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The role of non-verbal working memory in morphosyntactic processing by school-aged monolingual and bilingual children

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Abstract

The current study examined the relationship between non-verbal working memory and morphosyntactic processing in monolingual native speakers of English and bilingual speakers of English and Spanish. We tested 42 monolingual children and 42 bilingual children between the ages of 8 and 10, matched on age and non-verbal IQ. Children were administered an auditory Grammaticality Judgment task in English to measure morphosyntactic processing, and a visual N-Back task and a Corsi Blocks task to measure non-verbal working memory capacity. Analyses revealed that monolinguals were more sensitive to English morphosyntactic information than bilinguals, but the groups did not differ in reaction times or response bias. Furthermore, higher non-verbal working memory capacity was associated with greater sensitivity to morphosyntactic violations in bilinguals, but not in monolinguals. The findings suggest that non-verbal working memory skills link more tightly to syntactic processing in populations with lower levels of language knowledge.

Keywords

working memory; morphosyntactic processing; bilingualism

Working memory (WM) is typically defined as a system responsible for storage and manipulation of information during performance on complex cognitive tasks, such as language comprehension (Baddeley, 1992). A large body of research has established the relationship between working memory and language processing in adults (e.g., Masson & Miller, 1983) and children (e.g., Gaulin & Campbell, 1994). Morphosyntactic processing, i.e., the ability to parse and integrate morphological and syntactic information in sentence contexts, in particular, has been linked to working memory capacity (e.g., Blackwell & Bates, 1995). However, the understanding of the relationship between working memory and syntactic processing is incomplete due to at least two considerations. First, previously identified associations between WM and syntactic processing may have been conditioned by

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the fact that traditionally, working memory has been measured via verbal tasks that draw upon language knowledge (e.g., Daneman & Carpenter, 1980). As a result, the association between performance on working memory and syntactic processing tasks observed by prior research may have been driven by the use of language in both types of tasks rather than by the reliance on working memory during syntactic processing. Second, the relationships between WM and syntactic processing have rarely been investigated and contrasted in populations characterized by varying levels of language knowledge and experience, such as bilinguals and monolinguals. Bilingual children tend to be less successful than monolingual children on language-specific processing tasks, likely because of their reduced exposure and experience with language-specific information (e.g., Thordardottir, Rothenberg, Rivard, & Naves, 2006). It is possible that increased processing demands associated with bilingual language processing lead to distinct patterns of reliance on the working memory mechanisms that may be observed in bilinguals vs. monolinguals. To better understand the link between working memory and syntactic processing, in the present study, we examined the association between performance on a Grammaticality Judgment (GJ) task, measuring morphosyntactic processing, in English and non-verbal WM tasks in two groups of children that differed in their levels of English knowledge: monolingual English-speaking children and Spanish-English bilingual children.

Working Memory and Syntactic Processing

Although a number of different models of working memory exist, perhaps the most influential of these is the working memory model proposed by Baddeley and Hitch (1974). In it, WM is construed as a multi-component system (Baddeley, 2000) that is responsible for the storage, maintenance, and manipulation of different types of information, verbal and non-verbal. The model incorporates three storage systems: the phonological loop that processes verbal input, the visuo-spatial sketchpad that processes visual and spatial input, and the episodic buffer that integrates information from these domains and communicates with long-term memory. The Central Executive (CE) is an attention-allocation component of the model that coordinates the function of the storage systems. Performance on verbal working memory tasks that require storage and manipulation of verbal information is thus coordinated by the phonological loop (which stores the information) and the CE (which directs attention to relevant information and suppresses irrelevant information). For instance, the listening/reading span task (Daneman & Carpenter, 1980), one of the best-known verbal WM measures, requires one to operate upon a sentence (by reading/repeating it out loud or by making a grammaticality/semantic judgment upon it), and to memorize and later recall the last word of the sentence, in ever-increasing sets.

Verbal WM capacity has been linked to performance on many language processing tasks. For instance, reading/listening span tasks have been found to predict novel word learning (Atkins & Baddeley, 1998), reading comprehension (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Daneman & Carpenter, 1980, 1983; Turner & Engle, 1989), understanding complex and ambiguous structures (King & Just, 1991; Miyake, Just, & Carpenter, 1994), and the ability to draw inferences (Cochran & Davis, 1987; Masson & Miller, 1983). In one of the first studies to investigate the relationship between verbal working memory and language processing, Daneman and Carpenter (1980) tested the relationship between a

reading comprehension task (where participants read passages varying in length and were asked questions about the passages) and a reading span task (where participants read sentences, and were asked to recall the last word of every sentence in the same order they were read). The study revealed that individuals with greater reading span capacity performed better on the reading comprehension task.

The results of the Daneman and Carpenter (1980) study set the tone for later studies that further explored the relationship between verbal WM and language processing. These studies have generally yielded robust correlations between measures of verbal working memory (reading span and listening span) and measures of language processing and information integration both in adults (Bock & Miller, 1991; Daneman, 1987, 1991; Daneman & Green, 1986; Masson & Miller, 1983), and in children (Gaulin & Campbell, 1994; Swanson, 1996). Syntactic processing in particular has been shown to link tightly to verbal WM function, especially when syntactic processing is probed via Grammaticality Judgment tasks (Baddeley & Hitch, 1974; Ellis, 1991; McDonald, 2008a, 2008b; Wulfeck, 1993). In GJ tasks, grammatical structures of interest are manipulated, and errors are intentionally embedded in a sub-set of sentences. Participants have to decide whether each sentence is grammatical or ungrammatical. Numerous studies have documented the relationship between verbal working memory and error detection in GJ tasks such that better working memory capacity leads to more accurate and rapid detection of errors (Casasanto, Hofmeister, & Sag, 2010; Ellis Weismer, Evans, & Hesketh, 1999; Gottardo, Stanovich, & Siegel, 1996; Hayiou-Thomas, Bishop, & Plunkett, 2004; McDonald, 2008a, 2008b; Montgomery, 2000a; Seger, Prabhakaran, Poldrack, & Gabrieli, 2000). For example, McDonald (2008b) examined the role of verbal working memory span, measured by a size judgment task, in grammaticality judgment performance by school-aged children and adults. In the size judgment task, participants were given names of objects, which they needed to repeat back in the order of physically smallest to physically largest. The study revealed significant correlations between working memory capacity and GJ performance.

Together then, prior studies provide evidence of a robust relationship between WM capacity and syntactic processing. However, the majority of existing studies have used *verbal* tasks as measures of WM capacity (Atkins & Baddeley, 1998; Daneman & Carpenter, 1980, 1983; King & Just, 1991, Masson & Miller, 1983). The exception is the study by Noonan, Redmond, and Archibald (2014), who used the Automated Working Memory Assessment (AWMA; Alloway, 2007), which incorporated both a visuo-spatial and a verbal component as a measure of WM. However, since the AWMA combines both verbal and visuo-spatial scores, it is not entirely language-free. To our knowledge, there have been no studies on the relationship between WM and syntactic processing that assessed WM using non-verbal measures. This complicates the interpretation of the relationship previously observed between working memory and syntactic processing in that the association could have been driven by language rather than working memory itself. A similar argument has been made by MacDonald and colleagues (MacDonald, Almor, Henderson, Kempler, & Andersen, 2001; MacDonald & Christiansen, 2002), who suggested that reading and listening span tasks measure language processing and rely on language comprehension processes. As a result, the correlations observed between the reading/listening span tasks and language

processing tasks are due to the overlap at the level of the language comprehension mechanisms, rather than working memory mechanisms. Another factor that complicates the interpretation of the relationship between WM capacity and syntactic processing, as measured by GJ tasks, is that the degree to which WM is involved in syntactic processing appears to fluctuate with the location of the error in the sentence – early vs. late.

WM and Error Position Effects in Syntactic Processing

Prior studies that have attempted to consider the location of the error in the sentence in relation to WM demands have been framed within one of two theoretical accounts. The first account, termed *the WM account*, posits that as a sentence unfolds, more information must be processed and integrated, and the likelihood of exceeding working memory capacity increases (Noonan et al., 2014; Salamé, & Baddeley, 1987). As a result, errors that occur late in the sentence should place higher demands on working memory than errors that occur early in the sentence, and thus should be more difficult to detect. The second account, termed *the wrap-up account*, posits a facilitation effect associated with late (vs. early) placement of an error on syntactic processing (Blackwell & Bates, 1995). This account emphasizes the role of sentence context in error detection and in syntactic processing more generally, and predicts that detection of an error late in the sentence (vs. early in the sentence) benefits from “wrap-up” effects associated with being able to utilize sentence context. The ability to integrate information and to build up context as the sentence unfolds acts as a buffer against working memory load and reduces the burden on WM. In the wrap-up account, early errors are supported by contextual information *less* than late errors, and as a result, detection of early errors in a sentence task relies on WM *more* than late errors. There is evidence for both the WM and the wrap-up accounts of morphosyntactic processing, and in general, the few studies that have attempted to manipulate error position in GJ tasks have yielded complicated findings.

In support of wrap-up effects, Blackwell and Bates (1995) found that when they increased the difficulty of the GJ task by incorporating a secondary digit-span task, their adult participants' GJ performance suffered disproportionately for sentences that involved early-occurring errors (rather than late-occurring errors). A study by Wulfeck, Bates, Krupa-Kwiatkowski, and Saltzman (2004) conducted in children yielded similar findings. These authors examined the effect of error position on GJ performance in typically-developing children, children with specific language impairment (SLI), and children with focal brain lesions. They found that all children were more accurate and faster at detecting late errors than early errors, and suggested that greater sensitivity to and faster processing of late errors may be due to the build-up of contextual information, irrespective of language profile. However, these studies stand in contrast to a more recent study by Noonan et al. (2014).

Noonan et al. (2014) investigated the effects of error position on morphosyntactic processing in children with lower language abilities and found that children with a co-occurrence of language and working memory impairments were the least accurate on a grammaticality judgment task when it involved detection of *late* errors (vs. early errors). The results were interpreted to support the WM account of error detection, and suggested that children who had deficits in both language and working memory performed most poorly in this condition

because late errors posed the greatest WM demands. However, the study also found the reverse pattern of results for typically-developing children (matched on age and non-verbal IQ) without language or WM impairments. Typically-developing children were more accurate at detecting *late* errors than early errors. Since late errors are hypothesized to be more difficult to detect based on the WM account, but easier to detect based on the wrap-up account, these findings appear to support the wrap-up account. To make matters even more complicated, in the same study it was also revealed that children who had language impairment, but intact WM skills, were able to detect late errors as well as early errors. More broadly then, the findings of the Noonan et al. (2014) study may be interpreted to indicate that the location of the error in a sentence may influence syntactic processing differently in children with different levels of language and WM abilities.

To summarize, Noonan et al. (2014) found that typically-developing children were more accurate at detecting late errors than early errors, while children with language and WM impairments were less accurate at detecting late errors than early errors. That is, language and WM deficits may influence late-error detection because both would make it difficult for children to integrate information and to use context during the syntactic processing task. However, Wulfeck et al. (2004) found that children with language impairment (but without WM impairment) were better at detecting late errors than early errors, similar to the typically-developing group. This finding suggests even children with language impairment (but without WM impairment) may benefit from sentence context, alleviating the burden on the WM system. The difficulty with distinguishing the contributions of language skills vs. WM skills to GJ performance in typical and atypical populations stems from the fact that in these populations, language and WM go hand-in-hand. That is, in typically-developing individuals, both language and WM skills function efficiently, whereas in language impairment, both language and WM skills tend to function less efficiently (Archibald & Gathercole, 2006; Montgomery, 2000b).

In order to examine whether WM capacity *specifically* contributes differently to early vs. late error detection in children with different levels of language ability, it may be most fruitful to compare two typical populations with different levels of language skills, but comparable WM skills. A comparison of monolingual children and bilingual children can serve such a purpose, since bilingual children tend to lag behind monolingual children in the development of language-specific skills (Gathercole & Thomas, 2009; Thordardottir et al., 2006), but not working-memory skills (de Abreu, Cruz-Santos, Tourinho, Martin, & Bialystok, 2012; Bonifacci, Giombini, Bellocchi, & Conteno, 2011).

Working Memory and Syntactic Processing in Bilinguals

Adult second language (L2) learners have been shown to perform less well on oral and written GJ tasks in the L2 than native speakers or early L2 learners (Bialystok & Miller, 1999; Birdsong & Molis, 2001; Johnson, 1992; McDonald, 2000; Weber-Fox and Neville, 1996). Similarly, bilingual children tend to lag behind their monolingual peers in acquiring language-specific information – phonological, lexical, morphological, and syntactic (Gathercole & Thomas, 2009; Thordardottir et al., 2006). For instance, bilinguals often underperform relative to their monolingual peers on standardized language measures (Ben-

Zeev, 1977; Bialystok, Luk, Peets, & Yang, 2010; Hemsley, Holm, & Dodd, 2006; Hoff, Core, Place, Rumiche, Señor, & Parra, 2012; Marchman, Fernald, & Hurtado, 2010; Uccelli & Paez, 2007; Vagh, Pan, & Mancilla-Martinez, 2009), and perform less well than monolinguals on processing tasks that require rapid access to language-specific knowledge (Bialystok & Feng, 2009; Costa, 2009; Ivanova & Costa, 2008). Such differences between bilinguals and monolinguals have been well established in children in the lexical domain (Schwartz & Katzir, 2012; Yan & Nicoladis, 2009), and there have been studies indicating similar discrepancies between bilingual and monolingual children in morphosyntactic and syntactic domains (Gathercole, 2007; Nicoladis, Palmer, & Marentette, 2007; Paradis, 2010a, 2010b; Thordardottir et al., 2006).

While language-specific syntactic processing may be more taxing for bilingual speakers than for the monolingual speakers, a number of studies have demonstrated that just like monolinguals, bilinguals recruit working memory resources during syntactic processing. At the neural level (Abutalebi & Green, 2008; Hernandez & Meschyan, 2006), the dependency on WM resources is especially robust for bilinguals with lower levels of L2 proficiency. There is also a substantial body of work implicating WM in L2 learning (e.g., Linck & Weiss, 2011), and L2 syntactic and morphosyntactic processing (Miyake & Friedman, 1998; McDonald, 2006; Sagarra, 2007; Sagarra & Herschensohn, 2010). For instance, McDonald (2006) showed that late L2 learners performed significantly worse than native speakers on a GJ task, and found strong correlations between L2 learners' working memory and GJ performance. Similarly, Sagarra and Herschensohn (2010) found that intermediate L2 speakers showed greater sensitivity on an offline GJ task than beginner L2 speakers, and L2 speakers with greater working memory capacity were more successful at answering comprehension questions than speakers with lower WM capacity. However, just like the monolingual literature, the bilingual literature has utilized verbal WM tasks to index WM capacity, thus confounding linguistic processing and WM. Furthermore, rarely have there been attempts to compare the strength of the links between syntactic processing and WM capacity in bilingual vs. monolingual speakers. Yet, the strength of links that bind syntactic processing and working memory may in fact vary depending on the participants' language skills. For instance, since L2 processing is more demanding than L1 processing (Bialystok & Miller, 1999; McDonald, 2000), it may be that L2 processing would be more reliant on WM resources than L1 processing.

Current Study

Extensive prior research indicates that working memory contributes to morphosyntactic processing. However, this relationship may have been driven by overlap in language demands rather than working memory demands. There also exists a lack of clarity with respect to how error position interfaces with WM demands in constraining GJ performance. Finally, there is a general dearth of work examining the relationship between WM and syntactic processing in populations with different levels of language ability.

In the present study, we used non-verbal WM measures to assess working memory in order to disentangle the contributions of WM and language to syntactic processing. Based on Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000), both

verbal and non-verbal information is managed and coordinated by the Central Executive (CE) – a domain-general mechanism. Non-verbal WM measures capture the functioning of the CE. It follows that if the relationship between working memory capacity and syntactic processing is rooted in the ability to maintain and selectively attend to the information in working memory, then performance on non-verbal working memory tasks would be associated with performance on the syntactic processing task.

We manipulated the position of the error in the sentence to investigate the relationships between non-verbal WM capacity and the ability to detect early vs. late errors. The WM and the wrap-up accounts of sentence processing yield distinct predictions with respect to late errors. While the WM account predicts a heavier burden on the WM system associated with late placement of an error, the wrap-up account predicts a lighter burden on the WM system associated with late placement of an error. Importantly, while both accounts propose a link between WM capacity and syntactic processing, thus far, no study has examined the link between GJ performance (with error placement manipulated) and WM capacity.

Finally, we asked whether the strength of the relationship between WM capacity and syntactic processing would vary as a function of variability in language skills. Prior studies that have attempted to ask this question have done so by contrasting typically-developing children and children with language and/or WM impairments (Noonan et al., 2014; Wulfeck et al., 2004). These studies have yielded highly discrepant results, and one possibility for these conflicting findings is that children with language impairments often present with impairments in other cognitive domains, including WM (Archibald & Gathercole, 2006). Bilingual children tested in one of their languages are an ideal test-case for examining the role of WM in syntactic processing in a population that presents with lower levels of language skills, but is not compromised in any other cognitive domain. We therefore compared monolingual English-speaking children and Spanish-English bilingual children who differed in their levels of English language knowledge (as captured by parent ratings and standardized language measures), but who performed highly similarly on WM measures. Since language-specific processing was expected to be more taxing for bilinguals, we hypothesized that a stronger link would be observed between GJ performance and WM measures for bilinguals than for monolinguals.

Method

Participants

The children in the present study were recruited from local schools in Madison, WI. A total of 70 monolinguals and 45 simultaneous bilinguals were tested. Exclusionary criteria for all the children included a diagnosis of language impairment, learning disability, psychological/behavioral disorders, neurological impairments, or other developmental disabilities. Monolingual children spoke English as their native language; any exposure to a language other than English was an exclusionary criterion. Bilingual children spoke both English and Spanish; exposure to a third language (defined as >5% during the week) was an exclusionary criterion. All bilingual children were simultaneous bilinguals in that they acquired both languages at or before the age of three. From the original participant pool, sub-samples of monolingual and simultaneous bilingual children were selected to match on

age and non-verbal IQ. The resulting groups consisted of 42 monolingual children (22 males) with an average age of 9.25 years ($SD = 1.03$), and 42 simultaneous bilingual children (20 males) with an average age of 9.38 years ($SD = 1.03$). All children passed a hearing screening at 20 dB at 1000, 2000, and 4000 Hz.

The parents were interviewed in their native or preferred language regarding their children's language acquisition history, and prior and current language exposure. The demographic characteristics of the monolingual and the bilingual children can be found in Table 1, and language characteristics of the bilingual children can be found in Table 2. Maternal years of education served as proxy for the child's socio-economic status (SES). The two groups differed significantly in SES and in their performance on the English standardized language measure (Clinical Evaluation of Language Fundamentals-4th Edition; CELF-4, Semel, Wiig, & Secord, 2003), with the bilingual group scoring significantly lower than the monolingual group.

Despite this discrepancy in English language skills between bilinguals and monolinguals, the bilingual children in the present study were English-dominant, based both on their performance on the standardized language measures and on parents' ratings of the children's language proficiency. Bilingual children performed better on English than Spanish Core and Expressive indexes of the CELF-4 (p values < 0.05), but not on the Receptive index. Parental ratings of proficiency in understanding English were similar to ratings of understanding Spanish ($p = 0.06$), whereas ratings of proficiency in speaking English were higher than for speaking Spanish ($p < 0.01$). This profile is not uncommon for school-age bilingual children who tend to shift language dominance from the minority language (Spanish, in this case) to the majority language (English) upon school entry (Kan & Kohnert, 2005), especially in the expressive domain (Oller, Jarmulowicz, Pearson, & Cobo-Lewis, 2011). In our bilingual sample, 52.4% of the children attended dual-immersion classrooms, and 47.6% attended English-only classrooms.

Procedure

Children were tested on standardized assessments and experimental tasks over the course of two to three two-hour visits to the laboratory. Trained bilingual English-Spanish research assistants administered the Spanish measures to the bilingual children.

Standardized measures—The Perceptual Reasoning Index of the Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV; Wechsler, 2003) was administered as a measure of nonverbal intelligence. The index consists of scores from three different subtests of the WISC-IV – Block Design, Picture Concepts, and Matrix Reasoning. English language skills were evaluated by administering the CELF-4 (Semel, Wiig, & Secord, 2003). Spanish language skills for bilingual children were evaluated by administering the Spanish Edition of the CELF-4 (Semel, Wiig, & Secord, 2006).

Experimental tasks

Non-verbal working memory: Two measures of non-verbal WM were administered: The visual N-Back task and the Corsi Blocks task. A visual schematic of the N-Back stimuli is

shown in Appendix A. In this task, participants were asked to match the shape on the computer screen to what they saw N shapes before (Smith & Jonides, 1999; Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011). The task was designed using a series of shapes that cannot be easily labeled (Attneave & Arnoult, 1956; Vanderplas & Garvin, 1959). The shapes were chosen to make the task as non-linguistic as possible, reducing the likelihood of verbal mediation and verbal rehearsal strategies. The task had three levels of difficulty – 0-back, 1-back, and 2-back. In the 0-back condition, children were presented with a single target shape, and were required to press the green button on the response box every time they saw it and the red button if they saw any other shape. In the 1-back condition, children were instructed to press the green button on a given trial if the current shape matched the shape that appeared one trial before and press the red button if it was different. In the 2-back condition, children were instructed to press the green button on a given trial if the shape was the same as the shape that appeared two trials before and the red button if it was different. The children completed five practice trials in the 0-back and 1-back conditions and eight practice trials in the 2-back condition to ensure understanding of the task.

For all three conditions, each stimulus was presented for 1500ms, followed by an inter-stimulus interval (ISI) of 500ms. Each condition contained a total of 40 trials including 10 “hits” (target events that required the child to press the green button) and 30 “misses” (non-target events that required the child to press the red button). The trials were presented in a fixed pseudo-randomized sequence to ensure that in the 0-back condition, at least two intervening trials occurred between presentations of the target shape, and that in the 1-back and 2-back conditions, the N-1 and N-2 sequences did not repeat beyond 10 times. Overall accuracy (i.e., the summed performance across all three levels) was used for the analyses, with higher accuracy reflecting greater working memory capacity.

The second measure of non-verbal working memory was the visuo-spatial Corsi Blocks task. In this task, nine identical squares were irregularly positioned on the computer screen (see Appendix B). Participants watched a sequence of squares turn black one by one, and were then asked to click the squares (with a mouse) in the same order. Six practice items were administered using a sequence of two squares to ensure understanding of the task. Test items were then administered starting with a sequence of 2 squares, and proceeding to sequences of up to 9 squares. For every level (number of squares turning black), three sequences were presented (out of six possible random orders). Therefore, the task consisted of 24 trials, with three trials per span length starting with two and ending with nine. If the child correctly answered at least one trial at each level, the task advanced to the next level. The task was discontinued if the child incorrectly responded to all three trials within a given level. A capacity score was computed for each child using the maximum level reached where at least two out of the three trials were correct.

Grammaticality judgment: Morphosyntactic processing was evaluated via a computerized, auditory grammaticality judgment task where children were asked to listen to sentences and judge whether they were grammatically correct or incorrect. This task was adapted from a grammatical judgment task developed by Wulfeck et al. (2004). In our version of the task, we focused on the errors of omission because bilingual children in the course of second

language acquisition tend to drop grammatical morphemes rather than make other error types (Paradis, 2005; Paradis, Rice, Crago, & Marquis, 2008). We targeted omission of auxiliary markers and regular past-tense *-ed* markers because, while monolingual children acquiring English tend to acquire these morphosyntactic structures rather early, at 3–4 years of age (Brown, 1973), bilingual children acquiring English appear to have particular difficulty with them, and their acquisition can protract into the school-age years (Paradis, 2005; Paradis & Crago, 2000). The position of the errors was manipulated by placing them either early or late in a sentence (see Appendix C for the complete list of stimuli).

The stimuli consisted of 56 sentences – 28 ungrammatical sentences and 28 corresponding grammatical controls (GC) matched for length. The sentences were recorded and standardized to the same amplitude. A buffer of 3 msec was added to the beginning and the end of each sentence. Ungrammatical sentences included omissions of structure (auxiliary or tense) early or late in the sentence. Therefore, the ungrammatical conditions were: Early auxiliary omission (EAO), early tense omission (ETO), late auxiliary omission (LAO), and late tense omission (LTO). Following Wulfeck et al. (2004), early errors occurred within the first 1200ms of the sentence and late errors occurred after 1200ms. Children were administered 6 practice sentences before the task with appropriate verbal feedback. The practice sentences did not appear in the experimental set.

The experiment was designed using E-Prime Studio 2.0. Sentences were presented using computer speakers, and responses were collected via a serial response box attached to a desktop computer. The children were asked to judge the grammaticality of the sentences by pushing the “smiling face” button on the serial response box if the sentence “sounded good and like something a person would really say” or by pushing the “frowning face” button if the sentence “sounded bad and like something a person would not really say”. They were asked to push the button as soon as they knew whether the sentence was grammatical or ungrammatical. The sentences, however, played to the end even if the button press occurred prior to the end of the sentence. The presentation of the various conditions was pseudorandomized so that the same ungrammatical manipulations never occurred together (i.e., early tense and late tense) and no more than three grammatical or ungrammatical sentences were presented in sequence. Children had up to 2000ms to respond after the sentence ended and the inter-stimulus interval between each sentence was set to 750ms. Children were permitted to take breaks during this task, but no more than three breaks were allowed.

Raw accuracies (i.e., the total number of correct answers) were calculated for each child for every grammatical and ungrammatical condition. For ungrammatical sentences, sensitivity and response bias scores were calculated according to the procedure outlined by Stanislaw and Todorov (1999). Sensitivity (A') measured the degree of overlap between the distribution of correct and incorrect responses for each child and each condition, and indexed how sensitive a child was to errors in a particular condition. Sensitivity scores typically fall between 0.5 and 1, where a score of 0.5 indicates an inability to distinguish between grammatical and ungrammatical sentences and a score of 1 indicates perfect performance. However, values less than 0.5 can occur due to response confusion. Response bias (B'') measured the child's general tendency to respond ‘yes’ or ‘no’. Bias scores fell

between -1 and 1, where a score of -1 indicates a child with an extreme bias toward pressing 'yes' for every response. These measures have been previously used to assess performance on forced-choice tasks like the grammaticality judgment task (Berndt, Salasoo, Mitchum, & Blumstein, 1988; Grier, 1971).

Sensitivity and response biases were calculated using the following formulas:

$$A' = \begin{cases} 0.5 + \frac{(H-FA)(1+H-FA)}{4H(1-FA)} & \text{when } H \geq FA \\ 0.5 - \frac{(FA-H)(1+FA-H)}{4FA(1-H)} & \text{when } H < FA \end{cases}$$

$$B'' = \begin{cases} \frac{H(1-H)-FA(1-FA)}{H(1-H)+FA(1-FA)} & \text{when } H \geq FA \\ \frac{FA(1-FA)-H(1-H)}{FA(1-FA)+H(1-H)} & \text{when } H < FA \end{cases}$$

Each participant's hit rates (H) and false alarm rates (FA) were determined for each condition. A hit was defined as correctly identifying the presence of an error in a sentence (i.e., the child deciding that the sentence was ungrammatical when in fact it was). A false alarm was defined as incorrectly identifying the presence of an error in a sentence (i.e., the child deciding that the sentence was ungrammatical when in fact it was not).

Reaction times for every child were recorded for both grammatical and ungrammatical sentences. For ungrammatical sentences, reaction times were calculated by taking into account the point at which the violation occurred in each sentence. The point of violation was defined as the offset of the word prior to the error (Wulfeck et al, 2004). These points were calculated for all ungrammatical sentences and subtracted from the child's response time for each of those sentences, yielding true reaction times. Reaction time data were analyzed for correct responses only and were trimmed to remove outliers. At the child level, trials were excluded for response times that fell beyond 2.5SD of that child's mean RT for all ungrammatical sentences. Trials that had RTs of 0ms or less were eliminated (since these response times indicated responses that occurred prior to the occurrence of the error in the sentence). In total, 0.8% of all trials were eliminated.

Analyses

Independent sample t-tests were conducted for each non-verbal WM measure (N-Back and Corsi Blocks) between the monolingual and bilingual groups.

For the GJ task, separate analyses were conducted on sensitivity (A') and bias (B'') scores. Measures of sensitivity and bias were analyzed using a $2 \times 2 \times 2$ ANOVA with position (early vs. late) and structure (auxiliary vs. tense) as within-subjects variables and group (monolingual vs. bilingual) as the between-subjects variable. RT data were also analyzed using a $2 \times 2 \times 2$ ANOVA.

Lastly, multiple regressions were performed separately for the two groups of children (monolingual and bilingual) to examine whether non-verbal working memory capacity

(composite of N-Back and Corsi Blocks tasks) predicted performance on morphosyntactic processing measures (A' , B'' and RTs).

Results

Monolingual children differed significantly on SES from the bilingual children. This difference is a pre-existing characteristic of the two groups, in that it is an unfortunate demographic reality that Hispanic children in the United States tend to come from lower SES backgrounds than Caucasian children (Camarota, 2012). Therefore, SES in the present study was not independent of group membership, and best statistical practices discourage controlling for SES statistically in such situations (Miller & Chapman, 2001). We thus did not co-vary SES out in the ANOVAs, but we did take SES into account in all regression analyses, which were conducted within each of the two groups separately. This was especially important to do because SES correlated with some of the dependent variables in each group (see supplemental data, Table A).

Non-Verbal Working Memory

Independent-samples t-tests were conducted on non-verbal WM tasks in order to determine whether the two groups differed on these measures. These analyses revealed no significant group difference on non-verbal WM measures, either on the N-Back task, $t(82) = 0.58$, $p = 0.56$, or the Corsi Blocks task, $t(82) = -0.74$, $p = 0.46$.

Grammaticality Judgment

For A' scores, the ANOVA revealed a main effect of structure, $F(1,76) = 6.23$, $p = 0.02$, $\eta_p^2 = 0.08$, but no significant position effects ($p > 0.05$). Children were better at detecting auxiliary errors ($M = 0.79$, $SE = 0.02$) than tense errors ($M = 0.75$, $SE = 0.012$). A main effect of group was also observed ($F(1,76) = 6.50$, $p = 0.01$, $\eta_p^2 = 0.08$); monolingual children were more sensitive to grammatical errors ($M = 0.81$, $SE = 0.02$) than bilingual children ($M = 0.73$, $SE = 0.02$). No significant interactions were observed. In order to examine whether the sensitivity differences between the two groups were caused by a greater number of bilingual children performing at or below chance, we screened the data for chance performers, defined as children whose A' scores fell at 0.5 or below. One monolingual child had an overall A' score of 0.5 or below (0.47) and four bilingual children had overall A' scores of 0.5 and below (0.5, 0.47, 0.42 and 0.25). When data were re-analyzed with these children taken out, all results obtained with the full sample were maintained. We therefore conclude that the bilingual group as a whole was characterized by lower levels of sensitivity to morphosyntactic errors in English than the monolingual group.

For B'' scores (Figure 1), the ANOVA revealed a main effect of position, $F(1,67) = 12.21$, $p = 0.001$, $\eta_p^2 = 0.15$, where children had a stronger “no” bias (i.e., the tendency to say that the sentence is grammatical) for early errors ($M = 0.32$, $SE = 0.05$) than for late errors ($M = 0.13$, $SE = 0.06$). A main effect of structure was also observed, $F(1,67) = 20.25$, $p < 0.001$, $\eta_p^2 = 0.23$, where children had a stronger “no” bias to tense errors ($M = 0.40$, $SE = 0.05$) than to auxiliary errors ($M = 0.05$, $SE = 0.07$). Additionally, a marginal effect of group was observed, $F(1,67) = 3.62$, $p = 0.06$, $\eta_p^2 = 0.05$, where bilingual children ($M = 0.31$, $SE =$

0.06) had a stronger “no” bias than monolingual children ($M = 0.15$, $SE = 0.06$). Finally, a significant interaction between position and structure was observed, $F(1,67) = 20.21$, $p < 0.001$, $\eta_p^2 = 0.23$.

To examine the position-structure interaction effect, paired-samples t -tests were performed to isolate the effect of position on structure and the effect of structure on position. Analyses revealed a significant effect of position for auxiliary omissions, $t(73) = 5.38$, $p < 0.001$, where children showed a stronger “no” bias (tendency to say that the sentence is grammatical) to early auxiliary errors ($M = 0.27$, $SD = 0.65$) and a stronger “yes” bias (i.e. the tendency to say that the sentence is ungrammatical) to late auxiliary errors ($M = -0.14$, $SD = 0.63$). Children did not show a bias for tense errors in either position ($p > 0.05$). Analyses also revealed a significant effect of structure, but only for the late omissions, $t(75) = -6.27$, $p < 0.001$, where children showed a stronger “no” bias to late tense errors ($M = 0.44$, $SD = 0.47$) and a stronger “yes” bias to late auxiliary errors ($M = -0.16$, $SD = 0.64$). Therefore, all children (monolingual and bilingual) showed similar response bias for identifying auxiliary and tense omissions in the early position. However, they had a tendency to respond ‘no’ (sentences is grammatical) to tense errors and ‘yes’ (sentence is ungrammatical) to auxiliary errors in the late position.

RT data were analyzed in two ways, conditioned by children's response strategy. Although children were instructed to respond as quickly as possible upon detecting an error, children responded to the vast majority of trials (including trials where errors occurred early in the sentence) *after* the sentence terminated. Specifically, for monolingual children, 64.79% of early-error trials and 70.70% of late-error trials elicited a response upon sentence termination; for bilingual children, 72.14% of early-error trials and 72.81% of late-error trials elicited a response upon sentence termination. We therefore first analyzed RT data for all the trials, independent of whether the child responded before or after sentence termination. We then re-analyzed RT data, including only those trials where children responded *prior* to sentence termination.

An ANOVA on all the RTs (Figure 2) revealed a main effect of position, $F(1,68) = 411.72$, $p < 0.001$, $\eta_p^2 = 0.86$, where children were faster at detecting late errors ($M = 1871.61$ ms, $SE = 35.27$) than early errors ($M = 3007.18$ ms, $SE = 67.57$). There was no significant effect of structure or group. However, analyses revealed an interaction between structure and group, $F(1,68) = 5.86$, $p = 0.02$, $\eta_p^2 = 0.08$, and an interaction between position and structure, $F(1,68) = 11.09$, $p = 0.001$, $\eta_p^2 = 0.14$. To further examine the structure by group interaction, RTs for auxiliary and tense errors were collapsed across position and paired-samples t -tests were conducted for each participant group. Monolingual children tended to be faster at detecting tense ($M = 2312.39$ ms, $SD = 425.51$) than auxiliary errors ($M = 2510.02$ ms, $SD = 391.96$), $t(37) = 3.75$, $p = 0.001$. However, bilingual children were equally fast at detecting tense ($M = 2486.66$ ms, $SD = 534.62$) and auxiliary errors ($M = 2448.52$ ms, $SD = 377.30$), $t(31) = -0.44$, $p > 0.05$.

Paired-samples t -tests were also conducted to examine the position by structure interaction. An effect of position was observed for auxiliary errors, $t(78) = 20.71$, $p < 0.001$, and tense errors, $t(72) = 14.23$, $p < 0.001$. Thus, late auxiliary errors ($M = 1873.97$ ms, $SD = 290.91$)

were detected faster than early auxiliary errors ($M = 3123.34\text{ms}$, $SD = 581.14$), and late tense errors ($M = 1891.76\text{ms}$, $SD = 383.77$) were detected faster than early tense errors ($M = 2874.77\text{ms}$, $SD = 699.16$). However, the effect of structure was only observed for early errors, $t(73) = 2.62$, $p < 0.01$, where early tense errors ($M = 2888.72\text{ms}$, $SD = 703.29$) were detected faster than early auxiliary errors ($M = 3124.79\text{ms}$, $SD = 596.35$). The effect of structure was not significant for late errors, $t(76) = -1.27$, $p = 0.21$.

A $2 \times 2 \times 2$ ANOVA on RTs that included only those responses that were made *prior to* the termination of the sentence aligned with the results for all the RTs. The main effect of position was maintained, $F(1,23) = 135.35$, $p < 0.001$, $\eta_p^2 = 0.86$; children were faster at detecting late errors ($M = 1315.56\text{ms}$, $SE = 60.46$) than early errors ($M = 2264.35.18\text{ms}$, $SE = 75.84$). The interaction between position and structure was also maintained, $F(1,23) = 8.09$, $p < 0.01$, $\eta_p^2 = 0.26$. Only the interaction between group and structure was rendered non-significant, $F(1,23) = 0.18$, $p = 0.97$, $\eta_p^2 = 0.01$.

Relationship between non-verbal WM and GJ performance

To examine the relationship between non-verbal working memory and morphosyntactic processing, separate regression models were built for each group. In these analyses, we were interested in position rather than structure effects, and therefore GJ data were collapsed across structure (auxiliary and tense) yielding the following dependent variables – early A', late A', early B'', late B'', early RT, and late RT. Overall accuracy on the N-Back task and capacity score on the Corsi Blocks task were transformed into z-scores. These were further combined to form a composite measure of non-verbal working memory.

Children's SES was entered as the initial predictor (Model 1), followed by the WM composite (Model 2). In monolingual children (Table 3), SES explained 10.5% of the variance in early A' scores ($p = 0.04$), and the addition of the WM composite did not improve the model ($R^2 = 10.7\%$, $p = 0.12$). For late A' scores, SES explained 8.7% of the variance ($p = 0.06$), and the addition of the WM composite did not improve the model ($R^2 = 8.8\%$, $p = 0.18$). Therefore, after accounting for SES, WM did not significantly predict sensitivity to early or late errors in monolingual children. In bilingual children (Table 4), SES explained 14.1% of the variance in early A' scores ($p = 0.02$), and the addition of the WM composite further improved the model by a significant 10.4% ($p < 0.01$). For late A' scores, SES explained 8% of the variance ($p = 0.07$), and the addition of the WM composite improved the model significantly by 10.8% ($p = 0.02$). Therefore, after accounting for SES, WM significantly predicted sensitivity to early *and* late errors in bilingual children.

SES and WM did not significantly predict early B'' or late B'' or early RTs in either participant group (all $p > 0.05$). However, for bilingual children, SES significantly predicted 22.4% of the variance in late RTs ($p < 0.01$), although the addition of the WM composite did not improve the model ($R^2 = 22.4\%$, $p = 0.87$).

Discussion

The purpose of this study was to examine the relationship between non-verbal working memory (assessed by an N-Back and a Corsi Blocks task) and morphosyntactic processing

(measured by a grammaticality judgment task) in populations with varying levels of language-specific skills (monolingual and bilingual children). We found that children's sensitivity to errors was not contingent on the position of the errors in the sentence. However, children were less biased in their responses to late errors than early errors, and responded faster to sentences containing late errors vs. early errors. Most significantly, we found that non-verbal WM did not predict sensitivity to morphosyntactic errors in monolingual children, but did predict sensitivity to both early and late errors in bilingual children.

Group Differences in Morphosyntactic Processing

In the current study, we found that monolingual children were more sensitive to ungrammatical structures in English than their bilingual peers. However, the two groups did not differ in response bias or response times on the GJ task. The finding that monolingual children had greater sensitivity to morphosyntactic errors than bilingual children supports previous research that has found that monolinguals tend to outperform bilinguals on language-specific tasks (Gathercole & Thomas, 2009; Thordardottir et al., 2006). The findings of the present study are particularly notable in light of the fact that while the bilingual children did perform less well than monolingual children on the standardized English language measures, they presented with quite strong English language skills. The dominant language for 36 out of the 42 bilingual children was English, their standardized English language scores fell within 1 SD of the mean, and they were highly proficient in English based on parent ratings. We therefore suggest that lower levels of sensitivity to English morphosyntax in the bilingual group are likely the result of a combination of factors identified by prior studies as contributors to bilingual children's performance on language processing tasks. These include their more shallow language-specific skills (Gathercole & Thomas, 2009; Thordardottir et al., 2006), their difficulty with the particular structures we targeted in the present experiment (Paradis, 2005; Paradis & Crago, 2000), lower SES (which has been linked with less successful language performance in children, Calvo, & Bialystok, 2014; Qi, Kaiser, Milan, & Hancock, 2006), and distributed exposure to the two languages (Pearson, Fernandez, Lewedeg, & Oller, 1997; Thordardottir et al., 2006).

It is difficult to select one of these factors as the driving contributor to bilingual children's lower English GJ performance, especially since they are likely to interact with each other. In exploratory analyses (see supplemental data, Table B), we examined correlations between bilingual children's sensitivity scores and variables associated with language exposure. We found that children's *A'* scores correlated with SES ($r = 0.37, p = 0.02$), amount of English exposure ($r = 0.48, p = 0.001$), and age of English acquisition ($r = -0.43, p < 0.01$). It is clear then that there was great variability in bilingual children's GJ performance in the present study, and that some of this variability was due to differences in language exposure, language acquisition history, and SES. Future studies whose goal it will be to examine such variability in bilingual children's language performance would need to target all these variables. For our purposes, it is important to reiterate that the school-aged bilingual children tested in the present study, who were English-dominant, and who presented with fairly strong language skills in English according to standardized measures, continued to have difficulties with English morphosyntactic processing tasks. While the risks of over-

diagnosing typically-developing bilingual children with a language impairment are well-known for young children (Paradis 2005; Paradis & Crago, 2000, 2004), it is believed that by the school age, discrepancies in language skills between bilinguals and monolinguals diminish (Golberg, Paradis, & Crago, 2008; Hammer, Lawrence, & Miccio, 2007). Here, we show that differences in language-specific abilities between bilingual and monolingual children persist into the school age, and may be especially robust for tasks that involve time constraints. Such difficulties with English morphosyntactic processing would interfere with bilingual children's ability to function fully in the classroom, and future work will need to examine whether the patterns of findings observed in the present study have repercussions for children's ability to perform more ecologically-valid, academic tasks.

Error Position Effects in Morphosyntactic Processing—Most relevant to the goal of the present study, we did not observe a position effect in the sensitivity data, either for the monolingual or the bilingual group. We did observe an effect of structure, such that all children (both monolinguals and bilinguals) were better at detecting the omission of auxiliaries than of tense markers. This finding may be due to the phonological saliency of an auxiliary verb versus the tense marker *-ed*. Omission of an entire word (e.g., *is*, *was*) may have been more obvious to children than the omissions of a single, word-final morpheme (play-*ed*) that is notoriously phonologically subtle (Leonard, Eyer, Bedore, & Grela, 1997; Montgomery & Leonard, 1998). However, both monolingual and bilingual children were equally sensitive to errors that occurred early vs. late in a sentence. This finding is contrary to earlier studies that have shown that children were more accurate at identifying late errors than early errors (Wulfeck et al., 2004). We believe that distinct methodological details in our study vs. other studies are likely the culprits behind the discrepancy.

One difference between our study and prior work is the type of error targeted in ungrammatical sentences. For instance, previous studies focused on agreement and transposition errors (Blackwell & Bates, 1995; Wulfeck et al., 2004), or intrusion errors (Noonan et al., 2014), in addition to omission errors, whereas we only included errors of omission in our manipulation. Blackwell and Bates (1995) and Wulfeck et al. (2004) found that omission errors were detected equally well in early and late positions, and the position effect in their studies was primarily driven by agreement errors. Previous studies also manipulated morphosyntactic structures that were different from the ones targeted in the present study. For instance, prior work included determiners (Blackwell & Bates, 1995; Wulfeck et al., 2004), third person singular, possessive *-s*, and *ing* omissions (Noonan et al., 2014), in addition to auxiliary and past tense markers. Here too, Blackwell and Bates (1995), and Wulfeck et al. (2004) found that position effects in their data were largely driven by determiner errors (rather errors on auxiliary verbs). Therefore, the lack of a position effect in the sensitivity data in the current study may be driven by the possibility that omission of auxiliary and/or tense markers is less sensitive to wrap-up or working-memory influences than other error types. While our choice of target structures was conditioned by prior studies that have identified tense and auxiliary markers as being particularly difficult for bilingual children (Paradis, 2005; Paradis & Crago, 2000), a hypothesis confirmed by generally lower sensitivity scores in the bilingual group, future studies would need to

include a wider array of structures and error types in order to examine the generalizability of position effects.

Additional differences between our study and prior work stem from quantifications of grammaticality judgment performance. While earlier studies investigating morphosyntactic processing have also used A' statistic to index sensitivity (Blackwell & Bates, 1995; Miller, Leonard & Finneran, 2008; Noonan et al., 2014; Rice, Wexler, & Redmond, 1999; Wulfeck et al., 2004), their calculations of the A' statistic only accounted for levels of performance where hit rates were greater or equal to false alarm rates. That is, in prior work, only one equation was used to calculate A' scores (Grier, 1971). In the current study, an additional equation was used (Stanislaw & Todorov, 1999; Snodgrass & Corwin, 1988) to account for hit rates whose number was lower compared to false alarm rates. Another point of difference between our study and other studies is the inclusion of the separate statistic that indexes response bias (B''). In our study, we calculated response bias separately from sensitivity (A'), and used two equations for B'' scores to include a wider range of children's responses. In contrast, in other studies, the conceptualization of the A' statistic included both the sensitivity and the response bias (Blackwell & Bates, 1995; Miller et al., 2008; Noonan et al., 2014; Rice et al., 1999; Wulfeck et al., 2004), such that A' scores were defined as a non-parametric statistic of proportion correct that accounts for response bias. However, the original conceptualization of sensitivity and response bias on forced-choice tasks (Grier, 1971) defined sensitivity and bias as separate indexes, where A' *did not* account for response bias, and different formulas were provided for the two measures. Stanislaw and Todorov (1999) further demonstrated that discrimination tasks reflect two factors that are independent of each other – sensitivity and bias – and that they must be treated separately. It is likely then that by dissociating sensitivity and response bias, our study yielded findings that were distinct from those observed in prior work.

One piece of evidence to support this as the primary reason behind the pattern of findings observed here vs. prior work is that while we did not observe an effect of error position on sensitivity (A'), we *did* observe an effect of error position on response bias (B''). Specifically, we found that children were more likely to identify sentences as ungrammatical when the sentences contained *late* errors rather than *early* errors. This bias characterized omissions of auxiliary rather than tense structures, and it is important to note that the bias score for late errors was very close to 0, indicating that children showed almost *no* response bias to late errors. While lack of a response bias does not translate to better performance – that is, bias and sensitivity scores are not one and the same, this finding may be interpreted to suggest that children were better at distinguishing *late* errors than *early* errors from their grammatically correct controls. Furthermore, analyses of RT data revealed an effect of error position, in that late errors were identified significantly faster than early errors.

Our finding of RT differences for early vs. late errors aligns with previous work that examined RTs on a GJ task and found faster detection of late vs. early errors (Blackwell & Bates, 1995; Wulfeck et al., 2004). Previous studies have interpreted this finding to support the wrap-up account of morphosyntactic processing (Blackwell & Bates, 1995), in that it appeared to suggest that contextual information, which is more available later in the sentence, facilitates late error detection. However, it is important to note here that there is an

alternative explanation of faster RTs to late vs. early errors that has less to do with contextual build-up of information, and more to do with a late-response strategy that many children have adopted in completing the GJ task. That is, despite the instructions to respond as quickly as possible once the error was detected, many children responded to the ungrammatical sentences after they had finished playing. In fact, 50.73% of the trials in the early-error condition and 74.90% of the trials in the late-error condition were responded to *after* sentence termination across all the children. Thus, inevitably, RTs calculated from the offset of the word before the violation would be shorter for sentences that contained late errors than for sentences that contained early errors. In order to examine whether this was indeed the driving factor behind the RT results, we reanalyzed RT data including only those responses that were made *before* sentences terminated, and found the exact same position effect. Therefore, although it is impossible to completely rule out the contributions of the overall late-response strategy to the RT findings, we interpret this result to suggest that the position effects in RT data reflect a true contextual facilitation effect. That is, error detection in this study appears to have been facilitated by contextual information, which was more readily available for late errors than for early errors, with the end-result of faster (but not more accurate) detection of the late errors. How then do these findings fit with the conceptualization of working memory as a contributor to sentence processing performance?

WM and Morphosyntactic Processing

Much of prior work on the relationship between working memory and syntactic processing used verbal tasks to measure WM. Thus, it is difficult to interpret prior findings of the association between working memory and language processing as reflecting the role of WM in sentence processing (MacDonald et al., 2001; MacDonald & Christiansen, 2002). In the present study, we used non-verbal tasks to measure working memory capacity, and examined the relationship between these measures and GJ performance. We hypothesized that if violations late in the sentence imposed higher WM load than violations early in the sentence (Casasanto et al., 2010; Noonan et al., 2014), then WM capacity would predict performance on sentences containing late errors. However, if “wrap-up” effects relieved processing load (Blackwell & Bates, 1995; Wulfeck et al., 2004), then sentences containing early errors would place a greater burden on WM, and as a result, WM capacity would predict performance on sentences containing early errors. We further hypothesized that WM capacity would more strongly predict morphosyntactic processing in bilingual children than in monolingual children because English morphosyntactic processing may be more strenuous for bilingual children, thus taking up more WM resources.

Once we accounted for the role of SES in GJ performance, we did not observe relationships between non-verbal WM and GJ performance in *monolingual* children, and this was the case for all three measures of GJ performance – sensitivity, response bias, and RTs. One possibility for lack of such a relationship is that our findings are particular to a very special sample of school-age monolingual children – those who possess above-average language skills. Yet another, related, possibility is that the GJ task we used in our study was not challenging enough for the monolingual children, whose linguistic skills alone might have been sufficient to perform the task, and who did not need to draw upon domain-general WM resources. Future work would do well to include post-test questions regarding children's

impressions of the difficulty of the GJ task, in order to examine whether different populations of children find the same task subjectively more or less difficult, and whether these impressions converge with objective measures of performance. Future studies would also need to include parallel measures of verbal and non-verbal working memory in order to examine whether the relationships observed by prior studies between grammaticality judgment performance and WM capacity in monolinguals (McDonald, 2008a, 2008b; Wulfeck, 1993) are specific to verbal WM tasks only.

In contrast to monolingual children, we *did* observe significant relationships between non-verbal WM and sensitivity to grammatical errors, both early and late, in bilingual children, even after accounting for the effects of SES. That is, greater WM capacity was associated with heightened sensitivity to English morphosyntactic errors in bilingual children. This association between non-verbal WM and GJ performance was specific to the sensitivity data, and did not apply to response bias scores or to the RT data. What explains a significant relationship between non-verbal WM and morphosyntactic processing in the bilingual group but not in the monolingual group? Our preferred explanation is that this difference stems from bilingual children's lower English language skills, which make morphosyntactic processing in English more arduous for them, especially when it comes to their *sensitivity* to morphosyntactic errors.

Bilingual children are an ideal population for examining how fluctuations in language abilities may influence reliance on WM. Unlike children with language impairments, who often present with comorbid WM difficulties (Archibald & Gathercole, 2006; Montgomery, 2000b), simultaneous bilingual children like the ones studied here often perform less successfully than their monolingual peers on language tasks (Thordardottir et al., 2006), but perform similarly to them on non-verbal WM tasks (Namazi & Thordardottir, 2010). Although there have been some indications of bilingual advantages on non-verbal WM tasks (Hernández, Costa, & Humphreys, 2012; Morales, Calvo, & Bialystok, 2013), a number of studies have shown highly comparable WM profiles for bilingual and monolingual children (Bonifacci et al., 2011; de Abreu et al., 2012). In line with these latter studies, the bilinguals in our study performed very similarly to the monolingual children on the two non-verbal WM measures.

For the bilingual children like the ones studied here, language-specific morphosyntactic processing, which is cognitively challenging, may rely on domain-general WM resources (a relative strength). Just like for the monolingual children, for the bilingual children, no relationships were obtained between non-verbal WM and response times or response bias scores. That is, even in bilinguals, non-verbal WM was associated with the accuracy, rather than the speed, with which children performed the GJ task. Since we did not observe position effects in the sensitivity data, it is not surprising that the strength of the relationship between A' scores and non-verbal WM did not vary with the position of the error in the sentence. Rather, our findings indicate that in bilinguals, reliance on non-verbal WM seems to be a default strategy for language-specific morphosyntactic processing, throughout the sentence, and independent of error position.

Conclusion

In conclusion, we found that bilingual children were less sensitive to morphosyntactic violations in English than monolingual children, likely because of a variety of factors associated with bilingual language use and exposure that result in less robust language-specific abilities in bilingual children. We also found position effects in the grammaticality judgment data for both groups of children, with stronger performance on sentences containing late errors vs. early errors. This finding substantiates the wrap-up account of morphosyntactic processing, which posits that greater availability of context later in the sentence makes detection of errors late in the sentence easier. These position effects were observed for response bias and response time data and not for the sensitivity data, indicating that contextual availability enhanced primarily the efficiency, rather than the accuracy of error detection in our study. It is difficult to interpret these findings in relation to the working memory account of morphosyntactic processing, because we did not observe different degrees of reliance on WM for sentences that involved late errors vs. early errors. That is, were it the case that the processing of late errors benefited from reduced reliance on the WM system, we would have expected stronger relationships between grammaticality judgment performance and WM capacity for sentences containing early errors rather than late errors. Instead, we observed no relationship between non-verbal WM measures and morphosyntactic processing, either for late or early errors, in monolinguals, and an equally strong relationship between non-verbal WM measures and morphosyntactic processing, for late and early errors, in bilinguals.

Most significantly, we did observe a strong relationship between morphosyntactic processing and *non-verbal* WM capacity, albeit only in bilingual children, and only for the sensitivity measures. Prior studies examining contributions of WM to morphosyntactic processing have employed verbal tasks to measure WM, and thus the observed relationships may have been due to an overlap in language, rather than WM demands, between language processing and WM tasks. Here, we administered non-verbal tasks to measure WM capacity in order to substantiate the role of WM *per se* in morphosyntactic processing, and found no relationship between non-verbal working memory and morphosyntactic processing in monolingual children. We interpret this finding to indicate that language-free WM capacity contributes minimally to language processing in children with optimal linguistic skills. Alternatively, it is possible that because the GJ task was likely relatively easy for the monolingual children in the present study, there was not sufficient variability in GJ performance to allow the influences of individual differences in non-verbal WM to emerge. In contrast, because for bilinguals in the present study, the GJ task was likely quite difficult and processing-heavy, individual differences in non-verbal WM could contribute significantly to individual differences in morphosyntactic processing. Whatever the explanation for the different patterns of results observed in the two groups of children, these findings suggest that the relationship between language-free WM capacity and syntactic processing fluctuates with levels of linguistic ability such that, the effects of non-verbal WM on language processing are revealed more readily in children with lower language skills.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Appendix

0-Back:

Target ↓

Non-target ↑

“When you see this shape, press the green button.”
“For any other shape, press the red button.”

1-Back

Non-target ↓ Target ↓ Non-target ↓

“Press the green button if the shape is the same as the one before it.
Press the red button if it’s different.”

2-Back

Non-target ↓ Non-target ↓ Target ↓

“Press the green button if the shape is the same as the one two shapes before it.
Press the red button if it’s different.”

Appendix A.
N-Back task stimuli

2-Block sequence

“First, watch the blocks turn black.
Then click on the blocks in the same
order.”

4-Block sequence

6-Block sequence

Appendix B.
Corsi Blocks task stimuli

Appendix C

Grammaticality Judgment task stimuli

Early Auxiliary Omission	
Ungrammatical	Grammatical Control
1. *The children ___ asking if they could go outside at recess.	1. They were sharing several comic books while waiting for the next bus.

Early Auxiliary Omission	
Ungrammatical 2. *Zack's mom ____ guessing that they had gotten into trouble once again. 3. *My sister ____ opening her laptop when suddenly the power went out. 4. *Poor Mateo ____ feeling sick after riding the roller coaster. 5. *The children ____ going to the library after school today. 6. *The twins ____ working on painting their bedroom blue and green. 7. *The children ____ visiting a museum that has a collection of dinosaur fossils.	Grammatical Control 2. They were playing both soccer and baseball this spring. 3. Catalina was rolling the soccer ball down her neighbor's driveway. 4. Mom was emptying the dishwasher when she dropped the cup. 5. The kids were whispering about the substitute teacher when he walked in. 6. His phone was beeping in the middle of class. 7. The troop was meeting to discuss the upcoming cookie sale.
Late Auxiliary Omission	
Ungrammatical 1. *Even though they had both practiced the song, they ____ worrying about tonight. 2. *Despite his mom's warning, Mackenzie's little brother ____ annoying us again. 3. *The soccer players' exceptional teamwork ____ helping them win. 4. *Our dads get extremely focused when they ____ grilling the burgers. 5. *Little did they know that the principal ____ searching for them. 6. *Although they should leave their bug bites alone, they ____ scratching at them. 7. *Only Elmer's glue and a little tape ____ keeping it together.	Grammatical Control 1. The Nelson's two black labs were barking last night. 2. My sister was watching the band that was marching at halftime. 3. The piece came loose while they were hammering it in. 4. I tried lots of friends but no one was answering their phone. 5. Alejandro got really angry when he learned Nathan was insulting his brother. 6. Mia loved that mom was painting it orange. 7. While on vacation, our new neighbors were feeding our hamster.
Early Tense Omission	
Ungrammatical 1. *While Jacob wait__ for his friends, he played his Nintendo DS. 2. *His sister startle__ him when she held up the worm. 3. *Cousin Ethan yell__ for help when the bee stung him. 4. *My friend struggle__ with the heavy load as he climbed the hill. 5. *Curious Emma discover__ a secret notebook hidden in the basement. 6. *The player shield__ his eyes as he looked for the baseball. 7. *My grandma cook__ macaroni and cheese last night.	Grammatical Control 1. While Chloe looked at her new book, she sat on the couch. 2. Her dad surprised her by adopting the cute puppy she'd wanted. 3. Uncle William laughed while his friend made funny noises. 4. The truck driver stopped for the ducks crossing the road. 5. The cat climbed to the very top of the tree. 6. My dad mowed the grass by hand when the tractor broke. 7. Poor Sam jumped when his brother popped the balloon.
Late Tense Omission	
Ungrammatical 1. *Last evening in a beautiful park, a girl pick__ some flowers.	Grammatical Control 1. While he was listening to music, he tapped his foot.

Late Tense Omission	
Ungrammatical	Grammatical Control
2. *When the mailman spotted the sleeping dog, he quietly walk__ around it.	2. The chipmunk found the hole and squeezed through it.
3. *Caleb collected some of the eggs while Hannah gather__ some more.	3. Alyssa wanted to help so after dinner she washed her plate.
4. *The alert neighbor saw there was trouble and call__ for help.	4. The colorful costumes were the things that I enjoyed the most.
5. *Hailey was feeling homesick so she only stay__ until yesterday.	5. The powerful thunderstorm that moved through here last night destroyed the crops.
6. *It was very clear who spill__ the milk.	6. The police officer saw him speeding and pulled him over.
7. *My mom was excited when she plant__ the tomatoes.	7. Logan needed his keys so he carried them along.

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Highlights

- English-Spanish bilingual and English monolingual children were administered an English Grammaticality Judgment task and two non-verbal working memory measures.
- Monolingual children were more sensitive to grammatical violations than bilingual children on the Grammaticality Judgment task.
- Greater working memory capacity was associated with greater sensitivity to grammaticality in bilingual, but not monolingual children.
- Non-verbal working memory contributes to morphosyntactic processing in children with lower language skills.

Figure 1.
Monolingual and bilingual response bias data on the GJ task

Figure 2.
Monolingual and bilingual RT data on the GJ task

Table 1

Participant Characteristics

	Monolingual <i>n</i> = 42	Bilingual <i>n</i> = 42
Age (years)	9.25 (1.03)	9.38 (1.03)
Non-Verbal IQ (Perceptual Reasoning Index, WISC-IV)	107.83 (11.31)	106.48 (13.49)
Socioeconomic Status (SES) ^a	16.83 (3.06)	13.60 (3.98) ***
English Core Language (CELF-4)	108.32 (12.80)	95.00 (19.22) ***
English Receptive Language (CELF-4)	109.83 (14.77)	98.55 (19.30) **
English Expressive Language (CELF-4)	108.83 (13.21)	92.90 (18.92) ***

Note. The data in Table 1 represent Means and Standard Deviations. The means for standardized measures represent Standard Scores ($M = 100$, $SD = 15$).

^a Socioeconomic Status was indexed by total maternal years of education

** Significance level < 0.01

*** Significance level 0.001

Table 2**Bilingual Characteristics**

	<i>n</i> = 42
Spanish Core Language (CELF-4)	85.88 (12.07)
Spanish Receptive Language (CELF-4)	94.40 (11.30)
Spanish Expressive Language (CELF-4)	82.20 (13.19)
Current English Exposure (%) ^b	53.42 (20.44)
Current Spanish Exposure (%) ^c	46.56 (20.44)
English Age of Acquisition (months) ^d	8.02 (12.66)
Spanish Age of Acquisition (months) ^e	1.57 (6.59)
Dominant Language ^f	English–60%; Spanish–14%; Both–26%
School Language ^g	English–55%; Spanish–12%; Both–33%
English Proficiency ^h	Understanding – 8.45; Speaking – 8.31
Spanish Proficiency ^h	Understanding – 7.90; Speaking – 7.38

Note. The data in Table 2 represent Means and Standard Deviations. The means for standardized measures represent Standard Scores ($M = 100$, $SD = 15$).

The formula was adjusted to take into consideration special circumstances such as when a child heard one language more on certain days of the week.

^b English exposure = ((No. of hrs. of English heard on a weekday * 5 days per week) + (No. of hrs. of English heard on Sat. & Sun.)) / (No. of hrs. child is awake per week)

^c Spanish Exposure = 100 – percent of English exposure

^d Parent report: age when child started hearing English on a daily basis

^e Parent report: age when child started hearing Spanish on a daily basis

^f Parent report: child's dominant language

^g Parent report: child's language of instruction in school

^h Parent report: child's understanding of and speaking English/Spanish compared to children their age; 0 (not proficient) to 10 (perfect).

Table 3

Monolingual regression models

		Early A'		Early B''		Early RT	
		$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$
SES	0.33 *	0.31		0.13	0.12	0.09	0.14
WM		0.04			0.05		-0.11
R^2	0.11 *	0.11		0.02	0.02	0.01	0.02
F	4.47 *	2.21		0.65	0.36	0.38	0.40
R^2		0.002			0.002		0.01
F		0.07			0.07		0.44

		Late A'		Late B''		Late RT	
		$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$
SES	0.30	0.29		-0.08	-0.03	-0.04	0.01
WM		0.03			-0.16		-0.15
R^2	0.09	0.09		0.007	0.03	0.001	0.02
F	3.64	1.80		0.25	0.55	0.05	0.43
R^2		0.001			0.02		0.02
F		0.04			0.86		0.81

* Significance level $p < 0.05$

Table 4

Bilingual regression models

	Early <i>A'</i>		Early <i>B''</i>		Early RT	
	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$
SES	0.38 *	0.35 *	-0.05	-0.06	-0.09	-0.09
WM		0.32 *		0.19		-0.04
R^2	0.14 *	0.25 *	0.002	0.04	0.009	0.01
F	6.42 *	6.16 **	0.09	0.83	0.34	0.20
R^2		0.10 *		0.04		0.002
F		5.21 *		1.55		0.07

	Late <i>A'</i>		Late <i>B''</i>		Late RT	
	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$	$\beta 1$	$\beta 2$
SES	0.28	0.26	-0.09	-0.09	-0.47 **	-0.47 *
WM		0.33 *		-0.07		-0.02
R^2	0.08	0.19 *	0.009	0.01	0.22 **	0.22 **
F	3.39	4.39 *	0.35	0.27	11.23 **	5.49 **
R^2		0.11 *		0.005		0.001
F		5.03 *		0.19		0.03

* Significance level < 0.05

** Significance level < 0.01