videos, each containing a unique sentence in the artificial language.

Following artificial language training in Session 1, participants completed the PPVT-4 measure of receptive English vocabulary knowledge, backward and forward digit span measures of working memory, and computerized versions of the WCST, a the Visual Simon Task, and the ANT. Participants were assigned two experimental credits for their completion of Session 1.

During Session 2, which occurred between one and three days after Session 1, participants resumed artificial language training during which they viewed a new series of training videos for 15 minutes. These 150 videos were different from the videos viewed during Session 1. Across the two days, adult participants viewed each of the 300 animations that were presented twice to children in Study 1, but watched each animation only one time. After artificial language training was completed, participants' receptive and expressive knowledge of the artificial language was measured using the previously described measures.

Reliability Scoring

Participants' responses during the artificial language production tasks were scored online by the experimenter and audio recorded. Twenty percent of trials from each task were randomly selected and scored for reliability offline (i.e., from audio recordings) by a trained research assistant who had not done any of the online scoring. The average percentage agreement between the online and offline coding for each artificial language production task was over 90%. Scoring reliability for each task is presented in Table 13.

Results

Preliminary Analyses

Descriptive statistics were calculated for participant characteristics (age), artificial language outcome measures, and executive function performance. These descriptive statistics are presented in Tables 14. Preliminary analyses were conducted in order to ensure that participants' artificial language outcomes were not affected by variables that are not of interest for the current study. Artificial language outcomes were not significantly correlated with participants' age, their self-rated L2 proficiency, or the duration (years) that they had studied an L2. The number of days between Session 1 and Session 2, which varied between 1 and 3 days was significantly correlated with performance on the vocabulary memory probe (r = -.293, p = .009), which assessed participants' retention of the artificial language nouns between the first and second experimental sessions. As one might expect, participants with a shorter delay between sessions had higher memory probe scores compared to participants with a longer delay between training and testing. However, the timing between experimental sessions was not significantly correlated with any of the other artificial language measures which were completed after language training during Session 2, suggesting that the effect of the delay between sessions was attenuated by additional artificial language training on during the second session.

The average self-reported proficiency rating for L2 was 2.0, which corresponds with ‘fair,’ the average self-reported proficiency rating for an L3 was 2.0 or ‘fair,’ and the average self-reported proficiency rating for an L4 was 1.7 (i.e., between ‘poor’ and ‘fair’). Participants’ L2 and L3 proficiency was not found to correlate significantly with artificial language outcome measures. Participants’ L4 self-rated proficiency was significantly correlated with performance on the artificial language receptive vocabulary task ($r = -.39$, $p < .001$) and the receptive sentence task ($r = -.24$, $p = .04$), but these relationships were in the opposite direction than was predicted as knowledge of a third non-native language was negatively correlated with outcomes. Although these relationships between L4 proficiency and artificial receptive language outcomes are significant, they are difficult to interpret because of the small subsample of participants who had been exposed to an L4 ($n = 2$), and therefore, these participants were retained in the sample for analyses. Furthermore, including L4 proficiency as a predictor in regression analyses does not change the outcomes of these analyses without L4 proficiency (reported below).

Adults’ artificial language outcomes were averaged for each task and compared to chance performance. Performance on the vocabulary memory probe [$t(77) = 9.73$, $p < .001$], expressive vocabulary task [$t(77) = 22.47$, $p < .001$], and expressive sentence task [$t(77) = 20.14$, $p < .001$] were all significantly greater than 0. Likewise, adults exceeded chance performance (.50) on the grammaticality judgment task [$t(77) = 25.04$, $p < .01$] and on the receptive sentence task [$t(77) = 33.26$, $p < .001$]. Finally, average performance on the receptive vocabulary task exceeded chance performance (.25) [$t(77) = 66.06$, $p < .001$].

Correlation analyses were also conducted in order to quantify relationships among artificial language outcomes (Table 15) and cognitive measures (Table 16). All artificial language outcome measures are significantly positively correlated with each other with high correlations between receptive language tasks (receptive vocabulary task, receptive sentence task, and grammaticality judgment) and high correlations between expressive tasks (vocabulary memory probe, expressive vocabulary task, and expressive sentence task).

Regression Analyses

Hierarchical regressions were used to determine the amount of variance in each artificial language outcome that is predicted by the executive function measures (WCST, Simon, ANT) beyond that of English verbal ability (PPVT-4) and working memory (digit span). Changes in R^2 statistics were used to identify whether the amount of variance in the outcome predicted by the independent variables increases between the control model (verbal ability and working memory) and the final regression model (i.e., control model along with executive function measures). Partial correlations were calculated to identify the amount of variance in each outcome explained by individual predictors. Six regression analyses were conducted in order to assess the predictors with each of the dependent variables: artificial language vocabulary memory probe, expressive vocabulary, receptive vocabulary, expressive sentence task, receptive sentence task, and grammaticality judgment task.

The best executive function variables to include as predictors in regression analyses were selected if they were correlated with any of the artificial language outcome measures (Table 17).

This resulted in the inclusion of PPVT-4, digit span total, WCST percentage of correct responses, WCST percentage of perseverative errors, ANT average reaction time, and ANT executive network (incongruent RT – congruent RT). Prior to conducting regression analyses, Mahalanobis distances were calculated for the independent variables and no significant multivariate outliers were identified in the data as no participant's Mahalanobis distance was significant based on the χ^2 distribution (*p*s> .001). Additionally, residual scatter plots were used to confirm that the data are relatively normally distributed, linear, and residual distribution was homoscedastic.

Vocabulary Memory Probe

Both the control (R^2 = .24, p < .001) and final regression models (R^2 = .30, p < .001) predicted a significant amount of variance in vocabulary memory probe outcomes (Table 18). However, the R^2 change between the control and final models was not significant, and therefore, the control model best fits the data. Within the control model, PPVT significantly positively predicts performance on the vocabulary memory probe and digit span is marginally related with the outcome.

Expressive Vocabulary Task

Adults' performance on the expressive vocabulary task was significantly predicted by the control model (R^2 = .22, p < .001) and was marginally significantly predicted by the final model (R^2 = .31, p <.001) and the R^2 change between the two models is marginally significant (ΔR^2 = .09, p < .10). Within the final model (Table 19), performance on the expressive vocabulary task was positively predicted by PPVT and digit span performance (*p*s < .05) and was negatively related with ANT executive network scores (p < .01).

Receptive Vocabulary Task

Variance in the artificial language receptive vocabulary task was significantly predicted by the control model (R^2 = .21, p < .001) and the final model (R^2 = .23, p < .001), but the change in R^2 between the two models is not significant. These results indicate that including the executive function measures in the final model does not significantly increases the amount of predicted variance in the receptive vocabulary task beyond the control model. In the control model, digit span positively predicts receptive vocabulary performance (p < .01) as does PPVT (p < .10). See Table 20.

Expressive Sentence Task

Adults' performance on the expressive sentence task was significantly predicted by the control model (R^2 = .23, p < .001) and the final model (R^2 = .32, p < .001), and the change in R^2 between the models as marginally significant (ΔR^2 = .10, p < .10). In the final model (Table 21), PPVT positively predicted expressive sentence performance (p < .05) and ANT executive network score was negatively predicted with the outcome (p < .01). Thus, higher scores on the PPVT and lower (i.e., better) ANT executive network scores predicted better performance on the expressive sentence task.

Receptive Sentence Task

Both the control (R^2 = .24, p < .001) and final model (R^2 = .30, p < .001) accounted for a significant amount of variance in adults' performance on the artificial language receptive sentence task (Table 22). Although the inclusion of the executive function measures in the final model increased the amount of predicted variance by 6%, this change in R^2 is not statistically significant, and therefore, the best model to predict receptive sentence task performance is the control model. Within the control model, there is a significant positive relationship between PPVT and receptive sentence task performance (p < .05) and a marginally significant positive relationship between digit span and performance on the receptive sentence task ($p < .10$).

Grammaticality Judgment Task

Finally, adults' scores on the grammaticality judgment task were significantly predicted by the control ($R^2 = .26$, $p < .001$) and final model ($R^2 = .30$, $p < .001$), but again, the R^2 change between the two models did not reach significance as the addition of executive function measures does not significantly increase the amount of variance explained in the model (Table 23). Therefore, grammaticality judgment performance is best predicted by the control model in which both PPVT and digit span have a positive and statistically significant (*ps* < .01) relationship with the outcome.

Study 2 Discussion

Adults were successful in learning the lexical items and word order of a simple artificial language over the course of two test sessions. Participants' performance on tasks that required production of the language was significantly above zero, and they also performed above chance levels on receptive artificial language task, including the receptive vocabulary and sentence measures and the grammaticality judgment task.

As hypothesized, participants' English verbal ability and their working memory span significantly predicted their success in both producing and understanding a novel artificial language. In each of the six regression analyses, the control models predicting artificial language outcomes based on adults' performance on the PPVT and the digit span measures accounted for a significant amount of variance in outcomes. Both L1 verbal ability and working memory span were positively related to all artificial language outcomes such that better performance on these variables was related with better performance on the artificial language measures, which is in line with the predictions of Hypothesis 1.

Hypothesis 2 was partially supported by the results of Study 2. It was predicted that adults' executive function abilities would account for a significant amount of variance in their performance on all outcome measures after controlling for L1 verbal ability and working memory. The addition of executive function performance only improved explanatory power in regression models predicting artificial language expressive vocabulary and expressive sentence tasks. Therefore, only tasks that required adults to produce the artificial language are significantly predicted by their executive function abilities. Although this is counter to the hypothesis that all artificial language tasks would be predicted by executive function, this finding is consistent with the prediction that artificial language production would be particularly affected by individuals' executive function skills.

In the final model of adults' expressive vocabulary performance, the individual predictors that were significant were PPVT and digit span, which were both positively related to task performance and the ANT executive network score, which was negatively associated with task outcomes. Overall, higher verbal ability and working memory along with better inhibitory control (indexed by a lower executive network score) predicted more successful performance on the expressive vocabulary task. Similarly, outcomes on the artificial language expressive sentence task, in which participants produced a sentence in the artificial language to describe a video, were positively predicted by their PPVT performance and negatively associated with ANT executive network scores. Again, better verbal ability and inhibitory control predicted superior artificial language task performance.

Existing L2 research provides evidence of a positive relationship between L1 verbal ability (see Cummins, 1991 for review) and L2 acquisition and between verbal short term memory (Atkins & Baddeley, 1998) and L2 vocabulary learning. The results of the current study suggest that these relationships may extend to artificial language-learning as well. The current finding that better inhibitory control predicts improved ability to produce a novel artificial language fits well within theories of L2 lexical access, as many such theories assume that in order for words in a target language to be accessed, the non-target language must be inhibited. Research with bilinguals suggests that this inhibition may be especially necessary when a bilingual is speaking the weaker of his two languages (Mueter & Allport, 1999). The artificial language, which participants had learned over the course of two days was certainly weak compared to their native language, English, and therefore it was likely that it was necessary for participants to inhibit English during all artificial language tasks. Therefore, it is plausible that adults who were more successful at English inhibition (i.e., those adults with lower ANT executive network scores) were then better at producing the artificial language.

GENERAL DISCUSSION

The current research addresses an open question regarding the relationship between bilingualism and cognitive functioning by investigating the directionality of this relationship. It has been widely assumed within the field of second language development that managing two languages leads to enhanced executive function. However, the directionality of that effect has not to this point been definitively addressed; the possibility exists that the relationship between these two variables is bidirectional, such that bilingual experience improves cognitive control and individuals who come to the task of L2 learning with better executive function are advantaged language learners.

Indeed, results from Study 1 support the possibility that young children may at least in part rely on executive function skills in acquiring a language, as monolingual children's success in acquiring receptive knowledge of nouns in a small, artificial language system was significantly predicted by their English receptive vocabulary knowledge, working memory, and executive function abilities. Specifically, children's attentional flexibility/shifting and attentional monitoring abilities as indexed by their performance on the DCCS and on the ANT significantly predicted their performance in learning the meanings of novel nouns. Similarly, Study 2 provides evidence that executive function processes are involved in the process of language learning among adults. Adults' success on a non-verbal inhibitory control task was positively related to expressive vocabulary and expressive sentence performance on an artificial language. Variation in adults' success in labeling pictures using the artificial language was significantly accounted for by their English verbal ability, their working memory span, and their inhibitory control. Success in describing videos using the artificial language (i.e., producing nouns and verbs in the appropriate word order) was significantly predicted by adults' English verbal ability and their inhibitory control.

However, it is important to note that although executive function abilities were predictive of children's receptive artificial language vocabulary knowledge and of adults' success on expressive artificial language tasks; executive function did not predict performance on many of the artificial language outcome tasks. Children's executive function performance did not significantly predict their success in producing single words or sentences in the artificial language, nor was it predictive of their success in understanding sentences or recognizing the grammaticality of sentences in the artificial language. Among adults, executive function skills did not significantly predict their ability to understand single words or sentences in the artificial language or their ability to recognize grammatical strings in the language. As discussed further below, the lack of predictive relationship between executive function and these outcome measures may be due to inadequate statistical power to detect these relationships, an issue of floor or ceiling effects for children's and adults' expressive and receptive artificial language task performance, respectively, or may be due to the fact that the relationship between executive function and artificial language learning only exists in limited contexts. Additional research is necessary to further explore these possibilities.

With respect to the artificial language outcomes that were significantly predicted by executive function, it is important to note that the executive function task outcomes that were identified as significant predictors of artificial language learning in the current study are the same outcomes that have been previously identified as advantaged among bilinguals in previous research. Specifically, children and adults in the current study who performed better on the same executive function tasks on which bilinguals have been reported to have an advantage had better outcomes on the artificial language measures. This provides further support for the notion that the relationship between bilingualism and cognitive function might be bidirectional. Among children, DCCS scores and ANT reaction time were significantly predictive of receptive vocabulary knowledge in the artificial language. Bialystok (1999) reports a DCCS advantage among bilingual children compared to monolinguals while Kapa and Colombo (in press) report that simultaneous bilingual children have faster ANT reaction times compared to monolinguals. Among adults, ANT executive network scores accounted for a significant amount of variance in expressive artificial language task performance. Costa et al. (2008) found that bilingual adults have significantly smaller ANT executive network scores compared to monolingual adults. The overlap between the cognitive measures found to predict artificial language-learning outcomes in the current study and advantaged cognitive performance among bilinguals in past research also lends support to the possibility that the same cognitive skills are involved in learning a new artificial language and managing two languages.

Given the results of the present studies and the prior relevant research, the question remains as to why these specific executive function tasks are associated with L2 proficiency and acquisition. Existing models of bilingual lexical access posit the need for bilinguals to monitor the language environment in order to choose a target language and then employ inhibitory control either at the lexeme-level (Green, 1998) or to an entire language system (Costa & Caramazza, 1999) to select the target language while avoiding the non-target language. The tasks on which bilinguals have demonstrated an advantage in previous studies and which were found to be predictive of artificial language learning in the current study measure the same cognitive skills that are hypothesized to be involved in bilingual lexical access, namely attentional monitoring and inhibitory control.

Comparing between the results from child participants in Study 1 and adult participants in Study 2 provides interesting insight into possible developmental changes in the relationship between cognition and artificial language acquisition. Among children, executive function abilities only significantly predicted their artificial language *receptive* vocabulary performance, but predicted *expressive* language performance among adults. There are several possibilities to account for this finding. One possible cause for the difference between adults and children is the fact that children are in fact only using executive function during artificial language comprehension but not during language production, and conversely, adults are only using executive function during artificial language production, but not comprehension. However, such a conclusion is likely too strong based on the data at hand. Firstly, the relationship between executive function and expressive artificial language performance in children may be too small of an effect to detect with the current sample size (see “Caveats and Limitations” below). Another possibility is that the current analyses are limited because of floor and ceiling effects on outcome tasks. Children's executive function may indeed predict their expressive language abilities, but their scores may have been too low on the expressive language tasks included in the current study for the relationship to become apparent. Likewise, adults may use executive functioning while producing and comprehending an artificial language, but adults' performance on the receptive artificial language tasks used in Study 2 may have been too routinely high (i.e., ceiling effects) to observe a relationship between executive function performance and outcomes on receptive tasks.

Another interesting difference between adults and children is that among children, English verbal ability is negatively related to most artificial language outcomes, but this relationship is positive among the adults included in Study 2. Again, there are multiple possible explanations for this difference. One may be that adults, who have more language experience, are relying on their L1 language knowledge to facilitate learning the novel artificial language, whereas children are not using their L1 while acquiring the artificial language. Several studies provide evidence that early in L2 acquisition adult learners may rely on translation between the L1 and L2 instead of directly accessing the L2 lexicon (see Kroll & Tokowicz, 2001 for review). Therefore, in the case of adults in the current study, those adults with better verbal ability (i.e., a larger lexicon as measured by the PPVT) may be more efficient in the process of accessing and translating the target artificial language response (e.g., accessing *frog* and translating to *nɜrk*). However, perhaps children are not using this translation strategy, and therefore their L1 abilities are unrelated, or in some cases significantly negatively related to their artificial language performance.

A second possible explanation for the discrepancy in the role of L1 verbal ability in artificial language learning between children and adults is that both groups are relying on their

L1 to learn the artificial language, but the L1 lexicon is facilitative for adult learners but impeding for children. Thus, stronger L1 verbal abilities among adults predict better artificial language learning, but the opposite would be expected to be true among children. However, it is unclear why L1 abilities would be beneficial for adults but not for children. One possibility is that adults have stronger lexical representations in their L1 and therefore can efficiently translate between the L1 and artificial language, whereas children, who by comparison have weaker lexical representations and less efficient lexical access (Huang & Snedeker, 2011), cannot use translation as an efficient strategy. Another possibility is that adults are more successful at inhibiting their L1 because of more developed attentional control but children, whose executive functions are still developing, are less successful at inhibiting their L1. Regardless of its underlying source, the difference between the role of L1 in artificial language acquisition among children and adults is interesting as it suggests developmental differences in the processes through which children and adults learn a new language.

A final interesting point regarding the outcomes of Studies 1 and 2 is the fact that both children and adults demonstrated a relative weakness in acquiring the verbs in the artificial language as compared to nouns. None of the 4- and 5-year-olds included in Study 1 successfully produced the artificial language verbs, and their performance on receptive sentence task items that required verb knowledge was below chance (see Appendix C). Although some adults successfully learned the artificial language verbs, as a whole they were significantly less accurate when producing verbs compared to nouns. Multiple explanations may account for the inequality between noun and verb learning in the current studies.

First, the difference between noun and verb learning may result from the training procedures of the current studies. Children and adults were explicitly taught the artificial language nouns by repeating object labels after the experimenter while viewing corresponding pictures. In contrast, verbs were only presented in the training videos, and therefore successful verb acquisition required participants to recognize the regularity of the occurrence of seeing an action while hearing the verb. Thus, verbs had to be learned implicitly, while nouns were taught explicitly. This task may have been especially challenging because in order to succeed, participants had to generalize the verbs across multiple exemplars, which has been shown to impede verb learning in children (Maguire, Hirsh-Pasek, Golinkoff, & Brandone, 2008). A second possibility is that verbs are more difficult than nouns to acquire, regardless of training. This possibility is supported by evidence that English-speaking children (Bornstein et al., 2004) and adults (Ludington, 2013) have a noun bias, which leads to faster acquisition of nouns compared to lexical items from other word classes. Refer to future directions for a proposed method for testing between these competing explanations.

Caveats and Limitations

Although the current studies provide important evidence for the role of executive function in language learning among both child and adult participants, this evidence must be considered in light of limitations of the studies. In Study 1, children’s executive function skills were found to predict their success on a receptive vocabulary task in the artificial language, while no predictive relationship was established between executive function and any other language outcome measures. However, Study 1 features a relatively small sample size of children included in Study 1 and the inclusion of a large number of predictors. The possibility exists that the regression models generated may have approached saturation. The fact that the models did not appear to be over parameterized (i.e., the fit for no model approached perfection) suggests that this was not a factor, but it remains unclear as to whether the large number of independent variables may have obscured relationships between executive function and other language outcomes due to a lack of statistical power to detect these effects. Thus, perhaps the safest conclusion to draw from is that the results of Study 1 provide positive support for a relationship between executive function and receptive language development, but leave open the possibility that executive function and expressive language development are also related in childhood.

Another limitation of both Study 1 and Study 2 is the use of an artificial language system, which provides an interesting first step in assessing how children and adults may use executive functions while learning a new language, but which may not necessarily be directly translatable to natural language learning. Artificial languages are by design highly simplified compared to the complexities of natural languages. This simplification allows participants to acquire artificial languages in a fraction of the time required to acquire a natural language system, but because artificial languages are so much simpler than natural languages, the possibility of differences in processes of acquisition remains. The artificial language used in Study 1 and Study 2 is especially different from natural languages due to the extremely impoverished syntax, which was only represented by linear word order (i.e., verb-noun1-noun2). The task of learning the current artificial language was mainly one of lexical learning. Although this is part of learning a natural language, it does not capture the whole process. Thus, the findings of the current study could be limited to lexical learning and perhaps very simple syntax (linear word order), and may not extend to individuals' outcomes of learning other aspects of language such as complex syntax, morphology, or prosody.

Therefore, although Studies 1 and 2 provide evidence that children's and adults' executive function performance predicts their success in learning an extremely simple artificial language, the possibility remains that these relationships would not exist between executive function and natural language learning. This possibility is lessened, however, by the fact that artificial language learning was predicted by exactly those executive function components that have been associated in prior research with naturally occurring L2 proficiency.

Future Directions

Although the results of the current studies provide interesting and exciting evidence of a predictive relationship between executive function abilities and artificial language learning outcomes, there are several open questions that must be addressed by future research. One issue in the current studies is potential problems with floor and ceiling effects among children and adults respectively, which may be masking relationships between executive function and artificial language learning. A possible solution to this problem is to repeat the methods of the current studies but simplify the artificial language for children by reducing the number of lexical items and/or increasing total language training time, while increasing language difficulty for adults by adding more lexical items and/or reducing training time. Improving children's artificial language outcomes and worsening adults' outcomes may reveal that executive function is predictive of expressive artificial language outcomes among children and receptive outcomes among adults.

Another unresolved issue in the current studies is the discrepancy between artificial language noun and verb learning. As previously discussed, the relative deficit in verb acquisition has many possible sources. One means of testing whether differences in explicit versus implicit artificial language training may account for the asymmetry would be to conduct a study in which half of the artificial language lexical items (i.e., two verbs and six nouns) were trained explicitly using the picture labeling technique and the remaining half were learned only implicitly from the video training. Using this methodology will isolate the effects of explicit versus implicit training (e.g., explicit nouns versus implicit nouns) and reveal whether individuals can learn verbs and nouns equally if they are trained (e.g., explicit nouns versus explicit verbs).

An additional future change to the current studies that would address unresolved issues would be increasing the complexity of the artificial language syntax and/or adding morphology. As mentioned, the artificial language used in both studies was extremely simplified and lacked linguistic properties that occur in natural languages including syntax beyond linear word order and morphology. Because the language lacks these properties, it remains unclear whether the current findings extend beyond lexical learning to other aspects of language acquisition. Therefore, following the general methods of the current studies but using an artificial language with additional linguistic properties would be necessary for testing whether individuals' executive function also predicts their success in acquiring other linguistic properties.

Furthermore, the results of the current research could be expanded by testing participants who are acquiring a natural L2, instead of using an artificial language system. For example, the executive function skills of a group of children or adults may be tested before they begin learning an L2 and then used to predict their outcomes on the L2 tested subsequently. This type of expansion would be necessary to establish whether the current effects are limited to artificial languages.

The outcomes from this research have possible practical implications for L2 instruction with both children and adults. Because executive function abilities are predictive of L2 learning, it follows that improving an individual's executive function skills may also improve his/her language learning outcomes. Indeed, there is an emerging body of research supporting the possibility of executive function training programs (Diamond & Lee, 2011; Posner & Rothbart, 2005; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Tang & Posner, 2009). These training methods could theoretically be integrated into L2 instruction in order to improve executive function, which based on the results of this study would in turn result in better L2 learning outcomes. A future empirical investigation of this relationship may be achieved by comparing artificial language learning between children who have received executive function training and children with no such training, to discern whether improvements in executive function lead to improved artificial language learning.

Summary

In sum, the current studies tested the possibility that children's and adults' executive function skills are predictive of their ability to acquire a novel artificial language system. The results of Study 1 support the role of preschool children's executive function abilities, specifically attentional shifting and monitoring, in acquiring receptive knowledge of artificial language vocabulary. Study 2 suggests that adults' executive function abilities, particularly attentional inhibition, predict their success in producing a novel artificial language. A large body of previous research reports executive function advantages among bilingual individuals, and this relationship between executive function and bilingualism has been largely assumed to be unidirectional with bilingual language experience leading to improvements in executive function. However, the results of the current studies provide evidence that the relationship between executive function and language learning may be bidirectional as individuals' executive function abilities were found to be predictive of their ability to acquire an artificial language.

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Table 1

Artificial Language Lexical Items

Nouns	Gloss	Verbs	Gloss
/nɜrk/	frog	*/blɪt/*	move under
/nagɪd/	elephant	*/smɪt/*	move beside
/nagrʌ/	rhinoceros	*/flɪm/*	move around
/lædnʌ/	turtle	*/luks/*	move on top
/mɪsnʌ/	snake		
/mɜrnɪt/	boy		
/fɜrlukʌ/	girl		
/fumpogʌ/	bird		
/slɜrgan/	alligator		
/flugat/	bee		
/tombat/	giraffe		
/blɜrgən/	lion		

Table 2

Receptive Sentence Task Target and Foil Examples

Target	Foil	Error
blɪt blɜrgən lædnʌ	*smɪt blɜrgən lædnʌ*	Incorrect verb
luks fɜrlukʌ nɜrk	*luks flugat nɜrk*	Incorrect noun 1
flɪm nagrʌ tombat	*flɪm nagrʌ slɜrgan*	Incorrect noun 2
smɪt mɪsnʌ mɜrnat	*smɪt mɜrnat mɪsnʌ*	Reversal of noun 1 and noun 2

Table 3

Study 1 Descriptive Statistics

Measure	Mean	Std. Deviation	Range
Age (mo.)	56.7	6.2	48 – 71
Parent Education	3.2	.80	1 – 5
Days between Sessions	1.9	.83	1 – 4
PPVT	118.7	11.9	91 – 146
Forward Digit	5.2	1.5	2 – 8
Backward Digit	1.7	1.3	0 – 4
DCCS Pre-switch	5.9	.48	3 – 6
DCCS Post-switch	5.4	1.8	0 – 6
DCCS Advanced	6.4	3.0	0 – 11
Simon Effect	.02	.12	-.29 –.36
Simon Average RT (ms)	1279.3	317.2	678 – 2159
Simon Accuracy	.87	.12	.39 – 1.0
ANT Executive Network	.07	.20	-.31 –.75
ANT Median RT (ms)	1483.7	256.0	948 – 2064
ANT Accuracy	.83	.12	.56 –.98
Vocabulary Memory Probe	.09	.10	0 –.42
Expressive Vocabulary	.27	.18	0 –.67
Receptive Vocabulary	.80	.20	.33 – 1.0
Expressive Sentence: Total	.18	.11	0 –.52
Expressive Sentence: Word Order	.33	.39	0 – 1.0
Expressive Sentence: Verb	0	0	--
Expressive Sentence: Noun 1	.27	.17	0 –.67
Expressive Sentence: Noun 2	.26	.17	0 –.75
Receptive Sentence	.52	.08	.33 –.75
Grammaticality Judgment	.52	.04	.49 –.69

Table 4

Study 1 Correlations between Artificial Language Outcome Measures

	Memory Probe	Expressive Vocabulary	Receptive Vocabulary	Expressive Sentence	Receptive Sentence	Grammaticality Judgment Task
Memory Probe	--	.53***	.48***	.60***	.14	.31*
Expressive Vocabulary		--	.65***	.87***	.26†	.26†
Receptive Vocabulary			--	.68***	.23	.23
Expressive Sentence				--	.21	.24
Receptive Sentence					--	.11
Grammaticality Judgment Task						--

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 5

Study 1 Correlations between English Vocabulary, Working Memory, and Executive Function Measures

	PPVT	Digit	Simon Avg. RT	Simon Effect RT	Simon Effect Acc.	Simon Avg. Acc.	ANT Med. RT	ANT Conflict RT	ANT Conflict Acc.	ANT Avg. Acc.	DCCS
PPVT	--	.44**	.08	.14	-.08	.43**	-.18	.14	-.17	.04	.34*
Digit Span		--	-.08	.14	.11	.24	-.35*	.02	-.49**	.33*	.56***
Simon Avg. RT			--	.04	-.11	.01	.36*	-.02	.14	-.48**	.05
Simon Effect RT				--	-.15	.05	-.12	.24	-.36*	.17	.10
Simon Effect Acc.					--	-.13	-.14	.01	-.12	.24	.21
Simon Avg. Acc.						--	-.30†	.26	-.30†	.26	.09
ANT Med. RT							--	.09	.24	.45**	-.12
ANT Exec. Network RT								--	-.26	.18	-.15
ANT Exec. Network Acc.									--	-.16	-.20
ANT Avg. Acc.										--	.13
DCCS Total											--

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 6

Study 1 Correlations between Possible Predictors and Artificial Language Outcome Measures.

	Memory Probe	Expressive Vocabulary	Receptive Vocabulary	Expressive Sentence	Receptive Sentence	Grammaticality Judgment Task
PPVT	.01	.18	.16	.13	-.10	.26†
Digit Span	.19	.40**	.39**	.33*	.36*	.38*
Simon Average RT	.17	.20	-.15	.19	-.16	-.05
Simon Effect RT	.08	.23	.11	.13	.30†	.15
Simon Effect Accuracy	.07	-.13	.01	-.17	.07	.06
Simon Avg. Accuracy	-.12	-.07	-.04	-.16	-.07	-.06
ANT Median RT	-.04	-.31*	-.41**	-.23	-.16	-.26
ANT Exec. Network RT	-.14	-.20	-.20	-.12	.23	.02
ANT Exec. Network Acc.	-.25	-.08	-.01	-.02	-.34*	-.34*
ANT Avg. Accuracy	-.13	.17	.25	.07	.33*	-.02
DCCS Total	.23	.43**	.59**	.34*	.18	.28

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 7

Regression Model Predicting Children's Artificial Language Vocabulary Memory Probe Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.045	.045			
PPVT			-.085	-.092	-.518
Digit			.212	.234	1.32
Final Model	.117	.163			
PPVT			-.137	-.142	-.793
Digit			.053	.073	.304
DCCS Total			.206	.236	1.21
ANT Median RT			-.073	-.078	-.418
ANT Average Accuracy			-.230	-.251	-1.36
ANT Executive Network			-.200	-.217	-1.17

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 8

Regression Model Predicting Children's Artificial Language Expressive Vocabulary Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.154*	.154*			
PPVT			-.005	-.005	-.031
Digit			.362	.394	2.36*
Final Model	.117	.271†			
PPVT			-.062	-.060	-.359
Digit			.194	.254	1.14
DCCS Total			.269	.292	1.60
ANT Median RT			-.249	-.256	-1.48
ANT Average Accuracy			-.044	-.043	-.251
ANT Executive Network			.149	.149	.863

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 9

Regression Model Predicting Children's Artificial Language Receptive Vocabulary Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.161*	.161*			
PPVT			-.005	-.006	-.033
Digit			.370	.403	2.42*
Final Model	.384***	.545***			
PPVT			-.126	-.097	-.732
Digit			.080	.082	.464
DCCS Total			.591	.605	4.21***
ANT Median RT			-.426	-.371	-2.70*
ANT Average Accuracy			.014	.011	.083
ANT Executive Network			.270	.220	1.61

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 10

Regression Model Predicting Children's Artificial Language Expressive Sentence Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.107	.107			
PPVT			-.010	-.010	-.058
Digit			.302	.331	1.93†
Final Model	.116	.223			
PPVT			-.075	-.074	-.431
Digit			.186	.251	1.09
DCCS Total			.258	.289	1.54
ANT Median RT			-.213	-.224	-1.25
ANT Average Accuracy			-.120	-.123	-.692
ANT Executive Network			.176	.183	1.03

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 11

Regression Model Predicting Children's Artificial Language Receptive Sentence Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.218*	.218*			
PPVT			-.310	-.318	-1.98†
Digit			.457	.502	3.13**
Final Model	.078	.296†			
PPVT			-.295	-.292	-1.77†
Digit			.204	.264	1.20
DCCS Total			.109	.112	.629
ANT Median RT			.054	.053	.309
ANT Average Accuracy			.231	.230	1.36
ANT Executive Network			-.216	-.216	-1.27

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 12

Regression Model Predicting Children's Artificial Language Grammaticality Judgment Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.144†	.144†			
PPVT			.107	.110	.655
Digit			.298	.319	1.90†
Final Model	.100	.243			
PPVT			.069	.067	.395
Digit			.117	.155	.678
DCCS Total			.125	.134	.722
ANT Median RT			-.225	-.234	-1.33
ANT Average Accuracy			-.218	-.224	-1.28
ANT Executive Network			-.196	-.202	-1.15

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 13

Reliability Measures between Online and Offline Artificial Language Expressive Task Scoring

Task	% Agreement
Vocabulary Memory Probe	90.4%
Expressive Vocabulary	98.7%
Expressive Sentence: Word Order	95.8%
Expressive Sentence: Verb	99.6%
Expressive Sentence: Noun 1	97.2%
Expressive Sentence: Noun 2	93.1%

Table 14

Study 2 Descriptive Statistics.

Measure	Mean	Std. Deviation	Range
Age (mo.)	235.6	15.7	220 – 332
Days between Sessions	1.8	.69	1 – 3
PPVT	106	12.9	81 – 135
Forward Digit	10.9	1.7	8 – 14
Backward Digit	7.7	2.1	2 – 12
WCST Perseverative Errors	.10	.05	.05 –.28
WCST Correct	.80	.10	.47 – .91
Simon Effect (ms)	16.8	37.8	-76 – 115
Simon Average RT (ms)	426.2	56.8	322 – 619
Simon Accuracy	.95	.05	.79 – 1.0
ANT Executive Network (ms)	107.2	38.5	45 – 307
ANT Average RT (ms)	506.9	57.7	141 – 715
ANT Accuracy	.97	.03	.89 – 1.0
Vocabulary Memory Probe	.25	.23	0 – 1.0
Expressive Vocabulary	.75	.29	0 – 1.0
Receptive Vocabulary	.96	.09	.58 – 1.0
Expressive Sentence: Total	.70	.30	.01 – 1.0
Expressive Sentence: Word Order	.85	.30	0 – 1.0
Expressive Sentence: Verb	.57	.44	0 – 1.0
Expressive Sentence: Noun 1	.76	.28	0 – 1.0
Expressive Sentence: Noun 2	.75	.30	0 – 1.0
Receptive Sentence	.93	.11	.58 – 1.0
Grammaticality Judgment	.90	.14	.50 – 1.0

Table 15

Study 2 Correlations between Artificial Language Outcome Measures

	Memory Probe	Expressive Vocabulary	Receptive Vocabulary	Expressive Sentence	Receptive Sentence	Grammaticality Judgment Task
Memory Probe	--	.58***	.29*	.57***	.38**	.44***
Expressive Vocabulary		--	.65***	.85***	.64***	.65***
Receptive Vocabulary			--	.59***	.64***	.62***
Expressive Sentence				--	.74***	.76***
Receptive Sentence					--	.82***
Grammaticality Judgment Task					.	--

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 16

Study 2 Correlations between English Vocabulary, Working Memory, and Executive Function Measures

	PPVT	Digit	Simon Avg. RT	Simon Effect RT	Simon Avg. Acc.	ANT Avg. RT	ANT Conflict RT	ANT Avg. Acc.	WCST % Correct	WCST Perseverative
PPVT	--	.283*	.09	-.02	.07	-.18	-.14	.06	.36**	-.40***
Digit Span		--	-.29*	.09	-.02	-.32**	-.21	.12	.27*	-.28*
Simon Avg. RT			--	-.10	.05	.39**	.05	-.06	-.05	-.02
Simon Effect RT				--	.13	.04	.19†	-.18	-.18	.01
Simon Avg. Acc.					--	.27*	.21†	.32**	-.04	.01
ANT Avg. RT						--	.53***	.11	-.09	.07
ANT Exec. Network							--	.06	-.07	-.02
ANT Avg. Acc.								--	.17	-.19
WCST % Correct									--	-.88***
WCST Perseverative										--

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 17

Study 2 Correlations between Possible Predictors and Artificial Language Outcome Measures.

	Memory Probe	Expressive Vocabulary	Receptive Vocabulary	Expressive Sentence	Receptive Sentence	Grammaticality Judgment Task
PPVT	.44***	.35**	.28*	.41***	.43***	.40***
Digit Span	.29**	.37**	.39**	.35**	.30**	.35**
Simon Average RT	-.07	-.13	-.14	-.10	-.15	-.19
Simon Effect	-.03	-.08	.00	-.08	-.08	-.07
Simon Accuracy	.10	.00	-.04	-.15	-.14	-.09
ANT Average RT	$-.21^{\dagger}$	-.28*	$-.22^{\dagger}$	-.27*	-.31**	-.28*
ANT Executive Network	-.28*	-.39***	-.23*	-.38**	-.28*	-.29*
ANT Accuracy	.17	.22	.13	.09	.03	.06
WCST % Correct	.12	.16	.14	.23*	.27*	.24*
WCST % Persev. Errors	$-.19^{\dagger}$	-.17	-.01	-.25*	-.36*	$-.20^{\dagger}$

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 18

Regression Model Predicting Adults' Artificial Language Vocabulary Memory Probe Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.226***	.226***			
PPVT			.392	.391	3.59***
Digit			.194	.182	$1.71^{\dagger}$
Final Model	.061	.287***			
PPVT			.366	.373	3.31**
Digit			.157	.150	1.34
ANT Average RT			.021	.022	.181
ANT Executive Network			-.229	-.227	$-1.98^{\dagger}$
WCST % Correct			-.176	-.318	-1.51
WCST Perseverative			-.152	-.281	-1.30

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 19

Regression Model Predicting Adults' Artificial Language Expressive Vocabulary Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.200***	.200***			
PPVT			.270	.262	2.43*
Digit			.302	.296	2.74**
Final Model	.097†	.297***			
PPVT			.234	.227	2.03*
Digit			.243	.235	2.11*
ANT Average RT			.010	.011	-.088
ANT Executive Network			-.312	-.331	-2.77**
WCST % Correct			-.084	-.149	-.714
WCST Perseverative			-.086	-.157	-.730

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 20

Regression Model Predicting Adults' Artificial Language Receptive Vocabulary Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.178**	.178**			
PPVT			.188	.181	1.66
Digit			.333	.333	3.05**
Final Model	.026	.204*			
PPVT			.190	.194	1.63
Digit			.300	.313	2.65*
ANT Average RT			-.032	-.034	-.266
ANT Executive Network			-.093	-.100	-.790
WCST % Correct			.073	.137	.615
WCST Perseverative			.097	.188	.824

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 21

Regression Model Predicting Adults' Artificial Language Expressive Sentence Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.228***	.228***			
PPVT			.348	.340	3.22**
Digit			.266	.252	2.39*
Final Model	.095†	.323***			
PPVT			.291	.282	2.57*
Digit			.192	.179	1.65
ANT Average RT			.009	.010	.080
ANT Executive Network			-.311	-.324	-2.76**
WCST % Correct			-.079	-.137	-.667
WCST Perseverative			-.120	-.215	-1.02

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 22

Regression Model Predicting Adults' Artificial Language Receptive Sentence Task Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.216***	.216***			
PPVT			.377	.376	3.61**
Digit			.199	.187	1.96†
Final Model	.061	.277**			
PPVT			.318	.320	2.82**
Digit			.104	.099	.884
ANT Average RT			-.132	-.138	-1.23
ANT Executive Network			-.134	-.138	-1.24
WCST % Correct			.063	.113	.534
WCST Perseverative			.004	.007	.033

Note: † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table 23

Regression Model Predicting Adults' Artificial Language Grammaticality Judgment Performance from English Verbal Ability, Working Memory, and Executive Function.

Measure	ΔR^2	Cumulative R^2	sr^2	β	t
Control	.218***	.218***			
PPVT			.329	.322	3.02**
Digit			.270	.259	2.43*
Final Model	.050	.304**			
PPVT			.291	.293	2.57*
Digit			.202	.197	1.74[†]
ANT Average RT			-.074	-.077	-.622
ANT Executive Network			-.147	-.153	-1.25
WCST % Correct			.101	.183	.859
WCST Perseverative			.073	.134	.613

Note: [†] $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Appendix A

Child Questionnaire (completed by parent/guardian)
Date of birth (mm/dd/yy): ________________________
Age ____y ______m _______d
Sex: ☐male ☐female
Vision: ☐normal
☐corrected normal (explain)____
☐uncorrected problem (explain)____
Hearing: ☐normal
☐corrected normal (explain) ____
☐uncorrected problem (explain)____
Languages spoken fluently: ____
____
Languages regularly heard: ____
____
Language 1 hrs/day_______ Language 2 hrs/day_______ Language 3 hrs/day_______
Mother's highest level of education:____________________________________
Father's highest level of education:_____________________________________

Adult Questionnaire (completed by participant)
Date of birth (mm/dd/yy): ________________________
Age ____y ______m _______d
Sex: ☐male ☐female
Vision: ☐normal
☐corrected normal (explain)____
☐uncorrected problem (explain)____
Hearing: ☐normal
☐corrected normal (explain)____
☐uncorrected problem (explain)____
Languages spoken fluently: ____
____
Languages regularly heard: ____
____
Are you currently enrolled in second language instruction? ☐yes ☐no
If yes, what language(s)? ____
How much instruction? ______hrs/week
Have you previously received second language instruction? ☐yes ☐no
If yes, what language(s)? 1______________ 2________________ 3________________
How long was each studied? 1_______________ 2_______________ 3______________
How would you rate your proficiency in each?
Language 1: ☐poor ☐fair ☐somewhat good ☐good ☐excellent
Language 2: ☐poor ☐fair ☐somewhat good ☐good ☐excellent
Language 3: ☐poor ☐fair ☐somewhat good ☐good ☐excellent

Appendix B

Verb accuracy	**Subject accuracy**	**Object accuracy**	**Word order accuracy**	**Overall accuracy**
a_____ # verb errors	c_____ # subject errors	e_____ # object errors	g_____ # word order errors	a + c + e + g = j____total errors
a_____/12 =b_____	c_____/12 =d_____	e_____/12 =f_____	g_____/h_____# scorable WO =i______	j____/36 + h_____ = k_____
1- b____ x 100= %	1- d_____ x 100= %	1- f______ x 100 = %	1-i______ x 100 = %	1- k_____ x 100 = %

Appendix C

Table C.1

Item-level Analyses of Children's Performance on the Artificial Language Vocabulary Probe

Item	% Correct Responses	*t*
/nɜrk/	33.3%	4.53***
/nagɪd/	2.4%	1.00
/nagrʌ/	0%	--
/lædnʌ/	0%	--
/mɪsnʌ/	0%	--
/mɜrnat/	7.1%	1.78†
/fɜrlukʌ/	11.9%	2.35*
/fumpogʌ/	9.5%	2.08*
/slɜrgan/	4.8%	1.43
/flugat/	14.3%	2.6*
/tombat/	26.2%	3.81***
/blɜrgən/	7.1%	1.78†

Note: *t* value is comparison to 0; † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table C.2

Item-level Analyses of Children's Performance on the Artificial Language Expressive Vocabulary Task

Item	% Correct Responses	*t*
/nɜrk/	52.4%	6.72***
/nagɪd/	14.3%	2.61*
/nagrʌ/	11.9%	2.35*
/lædnʌ/	7.1%	1.78†
/mɪsnʌ/	16.7%	2.86**
/mɜrnat/	9.5%	2.08*
/fɜrlukʌ/	38.4%	5.02***
/fumpogʌ/	23.8%	3.58**
/slɜrgan/	19.0%	3.11**
/flugat/	45.2%	5.82***
/tombat/	50.0%	6.40***
/blɜrgən/	38.1%	5.02***

Note: *t* value is comparison to 0; † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table C.3

Item-level Analyses for Children's Mean Performance on the Artificial Language Receptive Vocabulary Task

Item	% Correct Responses	*t*
/nɜrk/	95.2%	21.12***
/nagɪd/	81.0%	9.12***
/nagrʌ/	66.7%	5.66***
/lædnʌ/	52.4%	3.51**
/mɪsnʌ/	92.9%	16.87***
/mɜrnat/	73.8%	7.11***
/fɜrlukʌ/	92.9%	16.87***
/fumpogʌ/	71.4%	6.58***
/slɜrgan/	76.2%	7.70***
/flugat/	80.1%	9.12***
/tombat/	83.3%	10.02***
/blɜrgən/	88.1%	12.47***

Note: *t* value is comparison to chance (.25); † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table C.4

Item-level Analyses of children's Artificial Language Expressive Sentence Task Performance

Item	Verb	% Correct	t	Noun 1	% Correct	t	Noun 2	% Correct	t	Word Order # Scorable	% Correct	t
1	*/smɪt/*	0%	--	*/fɜrlukʌ/*	31.0%	4.3***	*/blɜrgən/*	40.5%	5.3***	5	*60.0%*	*.41*
2	*/blɪt/*	0%	--	*/flugat/*	45.2%	5.8***	*/mɜrnat/*	16.7%	2.9**	5	*80.0%*	*1.5*
3	*/luks/*	0%	--	*/nɜrk/*	47.6%	6.1***	*/fɜrlukʌ/*	28.6%	4.1***	5	*20.0%*	*-1.5*
4	*/smɪt/*	0%	--	*/lædnʌ/*	9.5%	2.1*	*/fumpogʌ/*	19.0%	3.1**	2	*50.0%*	*.00*
5	*/flɪm/*	0%	--	*/slɜrgan/*	28.6%	4.1***	*/nɜrk/*	50.0%	6.4***	7	*28.6%*	*-1.2*
6	*/luks/*	0%	--	*/fumpogʌ/*	26.2%	3.8***	*/flugat/*	47.6%	6.1***	8	*25.0%*	*-1.5*
7	*/blɪt/*	0%	--	*/tombat/*	42.9%	5.5***	*/nagɪd/*	9.5%	2.1*	0	--	--
8	*/smɪt/*	0%	--	*/mɪsnʌ/*	16.7%	2.9**	*/tombat/*	47.6%	6.1***	5	*40.0%*	*-.41*
9	*/luks/*	0%	--	*/blɜrgən/*	42.9%	5.5***	*/nagrʌ/*	7.1%	1.8†	3	*0%*	--
10	*/flɪm/*	0%	--	*/nagɪd/*	7.1%	1.8†	*/lædnʌ/*	7.1%	1.8†	1	*100%*	--
11	*/blɪt/*	0%	--	*/nagrʌ/*	11.9%	2.4*	*/mɪsnʌ/*	16.7%	2.9**	1	*0%*	--
12	*/flɪm/*	0%	--	*/mɜrnat/*	21.4%	2.6*	*/slɜrgan/*	21.4%	3.3**	4	*100%*	*-1.00*

Note: Verb, Noun 1 and Noun 2 t value is comparison to 0; Word Order t value is comparison to chance (.50); † $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$

Table C.5

Children's Average Performance on Artificial Language Receptive Sentence Task Trial by Foil Type

Foil	% Correct Responses	*t*
Verb Error	43.7%	-2.03*
Object Error	59.9%	3.21**
Subject Error	58.7%	2.81**
Word Order Error	45.6%	-1.39

Note: *t* value is comparison to chance performance (.50); † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$

Table C.6

Children's Average Performance on Each Trial Type on the Artificial Language Grammaticality Judgment Task

Word Order	% Correct Responses	*t*
Verb-Noun-Noun (correct)	74.2%	12.41***
Noun-Verb-Noun	22.6%	-5.96***
Verb-Noun-Verb	42.9%	-1.32
Noun-Noun-Verb	34.5%	-2.97**
Noun-Verb-Verb	29.8%	-4.03***
Verb-Verb-Noun	26.2%	-4.93***
Verb-Verb-Verb	47.6%	-.305
Noun-Noun-Noun	14.3%	-6.54***

Note: *t* value is comparison to chance performance (.50); † $p < .10$, *$p < .05$, **$p < .01$, *** $p < .001$